College of Engineering

ISSN: 1813-162X (Print) ; 2312-7589 (Online)

Tikrit Journal of Engineering Sciences

available online at: http://www.tj-es.com

TJES Tikrit Journal of Engineering Sciences

Experimental Study on Bond Behavior between Rusty Steel Reinforcement and Concrete

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***Keywords*:**

Reinforcement rust
slip
normal concrete
high strength concrete
embedment length
bond epoxy

ARTICLE INFO

Article history:

Received 13 December 2016
Accepted 22 March 2017
Available online 17 June 2018

ABSTRACT

The effect of rust of the reinforcement bars on the bond and slip behavior between the rebars and the surrounding concrete is still under research judgement. This paper, investigated the effect of ranges of rebar rusting (0, 30-50% and 70-90%) of the limits of losing in mass that specified in the ASTM standard (6% of bar nominal mass) combined with other main parameters that affect the bond and slip behavior. A number of 72 pullout prepared specimens were tested. The studied parameters were using normal and high strength concrete (31 MPa and 76 MPa), different bars diameters (12, 16 and 25 mm), the change of embedment length (150 and 300 mm) and the using of bond epoxy coating for embedded length of reinforcing bars. The results showed that the rust within certain amount of permissible losing of mass (about 50%) led to increase the bond strength and decrease the slip between reinforcement bars and concrete. However, increasing rusting above 50% but within the permissible losing in mass would slightly decrease the bond strength and increase the slip comparing with zero rusting case for all tested bar sizes with and without using the bond improvement factors. The main recommendation of the study is to use the same criterion of acceptance of losing in mass specified by ASTM as the acceptance criterion of the amount of rust in the reinforcement bars and using one of the studied improvement factors when the rust amount exceed 50% of the permissible limit of losing in mass.

DOI: http://dx.doi.org/10.25130/tjes.25.2.06

دراسة تجريبية حول سلوك الربط بين حديد التسليح الصدأ والخرسانة

الخلاصة

يعد تأثير صدأ حديد التسليح على الربط بينه وبين الخرسانة المحيطة به من المواضيع التي لا زالت خاضعة الى البحث والتقييم. في هذا البحث تم دراسة تأثير نسب متفاوتة من صدأ الحديد (0، 30-50%،70-90%) من الحدود المسموحة للفقدان بالوزن التي توصي بها المواصفة الامريكية ASTM والبالغة 6% من الكتلة الاسمية لقضبان التسليح. تم تحضير وفحص 72 نموذج بطريقة السحب. وتم دراسة مجموعة من العوامل المؤثرة في قوة الربط بوجود او عدم وجود صدأ الحديد. العوامل التي تم دراستها هي استخدام خرسانة اعتيادية وعالية المقاومة (31 و76 ميكاباسكال) واقطار مختلفة لقضبان التسليح (12، 16، 25ملم) والتغيير في الطول المغمور (150 و300 ملم) بالإضافة الى استخدام الايبوكسي في طلاء الجزء المغمور من حديد التسليح. بينت النتائج بأن وجود صدأ الحديد بنسبة محددة (تصل الى 50%) من القيم المسموحة للفقدان بالوزن تزيد من مقدار الربط بين قضبان التسليح والخرسانة وتقلل من مقدار الانزلاق بينهما. بينما زيادة الصدأ اعلى من هذه النسبة ولكن ضمن الحدود المسموحة من الفقدان بالوزن تقلل بشكل طفيف من مقدار الربط مقارنة مع حالة انعدام الصدأ لكل النماذج المفحوصة. وهذه النتيجة انطبقت في جميع الحالات حتى مع استخدام العوامل التي تزيد من الربط. التوصية الرئيسية من البحث هي تبني نفس الشروط التي تتبناها المواصفة الامريكية ASTM في قبول الفقدان في وزن قضبان التسليح لتكون نفسها المعيار في قبول كمية صدأ حديد التسليح مع استخدام أحد العوامل المدروسة لتحسين الربط عندما تتجاوز نسبة الصدأ 50% من الحد المسموح من الفقدان في الوزن.

1. INTRODUCTION

The bond between steel reinforcement and concrete is essential for the composite action. Mainly the bond depends on the bar size, surface roughness and concrete strength. Rebars normally exposed to different weather conditions before being placed in its final position in the structural member, this will cause different level of rebar rusting before and may be after concrete casting. Mostly the rust of deformed reinforcing bars cannot be avoided and additional cost will be required for cleaning or even

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rejecting the rebars depending on the appearance. The effect and acceptance criteria of rust still under research judgment. The standards ASTM A 615/A 615M – 15a [1] and ACI 318M-14 [2], do not refer to specific limits of rebar rusting, however ASTM [1], refers to limits to the loss of mass which may be a result of many different reasons.

Several researches have been achieved on studying the parameters affecting the bond strength. Fu and Chung [3], investigated the effect of the corrosion on the bond between concrete and steel rebars. The main observation was that the corrosion of steel increased both bond strength and contact resistivity till 5 weeks of immersing the concrete in saturated Ca(OH)2 solution. After 5 weeks the bond strength was decreased and the contact resistivity continued in increasing. Wei-lian and Yu [4], studied the effect of reinforcement corrosion on the bond behavior and bending strength by testing four series of pullout and beam specimens. They showed that the effect of cracking of the concrete cover has the major effect on the bond strength. Also, they indicated that the bond strength increases with increasing corrosion, but with progressive corrosion, the bond strength decreases. Al-Negheimish and Al-Zaid [5] have prepared a series of 63 pullout test specimens for two different manufacturing processes and seven periods of exposure (0, 3, 6, 12, 18, 24 and 36 months) to the severe environment of the Arabian Gulf area. They showed that, the bond strength is improved by short exposure and decreased to about 10% of that of fresh bars in 36 months. Also, they indicated that, the manufacturing process affected the loss of mass during exposure periods, but the bond strength from the two manufacturing processes showed similar behavior. Duck et al. [6] have conducted a set of pullout tests for pre-corroded (16, 19, and 25mm) rebars embedded in (24 and 45 MPa) compressive strength concrete. They showed that up to 2% of rust the bond strength was increased regardless of concrete strength or bars diameters. However, the bond was increased when increasing the concrete strength or degreasing the bar diameters. Congqi et al. [7] have investigated the effect of steel corrosion on bond for different corrosion levels. They used pullout tests and finite elements analysis and compared the two results. For confined deformed bars, a medium level of 4% corrosion had no substantial influence on the bond strength, but substantial reduction took placed when corrosion increased thereafter to a higher level of 6%. It is demonstrated that the confinement supplies an effective way to counteract bond loss for corroded steel bars of medium (4%-6%) corrosion level. Valente [8], investigated the effects of natural corrosion, confinement, concrete cover, concrete strength and repeated cyclic loading on bond strength. The experimental results showed that the bond is affected by concrete cover and by the different corrosion levels of the longitudinal and transverse reinforcement. Also, the bond strength degradation was observed due to repeated cyclic loading. Juraj and Ivan [9], studied the effect of reinforcement corrosion from the point of view of expansion, loss of steel cross section and the loss of bond between steel and concrete. For the bond strength it is noticed that the bond strength is generally helped by the presence of residual rust up to the point where the dimensions of the ribs becomes critical. The presence of rust also inhibits further steel corrosion in good concrete. The effect of loss of section is too small to be significant, in the range from (0.008 to 0.04mm) with a section loss up to 1% compared to the widely accepted tolerance of 6-10% in most product standards. The initial increase in bond has been attributed to the expansive nature of iron oxide, while the subsequent decrease is related to the buildup of a soft layer of loose corrosion products at the bar-concrete interface. Huang [10], has investigated the effect of reinforcement corrosion on the bond properties between concrete and reinforcing steel bars. Pullout tests were conducted on a total of 20 specimens using corroded reinforcement bars embedded in concrete specimens. The specimens divided into two groups, the first with whole surface corroded and the second with partial surface corroded. Four level of corrosion were adopted 3,5,10 and 15%. The conclusions were that the ultimate bond strength of corroded bars may increase slightly with corrosion level less than 3%, but tend to decrease as the corrosion level exceeds 3%.

