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Investigation of Corrosion Effects on Bond-slip and Tensile Strength of Reinforced Concrete Members

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Investigation of Corrosion Effects on Bond-slip and Tensile Strength of Reinforced Concrete Members

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INTRODUCTION

Text: The corrosion effect on tensile strength of RC members is very important to region with high corrosion conditions. In this article a study on finding bond behaviour, crack pattern, crack spacing, and tensile strength of RC members is presented. For this purpose a comprehensive experimental program including reinforced concrete cylanders with different concrete covers and reinforcement ratios under various corrosion rates is conducted. The specimens are located in large tub containing water and salt (5% salt solution) with a devich for accelerated corrosion production. For each specimen, the variation of total tensile strength versus its average strain is plotted and the member behaviour at various load levels is investigated. Average crack spacing, and maximum bond stress developed at each corrosion level are studied and their apporoperiate relationship are proposed. The main parameterrs considerd in this investigation are: corrosion rate (C_w), reinforcement diameter (d), reinforcement ratio (ρ), c/d and d/ρ.

Keywords: tensile renforcement concrete member, corrosion rate, bond strength, average crack spacing

EXPERIMENTAL INVESTIGATION

Experimental Investigation: Specimen Design

Mediocre strength concrete about 26 MPa was used in all specimens. Type II cement is used. The sum of water-cement and supplementary cementing materials ratio (w/c+scm) is 0.52; unit quantities of water, cement, sand and coarse aggregate were 200, 385, 870, 885 kg/m^3, respectively. Physical and mechanical properties of utilized rebars and concrete, which are result of adequate number of tests, are available from Tab. 1. The compressive strength of specimens is obtained by testing cylinders having a diameter of 100 mm and height of 200mm. The specifications of specimens which are divided into seven types according to rebar sizes and concrete covers are available in Tab. 2. From each type two specimens (totally 14 specimens) has been tested without induring corrosion and the remainder of specimens experienced certain amount of reinforcement corrosion and has been tested by simple direct tension.
Concrete has been preperared in mixer, and then it has been put in 500 mm mold layer by layer and thereafter compaction was performed by vibration table. After 24 hours the molds were opened and specimens had been curried for 28 days in room temperature.

Experimental Investigation: Accelerated Corrosion Program

The specimens were prepared for corrosion procedure in this manner, firstly the exposed part of reinforcement and the end area at top and bottom of RC specimens was coated by means of epoxy painting and plastic sealings. Specimens have been put into a fiberglass tube which contains solution of water and salt (5% solution). An electric supplier with 24 Volts and 8 Ampere electric current output has been utilized. Anode has been connected to head of reinforcement and cathode has been connected to metal wire which is spread over specimens. (See Fig. 1)

Tab. 1. Material properties of RC specimens.

	Concrete		Reinforcement					
			d=12mm		d=18mm		d=25mm	
f_t	E_c	f_c	E_s	f_y	E_s	f_y	E_s	f_y
1.62	2440.0	26.0	205000	515	200000	350	202000	369

Note: All properties are in MPa.

Tab. 2. An overview on specimens with corroded reinforcement.

Specimen	c, mm	ρ	c/d	d/ρ	$C_{0, \%}$	$C_{cr, \%}$	$C_{u, \%}$
S12-60	24.0	0.04	2.0	300.0	0.9	2.8	10.0
S12-100	44.0	0.014	3.67	833.3	14.6	5.5	29.0
S18-60	21.0	0.09	1.167	200.0	0.5	1.5	10.0
S18-100	41.0	0.0324	2.278	555.6	1.1	4.5	21.0
S18-150	66.0	0.0144	3.67	1250.0	1.8	7.0	42.0
S25-100	37.5	0.0625	1.5	400.0	0.8	2.4	14.0
S25-150	62.5	0.0278	2.5	900.0	1.4	4.0	22.0

Fig. 1. An overview of the accelerated corrosion program.

Whenever the supplier is on, the direct current passes through the specimens and corrosion phenomen is going to be happening. Rate of corrosion with regarding the time of applying corrosion and quantity of electronic current would be calculated from Faraday's law. But this law has been used as estimation of required time of continuing accelerated corrosion program for each specimen. Therefore exact value of corrosion can be attained from weighing after the end of direct tension test.

When corrosion phenomen is happening the corrosion products leads to dilation of rebar. These products apply a radial pressure to surrounding concrete. This process causes some longitudinal cracks across the surface of specimens. Appearing of first longitudinal was defined as first level of corrosion and its relation to corrosion rate was expressed by parameter C_{cr}, to this level perfect bond between concrete and steel is assumed; but there is lower rate of corrosion than this limit in which bond strength is higher than ordinary situation (C_0). Last corrosion level in witch no more transversal crack could be observable is called as ultimate corrosion level (C_u). In this case, bond stress has its minimum value and is about to zero. It was observed that for specimens with same reinforcement diameter, amount of concrete cover has direct relation to first longitudinal crack corrosion rate. And for specimens with same diameter, rebar diameter had adverse relation to first longitudinal crack corrosion rate. So by these observations, according to experimental results and using mean square curve fitting technique these relations are established (see Fig. 2):

$$C_{cr} = 1.5c/d \quad , \quad C_u = 9c/d$$

(1)

In Tab. 2, these values are presented for all specimens.

Experimental Investigation: Tensile RC Specimens Test

After applying corrosion to specimens, direct tension test was carried out. Detail of tensile test setup is presented in Fig. 3; two metal rings attached to top and bottom of specimens by three screws for measuring
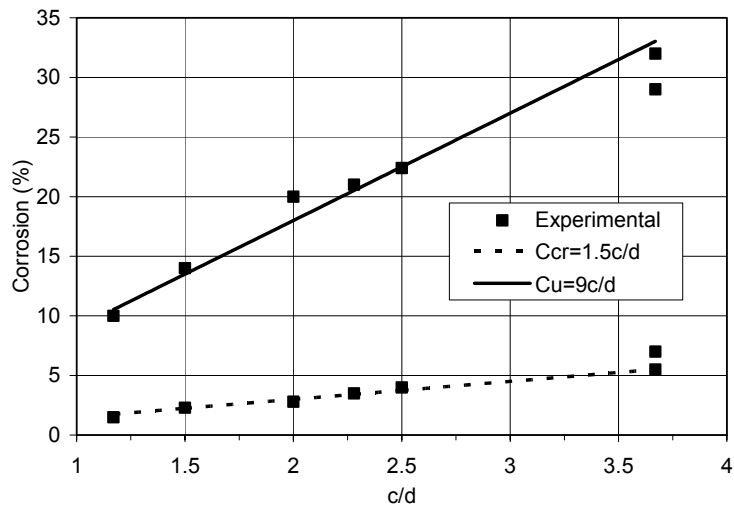
Fig. 2. Variation of important corrosion levels; a comparison between experiment result and proposed formulas.