In the present study, the effect of rebars rust on bond strength and slip between steel and concrete were investigated. A series of experimental testes have been carried out to 72 pullout specimens by considering the following parameters:

1. Normal and high strength concrete (31 MPa and 76 MPa).
2. Diameters of reinforcing bars (12 mm, 16mm and 25mm).
3. Embedded length of reinforcing bars (150 mm and 300 mm).
4. Epoxy coating for reinforcing bars.
5. Degrees of rust DR for deformed reinforcing bars (0, 30-50% and 70-90%) from the allowable loss of mass specified in ASTM [1].

2. DEGREES OF RUST DR FOR DEFORMED REINFORCING BARS

ASTM A 615/A 615M – 15a [1] standard specified the accepted mass of each bar diameter to be not less than 94% of the nominal mass per unit length, that's mean the upper permissible loss in mass to be 6% of the nominal mass of the rebar. Three ranges of DR for reinforcing bars were taken in the current study as a percentage from the upper permissible limit of losing of mass for each bar size. This procedure followed because if the rust is exceeding the upper limit of loss in mass the rebar will be rejected due to the loss in mass and not due to the effect of rusting on the bond performance. Table 1 shows the nominal mass, acceptable upper limit of losing in mass and the corresponding loss in mass for each DR of each deformed bar size that used in the study

As shown in Table 1, the selected range 20% between minimum and maximum limits of DR is due to dealing with small masses and to give a practical way of distinguishing the three ranges of rusting.

3. EXPERIMENTAL WORK

3.1. Preparing and Collecting Specimens

The deformed bars have been collected from same manufacture (Ukrainian) and divided into three groups. The first group stored inside building in good dry conditions, while the second and the third group were laid outside on the yard to be exposed to the atmosphere conditions of south Iraq (Basrah city). The third group were intentionally kept in more humidity to accelerate the rust development. The specimens collected from exposed bars by checking rust condition by weighting samples according to Practice E 29 [11] as referred in ASTM standard [1]. This check has been done every month till get the target DR and continued to about eleven months to find specific specimens that satisfy the range of DR for all bars dimeters. Fig. 1 shows samples from collected specimens compared with rustles ones.

3.2. Materials

Two types of concrete design mixes were used, normal NC and high strength HC, which made from ordinary Portland cement, gravel, sand, silica fume, superplasticizer and water. All materials were tested according to corresponding standards. Table 2 shows the mix proportions used for making concrete and corresponding standards.

The three bar sizes, 12, 16, and 25 mm with the three DR ranges (0, 30-50% and 70-90%) were imbedded into the two types of concrete, NC and HC, with two embedment lengths Lm, 150mm (cube mold) and 300 mm (cylindrical mold). The bonding slurry and anti–corrosive rebar coating epoxy (SikaTop-Armatec 110 EpoCem) was used to coat whole embedment length Lm of half of rebars specimens as shown in Fig. 2. Fig. 3 shows some of the samples that are ready to the pullout test. The marking (T_1, T_2, and T_3) in the figures and tables denote respectively to the three levels of DR.

Fig. 4 shows schematically the details of prepared specimens for pullout test. Tables 3-5 show the details of all 72 tested specimens for bar sizes 12, 16, and 25 mm, respectively.

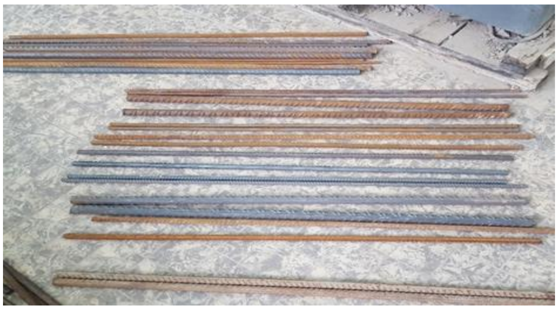

Fig. 1. Samples from collected specimens compared with rustles ones.

Fig. 2. Samples of reinforcement coated by Epoxy.

Table 1
Upper limit of losing of mass and losing mass for each DR of each used bar.

Bar dia. (mm)	Nominal mass (g/m)	upper limit of losing mass (g/m)	Degrees of rust DR limits % Min	Degrees of rust DR limits % Max	losing mass for each DR limits g/m Min	losing mass for each DR limits g/m Max	Variation of limits for each DR (g/m)
12	888	53.28	0	0	0	0	0
12	888	53.28	30	50	15.98	26.64	10.66
12	888	53.28	70	90	37.30	47.96	10.66
16	1578	94.68	0	0	0	0	0
16	1578	94.68	30	50	28.40	47.34	18.94
16	1578	94.68	70	90	66.28	85.22	18.94
25	3853	231.18	0	0	0	0	0
25	3853	231.18	30	50	69.35	115.59	46.24
25	3853	231.18	70	90	161.83	208.07	46.24

Fig. 3. Specimens ready for the pullout test.

Table 2

The concrete mix proportions.