axial deformation of concrete specimens. A LVDT system was used for measuring displacement. Some of specimen can be found in Fig. 4.
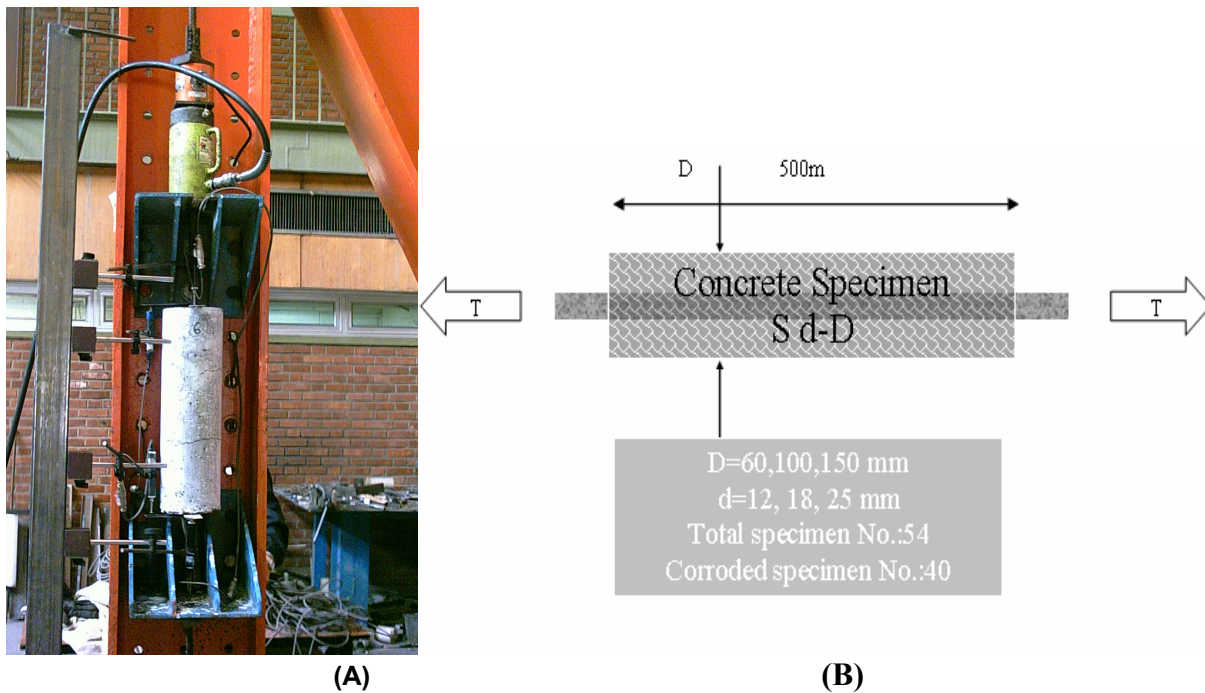

(A)   **(B)**

Fig. 3. Tensile test setup, tensile specimen tester (Fig. 5A), a summary of specimens (Fig. 5B).

Experimental Investigation: Ultimate Crack Spacing

According to experimental results (see Fig .5), average crack spacing is related to maximum and minimum crack spacing in this manner:

$$S_{min} = 0.72 S_m, \quad S_{max} = 1.35 S_m$$

(2)

Fig. 4. Some of tested specimens.

Also, by means of square curve fitting technique, these two formulas are proposed for average crack spacing parameter:

$$Propose1 \quad : \quad S_m = 0.6(d + 40.0) + 0.21c + 0.09d/\rho$$
$$Propose2 \quad : \quad S_m = 2.35c$$

(3)

In Fig. 6, this two proposed formula is compared with two similar ones proposed by CEB and Rizkalla et al. [1, 2]

For specimens with certain amount of rebar steel corrosion, average crack spacing shall be modified. From Fig. 7A it can be understand that for specimen with same reinforcement diameter whatever the RC specimen diameter is less, variation of S_m/S_{m0} ratio is higher. From Fig. 7B, it can be observed that for specimens with specific rate of corrosion, c/d ratio plays a key role. By the way, this formula is obtained by means of mean square curve fitting technique:

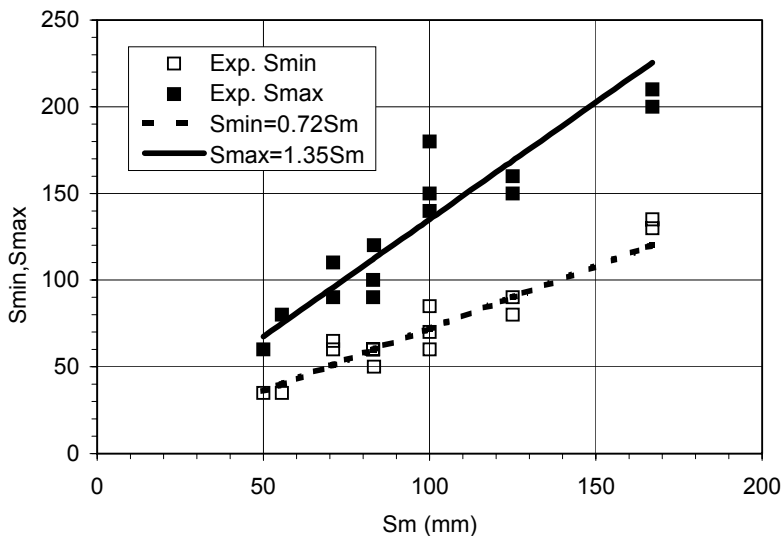$$S_m/S_{m0} = 1.533 - 0.3c/d + 4.2(C_w/C_u)^2$$