Material	Quantity, kg/m^3		Standards
	NC	HC	
ordinary portland cement	400	450	ASTM C150-04 [12]
crushed gravel	1100	1200	ASTM C33-03 [13]
natural sand	750	700	ASTM C33-03 [13]
silica fume	0	50	ASTM C1240-03 [14]
water	180	130	ASTM C1602_C1602M-04 [15]
superplasticizer	0	12	ASTM C494-04 [16]

Table 3
The details of specimens that used bar diameter 12 mm,

No.	Specimens symbol[1]	Bar dimeter (mm)	DR %	Lm (mm)	Type of concrete	using epoxy
1	N(12)-T1-N(150)	12	0	150	NC	No
2	N(12)-T2-N(150)	12	30 to 50	150	NC	No
3	N(12)-T3-N(150)	12	70 to 90	150	NC	No
4	H(12)-T1-N(150)	12	0	150	HC	No
5	H(12)-T2-N(150)	12	30 to 50	150	HC	No
6	H(12)-T3-N(150)	12	70 to 90	150	HC	No
7	N(12)-T1-Y(150)	12	0	150	NC	yes
8	N(12)-T2-Y(150)	12	30 to 50	150	NC	yes
9	N(12)-T3-Y(150)	12	70 to 90	150	NC	yes
10	H(12)-T1-Y(150)	12	0	150	HC	yes
11	H(12)-T2-Y(150)	12	30 to 50	150	HC	yes
12	H(12)-T3-Y(150)	12	70 to 90	150	HC	yes
13	N(12)-T1-N(300)	12	0	300	NC	No
14	N(12)-T2-N(300)	12	30 to 50	300	NC	No
15	N(12)-T3-N(300)	12	70 to 90	300	NC	No
16	H(12)-T1-N(300)	12	0	300	HC	No
17	H(12)-T2-N(300)	12	30 to 50	300	HC	No
18	H(12)-T3-N(300)	12	70 to 90	300	HC	No
19	N(12)-T1-Y(300)	12	0	300	NC	yes
20	N(12)-T2-Y(300)	12	30 to 50	300	NC	yes
21	N(12)-T3-Y(300)	12	70 to 90	300	NC	yes
22	H(12)-T1-Y(300)	12	0	300	HC	yes
23	H(12)-T2-Y(300)	12	30 to 50	300	HC	yes
24	H(12)-T3-Y(300)	12	70 to 90	300	HC	yes

1 Key of symbols of specimens:
Type of concrete (Bar diameter) - DR - Using epoxy (Embedded length)

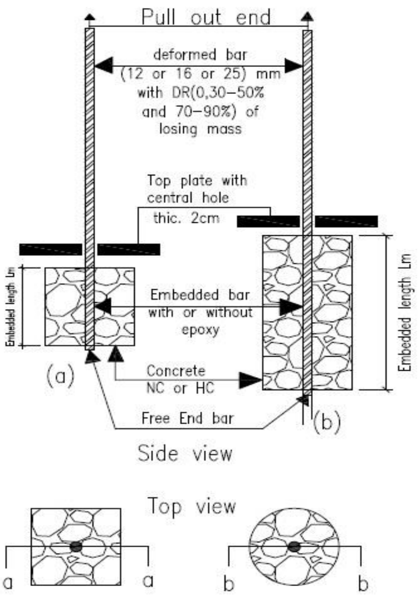

Fig. 4. Details of pull out specimens (a) 150 mm cube and (b) cylinder with *D* = 150 mm and height 300 mm.

Table 4
The details of specimens that used bar diameter 16 mm.

No.	Specimens symbol	Bar dimeter (mm)	DR (%)	Lm (mm)	Type of concrete	using epoxy
1	N(16)-T1-N(150)	16	0	150	NC	No
2	N(16)-T2-N(150)	16	30 to 50	150	NC	No
3	N(16)-T3-N(150)	16	70 to 90	150	NC	No
4	H(16)-T1-N(150)	16	0	150	HC	No
5	H(16)-T2-N(150)	16	30 to 50	150	HC	No
6	H(16)-T3-N(150)	16	70 to 90	150	HC	No
7	N(16)-T1-Y(150)	16	0	150	NC	yes
8	N(16)-T2-Y(150)	16	30 to 50	150	NC	yes
9	N(16)-T3-Y(150)	16	70 to 90	150	NC	yes
10	H(16)-T1-Y(150)	16	0	150	HC	yes
11	H(16)-T2-Y(150)	16	30 to 50	150	HC	yes
12	H(16)-T3-Y(150)	16	70 to 90	150	HC	yes
13	N(16)-T1-N(300)	16	0	300	NC	No
14	N(16)-T2-N(300)	16	30 to 50	300	NC	No
15	N(16)-T3-N(300)	16	70 to 90	300	NC	No
16	H(16)-T1-N(300)	16	0	300	HC	No
17	H(16)-T2-N(300)	16	30 to 50	300	HC	No
18	H(16)-T3-N(300)	16	70 to 90	300	HC	No
19	N(16)-T1-Y(300)	16	0	300	NC	yes
20	N(16)-T2-Y(300)	16	30 to 50	300	NC	yes
21	N(16)-T3-Y(300)	16	70 to 90	300	NC	yes
22	H(16)-T1-Y(300)	16	0	300	HC	yes
23	H(16)-T2-Y(300)	16	30 to 50	300	HC	yes
24	H(16)-T3-Y(300)	16	70 to 90	300	HC	yes

Table 5
The details of specimens that used bar diameter 25 mm.

No.	Specimens symbol	Bar dimeter (mm)	DR (%)	Lm (mm)	Type of concrete	using epoxy
1	N(25)-T1-N(150)	25	0	150	NC	No
2	N(25)-T2-N(150)	25	30 to 50	150	NC	No
3	N(25)-T3-N(150)	25	70 to 90	150	NC	No
4	H(25)-T1-N(150)	25	0	150	HC	No
5	H(25)-T2-N(150)	25	30 to 50	150	HC	No
6	H(25)-T3-N(150)	25	70 to 90	150	HC	No
7	N(25)-T1-Y(150)	25	0	150	NC	yes
8	N(25)-T2-Y(150)	25	30 to 50	150	NC	yes
9	N(25)-T3-Y(150)	25	70 to 90	150	NC	yes
10	H(25)-T1-Y(150)	25	0	150	HC	yes
11	H(25)-T2-Y(150)	25	30 to 50	150	HC	yes
12	H(25)-T3-Y(150)	25	70 to 90	150	HC	yes
13	N(25)-T1-N(300)	25	0	300	NC	No
14	N(25)-T2-N(300)	25	30 to 50	300	NC	No
15	N(25)-T3-N(300)	25	70 to 90	300	NC	No
16	H(25)-T1-N(300)	25	0	300	HC	No
17	H(25)-T2-N(300)	25	30 to 50	300	HC	No
18	H(25)-T3-N(300)	25	70 to 90	300	HC	No
19	N(25)-T1-Y(300)	25	0	300	NC	yes
20	N(25)-T2-Y(300)	25	30 to 50	300	NC	yes
21	N(25)-T3-Y(300)	25	70 to 90	300	NC	yes
22	H(25)-T1-Y(300)	25	0	300	HC	yes
23	H(25)-T2-Y(300)	25	30 to 50	300	HC	yes
24	H(25)-T3-Y(300)	25	70 to 90	300	HC	yes

3.3. Instrumentation and Testing Procedure

The configurations of the tested pullout specimens are shown in Fig. 4. By using universal testing machine (TORSEE) 200 tons' capacity, a tensile load was applied at pull out end. A thick plate (2 cm) was put between machine and the top face of concrete of the specimens. The plate covers all top face of concrete with a central opening to let reinforcement bar to be passed through it. Also, the specimens supported from the bottom side by BRC mesh for safety and to prevent additional pull force due to the weight of specimens. The measurements of slip were recorded at the end of each load increment for the free end at the bottom of specimens by using dial gauge of 0.01mm precision. Figs. 5 and 6 show samples of specimens under test.