(4)

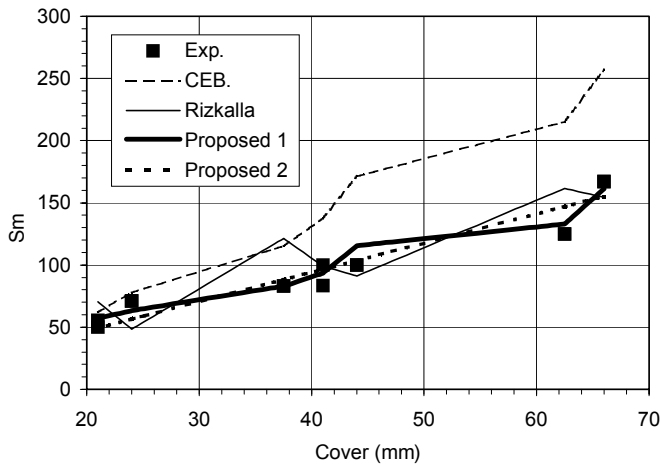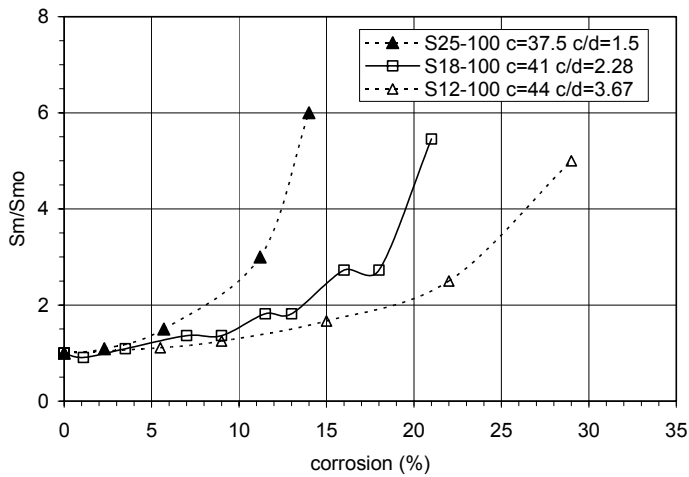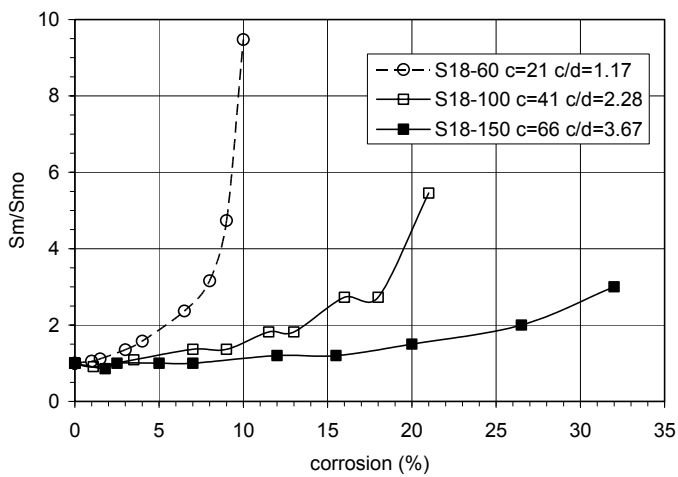**Fig. 5.** Variation of maximum and minimum crack spacing against average crack spacing.