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1. Concrete

Table 6 shows the test results of compressive strength, slump, and density of concrete that used to cast pullout tested specimens.

4.2. Reinforcement

The eight bars that had same DR as shown in Tables 3-5, which cut from collected bars specimens were tested according to ASTM A615-15a [1]. Table 7 shows the results of tensile test compared with the standard limitations.

Table 6
The test results of the two concrete mixes.

Concrete type	Slump mm	Concrete Density kg/m³	f_{cu} (MPa) 7 days	f_{cu} (MPa) 28 days
NS	130	2395	23.8	31.4
HS	129	2580	55.8	76.6

4.3. Bond Strength and Failure Modes

The bond strength can be obtained from equation below

$$\tau_s = \frac{P}{\pi \, d \, L_m} \quad (1)$$

where, τ_s: the bond strength, P: ultimate load, d: bar diameter and Lm: embedment length.

Tables 8-10 show the bond strength τ_s, the free end slip S_s at bond strength in addition to the failure modes for all tested specimens. The ultimate strength Fu is also given for some specimens, in which, the deformed bars failed without slip.

Fig. 5. Pull out specimen under test.

Fig. 6. Configuration of specimen, dial gauge and the reaction top plate.

Table 7. Tensile test results of deformed steel bars.

Bar Dia. (mm)	∅ 12 Average of 8 specimens			∅ 16 Average of 8 specimens			∅ 25 Average of 8 specimens			ASTM A615-15a [1]
DR%	0	30-50	70-90	0	30-50	70-90	0	30-50	70-90	Not less than
Yield strength (N/mm²)	480	480	480	485	480	480	520	500	490	420
Ultimate strength (N/mm²)	685	670	650	690	670	650	710	700	670	620
Elongation (%)	15	13	10	16	14	13	15	15	12	9 for ∅ (12,16) 8 for ∅ 25

From Tables 8-10 and as shown in Fig. 7 three types of failure modes were observed for the tested specimens. The dominant one was splitting the concrete into two halves or crushing into many parts. The second one was the failure happen in steel bars because the stress in bar reaches to its ultimate value before the bond strength was exceeded. The third mode of failure was the steel bar slip without crushing of concrete, this mode refers to the weakness of bond strength between bars and concrete and normally happened in small bars diameters due to smaller circumferential area of bond between rebar and concrete. Also, these tables show that, the bond strength for all bar sizes and for all

Table 8
The bond strength and failure modes of specimens with bar diameter 12 mm.

NO.	Specimen	P (N)	τ_s (N/mm^2)	Failure mode	Fu (N/mm^2)	S_s (mm)
1	N(12)-T1-N(150)	11772	2.08	slip	-	1.4
2	N(12)-T2-N(150)	12262	2.17	concrete	-	1.1
3	N(12)-T3-N(150)	10791	1.91	slip	-	1.6
4	H(12)-T1-N(150)	13734	2.43	concrete	-	1.8
5	H(12)-T2-N(150)	15696	2.78	concrete	-	1.4
6	H(12)-T3-N(150)	13734	2.43	concrete	-	2.2
7	N(12)-T1-Y(150)	14224	2.52	concrete	-	1.7
8	N(12)-T2-Y(150)	15696	2.78	concrete	-	1.5
9	N(12)-T3-Y(150)	13734	2.43	concrete	-	2.1
10	H(12)-T1-Y(150)	14715	2.60	concrete	-	1.1
11	H(12)-T2-Y(150)	18639	3.30	concrete	-	0.6
12	H(12)-T3-Y(150)	13734	2.43	concrete	-	1.5
13	N(12)-T1-N(300)	77489	6.86	Steel	685.5	0
14	N(12)-T2-N(300)	76027	6.73	Steel	672.5	0
15	N(12)-T3-N(300)	73378	6.49	Steel	649.1	0
16	H(12)-T1-N(300)	77008	6.81	Steel	681.2	0
17	H(12)-T2-N(300)	76321	6.75	Steel	675.1	0
18	H(12)-T3-N(300)	73084	6.47	Steel	646.5	0
19	N(12)-T1-Y(300)	77499	6.86	Steel	685.5	0
20	N(12)-T2-Y(300)	76125	6.73	Steel	673.4	0
21	N(12)-T3-Y(300)	73378	6.49	Steel	649.1	0
22	H(12)-T1-Y(300)	77499	6.86	Steel	685.5	0
23	H(12)-T2-Y(300)	76060	6.73	Steel	672.8	0
24	H(12)-T3-Y(300)	73010	6.46	Steel	645.8	0

Table 9
The bond strength and failure modes of specimens with bar diameter 16 mm.

NO.	Specimen	P (N)	τ_s (N/mm^2)	Failure mode	Fu (N/mm^2)	S_s (mm)
1	N(16)-T1-N(150)	12753	1.69	concrete	-	1.2
2	N(16)-T2-N(150)	13734	1.82	concrete	-	1.0
3	N(16)-T3-N(150)	12753	1.69	concrete	-	1.3
4	H(16)-T1-N(150)	14715	1.95	concrete	-	1.3
5	H(16)-T2-N(150)	18639	2.47	concrete	-	0.9
6	H(16)-T3-N(150)	14224	1.89	concrete	-	1.6
7	N(16)-T1-Y(150)	15696	2.08	concrete	-	1.3
8	N(16)-T2-Y(150)	17658	2.34	concrete	-	1.1
9	N(16)-T3-Y(150)	14322	1.90	concrete	-	1.8
10	H(16)-T1-Y(150)	16677	2.21	concrete	-	1.0
11	H(16)-T2-Y(150)	20601	2.73	concrete	-	0.7
12	H(16)-T3-Y(150)	14715	1.95	concrete	-	1.2
13	N(16)-T1-N(300)	94176	6.25	concrete	-	2.3
14	N(16)-T2-N(300)	109872	7.29	concrete	-	1.9
15	N(16)-T3-N(300)	92214	6.12	concrete	-	2.5
16	H(16)-T1-N(300)	138321	9.18	steel	688.3	0.0
17	H(16)-T2-N(300)	135600	9.00	steel	674.7	0.0
18	H(16)-T3-N(300)	130320	8.65	steel	648.4	0.0
19	N(16)-T1-Y(300)	108891	7.22	concrete	-	2.1
20	N(16)-T2-Y(300)	123606	8.20	concrete	-	1.7
21	N(16)-T3-Y(300)	98590	6.54	concrete	-	2.4
22	H(16)-T1-Y(300)	137340	9.11	steel	683.4	0.0
23	H(16)-T2-Y(300)	135400	8.98	steel	673.7	0.0
24	H(16)-T3-Y(300)	129640	8.60	steel	645.1	0.0

Table 10
The bond strength and failure modes of specimens with bar diameter 25 mm.

NO.	Specimen	P (N)	τ_s (N/mm^2)	Failure mode	Fu (N/mm^2)	S_s (mm)
1	N(25)-T1-N(150)	39240	3.33	concrete	-	0.9
2	N(25)-T2-N(150)	68670	5.83	concrete	-	0.7
3	N(25)-T3-N(150)	39730	3.37	concrete	-	1.1
4	H(25)-T1-N(150)	78480	6.66	concrete	-	1.1
5	H(25)-T2-N(150)	101043	8.58	concrete	-	0.6
6	H(25)-T3-N(150)	76518	6.50	concrete	-	1.3
7	N(25)-T1-Y(150)	58860	5.00	concrete	-	1.2
8	N(25)-T2-Y(150)	83385	7.08	concrete	-	0.7
9	N(25)-T3-Y(150)	58663	4.98	concrete	-	1.5
10	H(25)-T1-Y(150)	93195	7.91	concrete	-	0.7
11	H(25)-T2-Y(150)	120663	10.25	concrete	-	0.4
12	H(25)-T3-Y(150)	92998	7.90	concrete	-	1.1
13	N(25)-T1-N(300)	107910	4.58	concrete	-	0.6
14	N(25)-T2-N(300)	156960	6.66	concrete	-	0.3
15	N(25)-T3-N(300)	107713	4.57	concrete	-	0.7
16	H(25)-T1-N(300)	140283	5.96	concrete	-	0.5
17	H(25)-T2-N(300)	207972	8.83	concrete	-	0.2
18	H(25)-T3-N(300)	137340	5.83	concrete	-	0.6
19	N(25)-T1-Y(300)	115758	4.92	concrete	-	0.6
20	N(25)-T2-Y(300)	166770	7.08	concrete	-	0.3
21	N(25)-T3-Y(300)	107910	4.58	concrete	-	0.7
22	H(25)-T1-Y(300)	148131	6.29	concrete	-	0.4
23	H(25)-T2-Y(300)	227592	9.66	concrete	-	0.1
24	H(25)-T3-Y(300)	146169	6.21	concrete	-	0.6

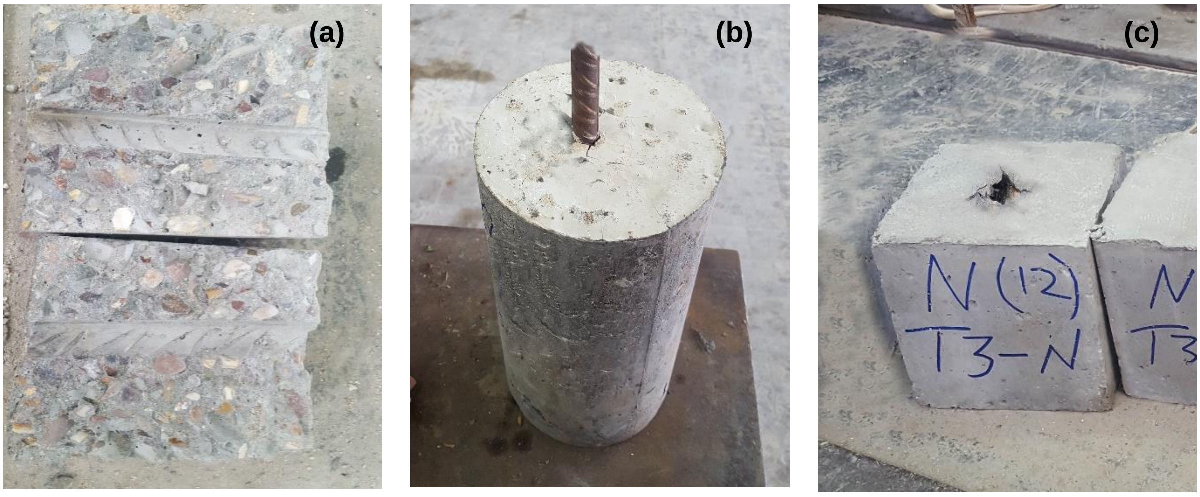

Fig. 7. Failure modes (a) concrete failure (b) steel failure and (c) slip of reinforcement.

cases was increased with 30-50% DR and then decreased with 70-90% DR compared with 0 DR. On the other hand, the relationship with end free slip at bond strength was inverted as shown in Figs. 8-13 when taking the average values of DR. It is also clear that the other three parameters, i.e. using bond epoxy coating or increasing the embedment length or using HC all of them would increase the bond strength and decrease free end slip, but this effect was not essentially significant for 70-90% DR.

4.4. Bond stress τ vs Free end Slip S Behavior

The relation between bond stress τ and free end slip *S* for the specimens of different DR (0, 30-50% and 70-90%), with different bar sizes (12, 16, and 25 mm), and with considering the use of epoxy, changing the embedment length and using NC and HC, are shown in Figs. 14- 31.

The main observations were that, the bond stress at the start of slip for specimens of 30-50% DR was greater than 0 DR about 115%, and 70-90% DR was less than 0 DR about 30%. The slip decreased in the same manner of increasing bond stress with respect to DR. Also, the epoxy coating, embedment length and HC significantly improved 30-50% DR and 0 DR specimens, but there was no essential change for the 70-90% DR specimens.

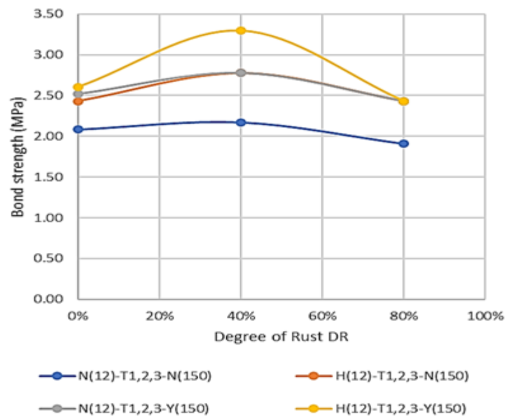

Fig. 8. DR-bond strength relationship for *d* = 12 mm.

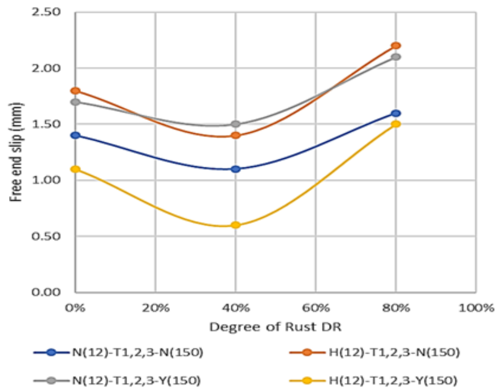

Fig. 9. DR-free end slip relationship for *d* = 12 mm.