Fig. 6. Crack spacing, a view over experimental data and analytical formulas.
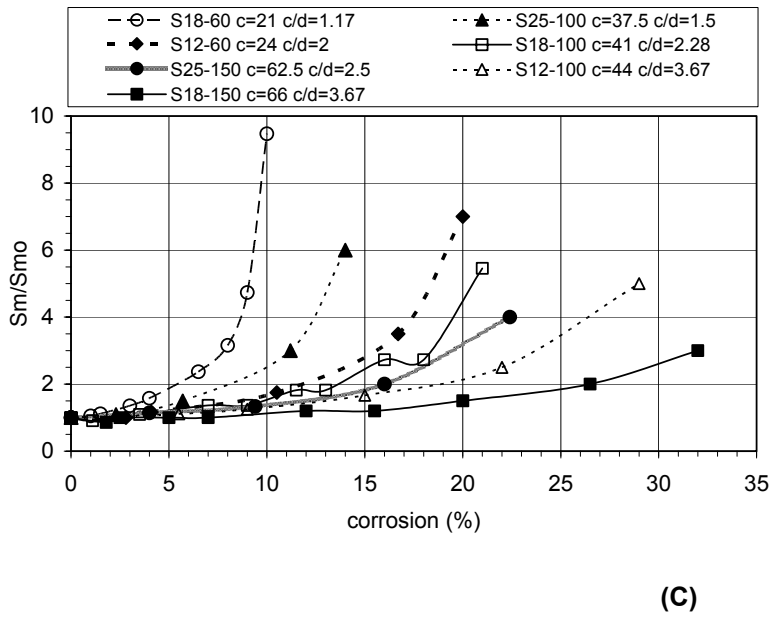

(A)

(B)

(C)

Fig. 7. Experimental result of crack spacing, effect of reinforcement diameter (Fig. 7A), effect of specimen diameter (Fig 7B), all specimens (Fig. 7C).

Experimental Investigation: Concrete Stress Contribution

By means of theses equations the concrete average stresss contribution could be computrd (see Fig. 8):

$$T = F_s + F_c \quad , \quad F_s = A_s . E_s . \varepsilon_{sm} \quad , \quad \sigma_{cm} = F_c / A_c \tag{5}$$