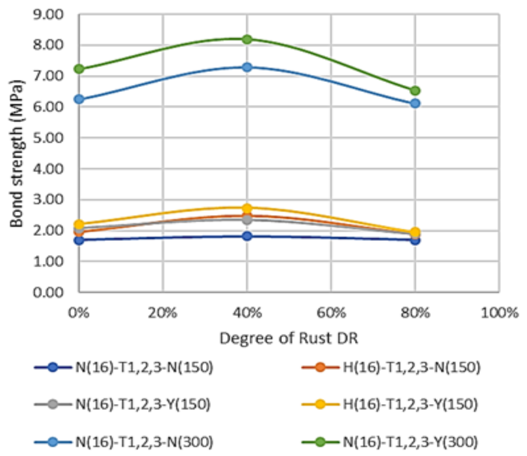

Fig. 10. DR-bond strength relationship for *d* =16 mm.

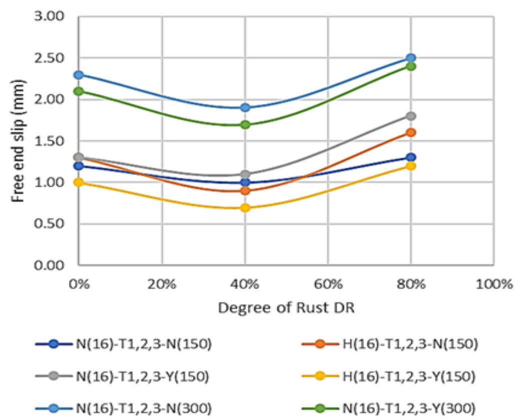

Fig. 11. DR-free end slip relationship for *d* = 16 mm.

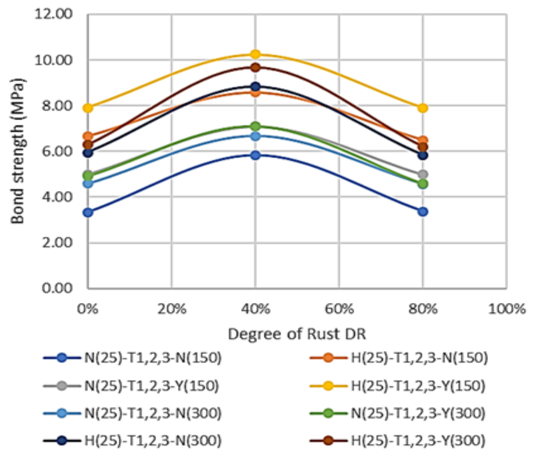

Fig. 12. DR-bond strength relationship for *d* = 16 mm.

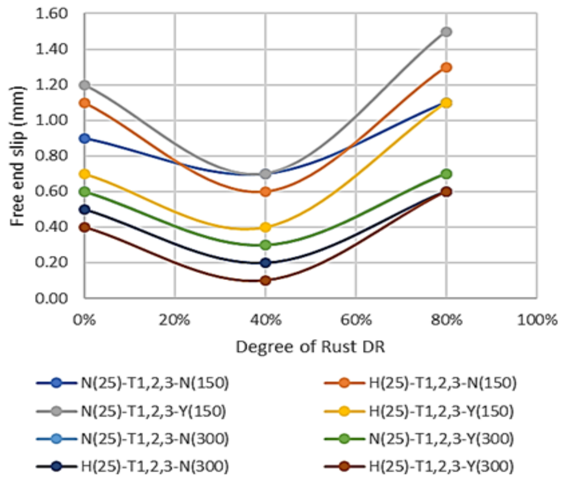

Fig. 13. DR-free end slip relationship for *d* = 16 mm.

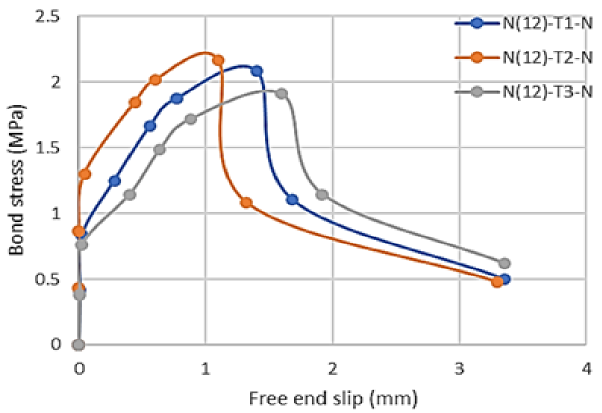

Fig. 14. τ-S (NC, No epoxy, *d* = 12 mm, *Lm* = 150 mm).

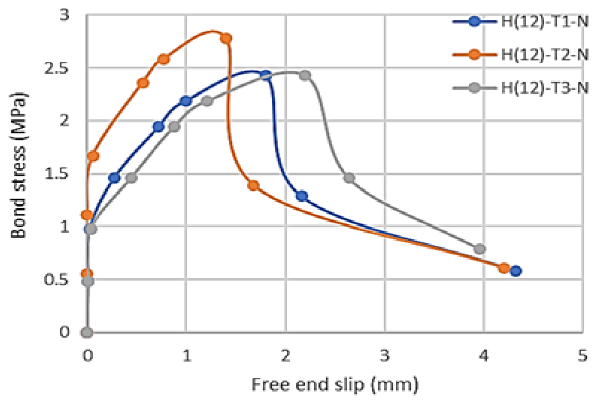

Fig. 15. τ-S (HC, No epoxy, *d* = 12 mm, *Lm* = 150 mm).

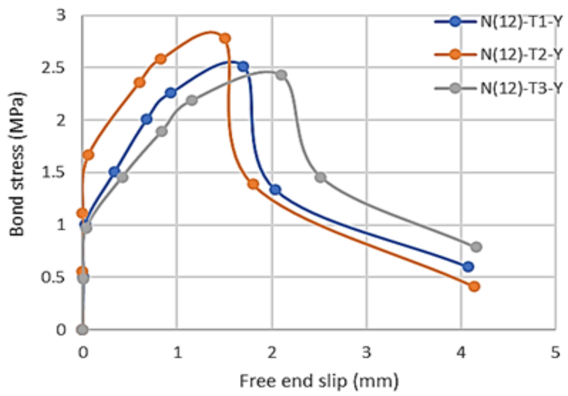

Fig. 16. τ-S (NC, Epoxy, *d* = 12 mm, *Lm* = 150 mm).

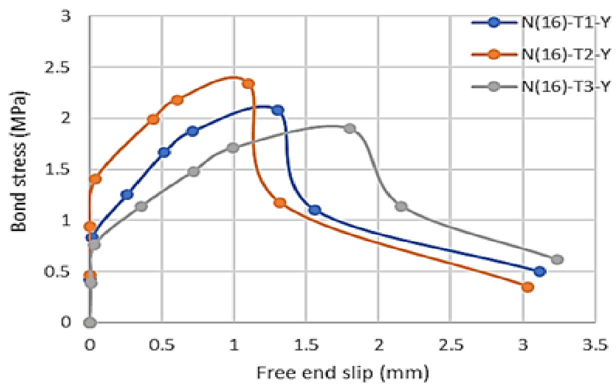

Fig. 20. τ-S (NC, Epxy, *d* = 16 mm, *Lm* = 150 mm).