ε_{sm} is measured during the test for each applied load (T). All of RC specimens after applying corrosion have been tested by direct tension test. The results can be seen in Fig. 9.
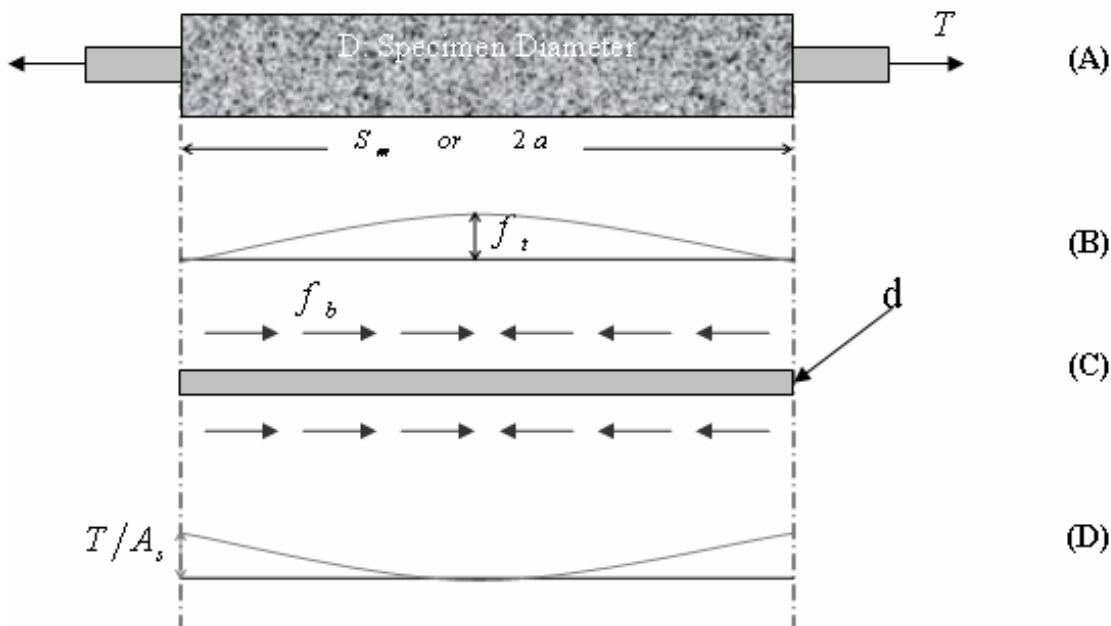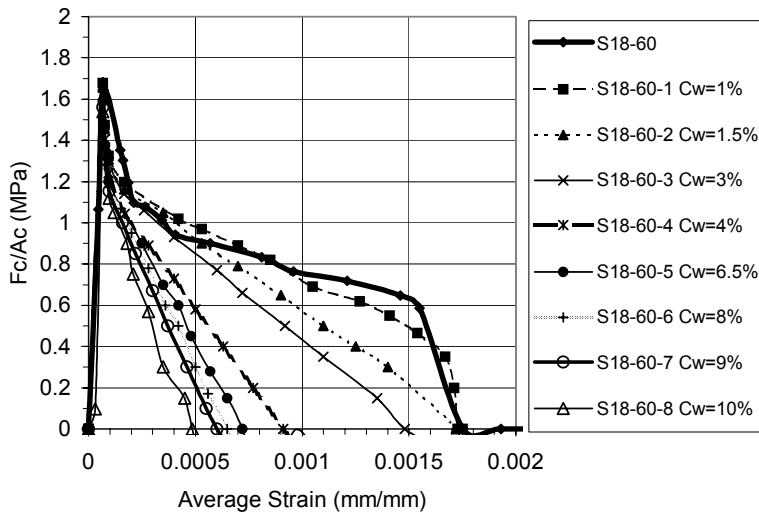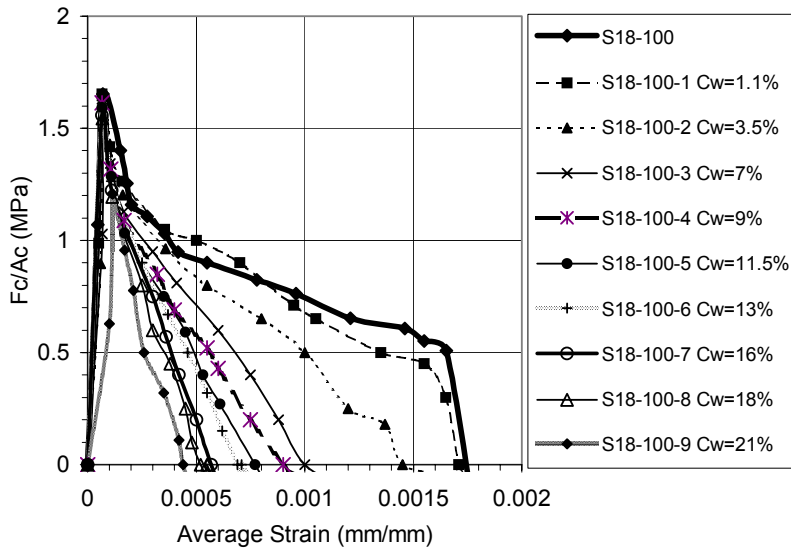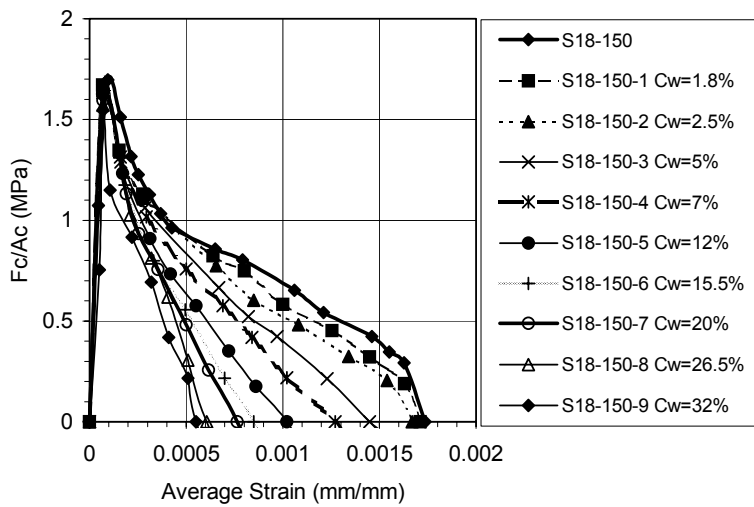