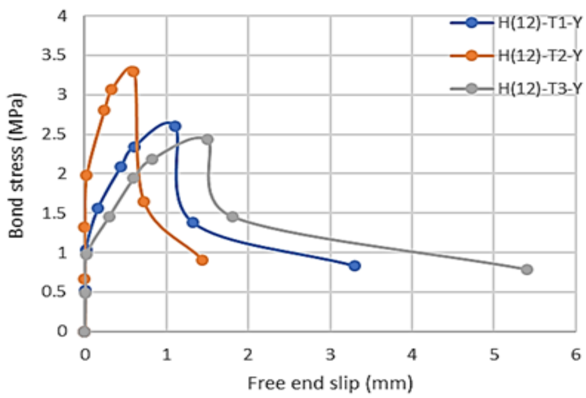

Fig. 17. τ-S (HC, Epoxy, *d* = 12 mm, *Lm* = 150 mm).

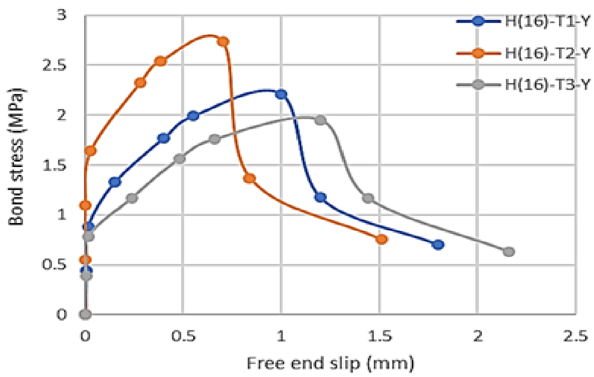

Fig. 21. τ-S (HC, Epoxy, *d* = 16 mm, *Lm* = 150 mm).

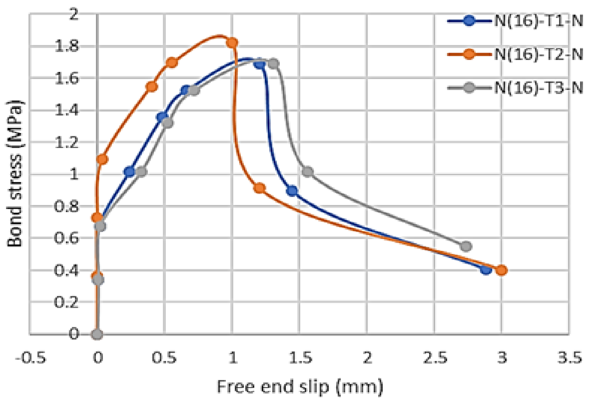

Fig. 18. τ-S (NC, No epoxy, *d* = 16 mm, *Lm* = 150 mm).

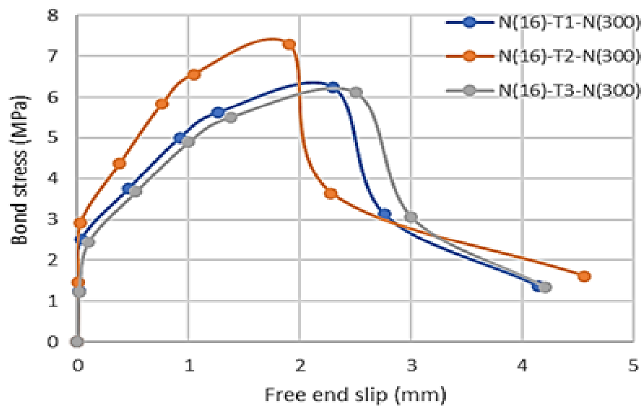

Fig. 22. τ-S (NC, No epoxy, *d* = 16 mm, *Lm* = 300 mm).

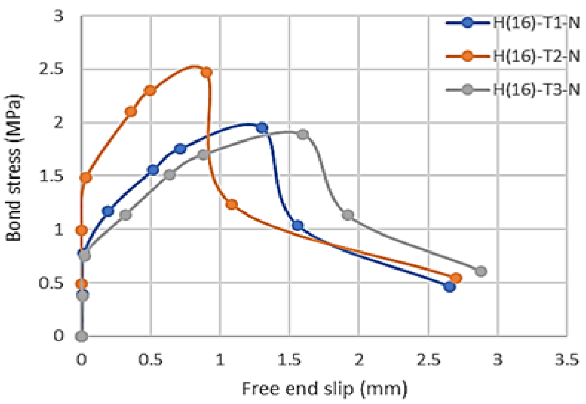

Fig. 19. τ-S (HC, No epoxy, *d* = 16 mm, *Lm* = 150 mm).

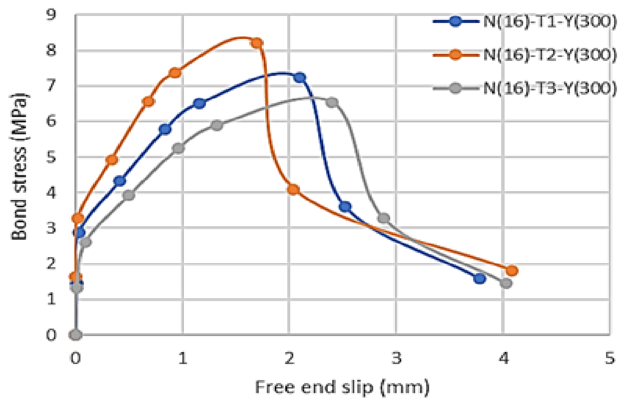

Fig. 23. τ-S (NC, Epoxy, *d* = 16 mm, *Lm* = 300 mm).

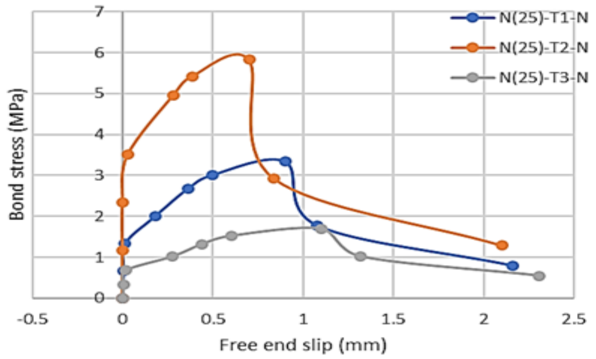

Fig. 24. τ-S (NC, No epoxy, *d* = 25 mm, *Lm* = 150 mm).