Fig. 8. Free body diagrams, tact concrete Between two faces of cracks (Fig. 8A) concrete stress contribution just before developing of new crack (Fig. 8B) distribution of bond stress on reinforcement (Fig. 8C) steel stress contribution (Fig. 8D).
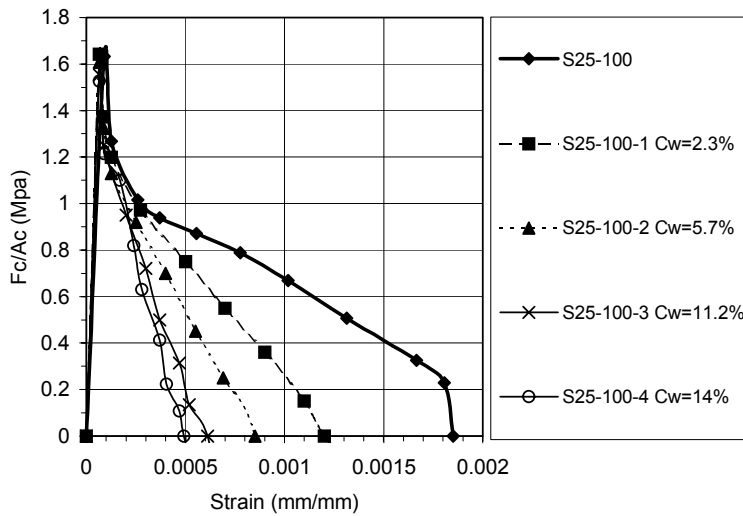
6

(A)

(B)

(C)

(D)

Fig. 9. Stress-strain curve of RC specimens in tension for, S 18-60 (Fig. 9A) S 18-100 (Fig. 9B) S18-150 (Fig. 9C) S 25-100 (Fig. 9D).

By means of mean square fitting curve technique, this formula is proposed for modifying ultimate rebar yield strain due corrosion:

$$\varepsilon_{cw}/\varepsilon_y = 0.907 - 0.757\,C_w/C_u - 0.0087\,c/d$$

(6)

Experimental Investigation: Bond-Slip Behavior of Specimens

Behaviour of RC member after first crack and subsequent cracks shows that bond stress is variable by slip. In this case, according to Fig. 8, if half of distance of two subsequent cracks is named a, the force which is applied to surrounding concrete is equal to $f_{bm}.\pi.a$; For developing a new crack, maximum concrete stress contribution has to reach to their maximum value, f_t:

$$f_{bm} = f_t . A_c / (\pi d a)$$

(7)

Between final crack and reinforcement yielding state (final cracking state) value of bond stress will be constant and maximum because crack spacing is constant and stable, so equation 7 converted to:
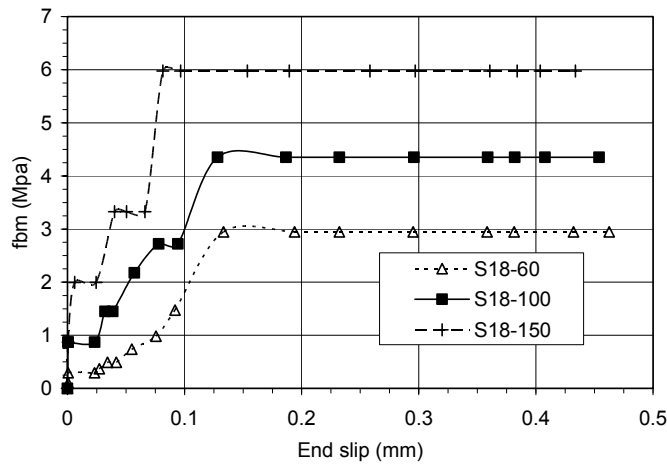
$$f_{bu} = 2 f_t A_c / (\pi . d . S_m)$$