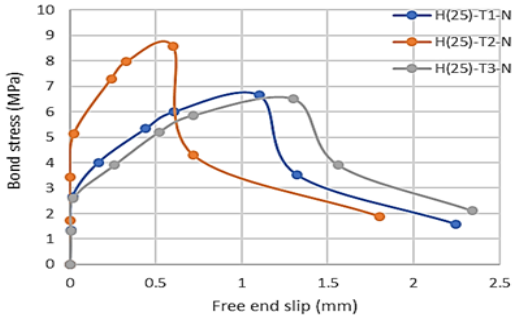

Fig. 25. τ-S (HC, No epoxy, *d* = 25 mm, *Lm* = 150 mm).

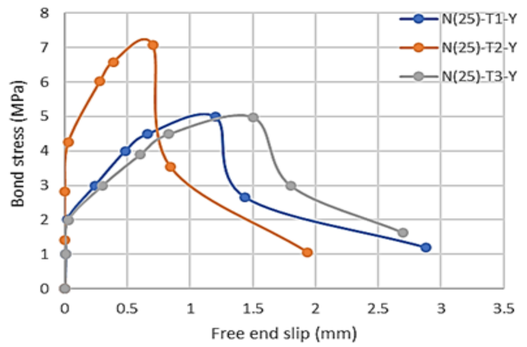

Fig. 26. τ-S (NC, Epoxy, *d* = 25 mm, *Lm* = 150 mm).

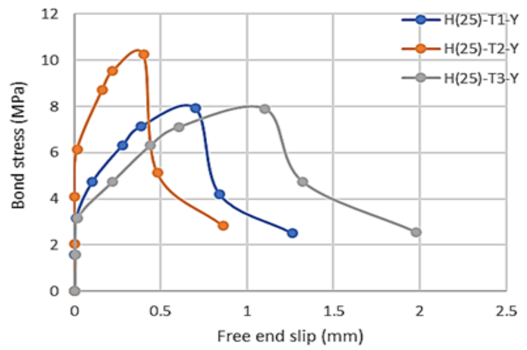

Fig. 27. τ-S (HC, Epoxy, *d* = 25 mm, *Lm* = 150 mm).

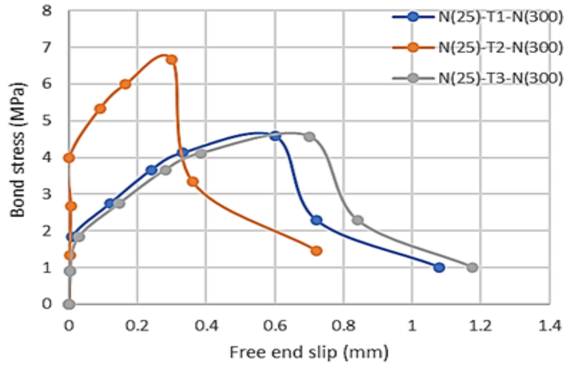

Fig. 28. τ-S (NC, No epoxy, *d* = 25 mm, *Lm* = 300 mm).

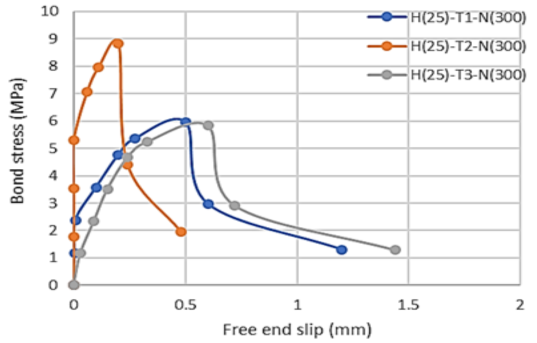

Fig. 29. τ-S (HC, No epoxy, *d* = 25 mm, *Lm* = 300 mm).

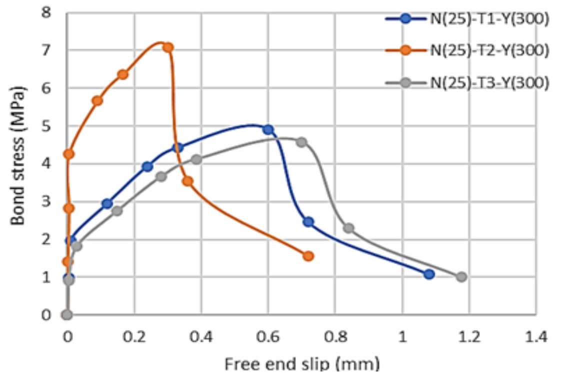

Fig. 30. τ-S (NC, Epoxy, *d* = 25 mm, *Lm* = 300 mm).

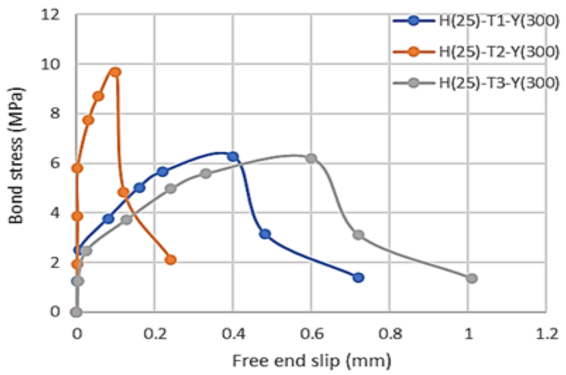

Fig. 31. τ-S (HC, Epoxy, *d* = 25 mm, *Lm* = 300 mm).

5. CONCLUSIONS

Following are the main conclusions and recommendations of the study:

1. The bond strength between reinforcement bars and concrete start to increase with increasing degree of rusting up to 50 % of the acceptable limit of loss in mass. After that and up to 90% the bond dropped again to reach slightly lower than the bond of zero rusting bars. This behavior stays the same when combined with the other studied parameters, i. e. using HC, coating with epoxy, or increasing the embedment length.
2. The free end slip behaved inversely of bond strength behavior with respect to DR.
3. The HC had significant effect to increase bond strength and decrease slip compared with NC. The using of HC gives more improvement of bond than increasing embedment length or using epoxy coating especially for the bars that have DR limits 30-50%.
4. The 50% DR increases bond stress at first slip, when increase DR till 90% will reduce it lower than bond stress of 0 DR for all cases of specimens with respect

to using NC or HC, using Epoxy, or increasing embedment length and for all bars sizes that considers in the study.

5. The bond stress-slip curves showed significant increase in stiffness of specimens with increase of DR till 50% specially with HC and using epoxy. After the percentage of 50% DR there were a major reduction in stiffness even when using HC or epoxy or increasing the embedment length when compared with 0 DR.
6. The above-mentioned conclusions lead to recommend using the same acceptance criterion for the loss of mass to be the criterion of acceptance of rusting level up to 50%. After this level of rusting it is recommending to use one of the studied bond improvement factors, i.e. using epoxy, or using HC, or increasing the embedment length, to reach to the same bond of the rustles reinforcement.

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