(8)

Now computing of average concrete contribution stress and end slip will be straight forward:
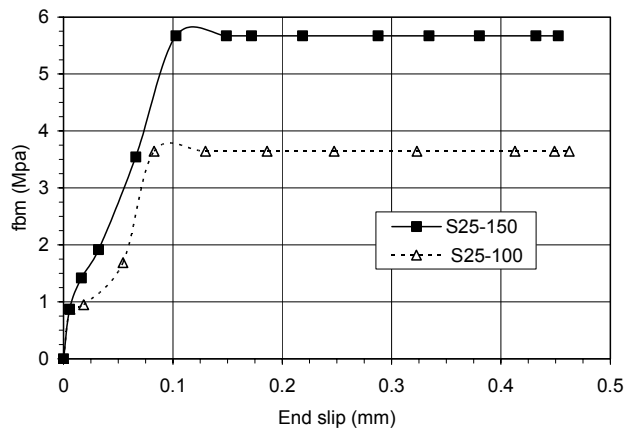
$$\varepsilon_{sm} = \sigma_{cm} / E_c$$

(9)

$$\Delta_s = u_s - u_c = (\varepsilon_{sm} - \varepsilon_{cm}).l/2$$

(10)

In above equations, value of σ_{cm} and ε_{sm} is known and computable similar to last subsection trend. Variation of mean bond stress against sum slips at end of crack face with above relations computed and plotted in Fig. 10.

(A)

(B)
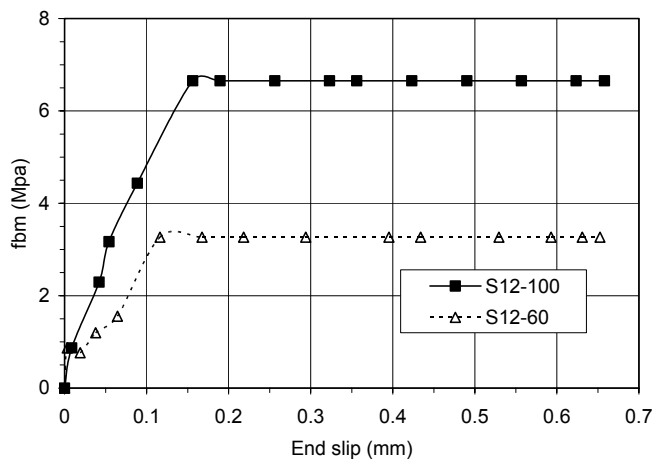
(C)

Fig. 10. Experimental observation on effect of rate of corrosion on bond strength, constant reinforcement diameter, d=18 mm (Fig. 10A) constant specimen diameter D=100 mm (Fig. 10B) all specimens (Fig. 10C).
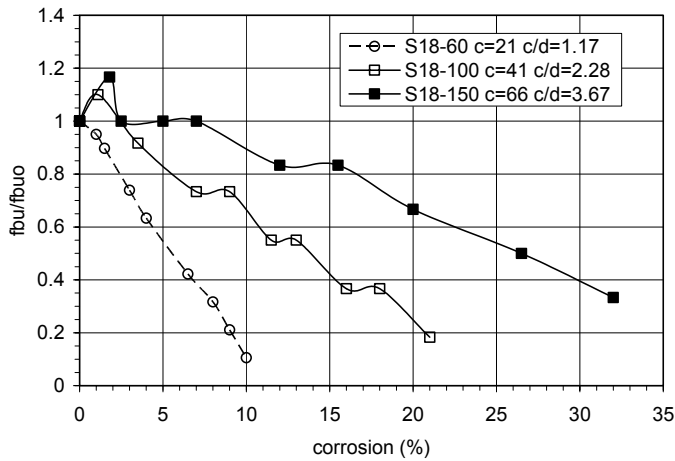
(A)
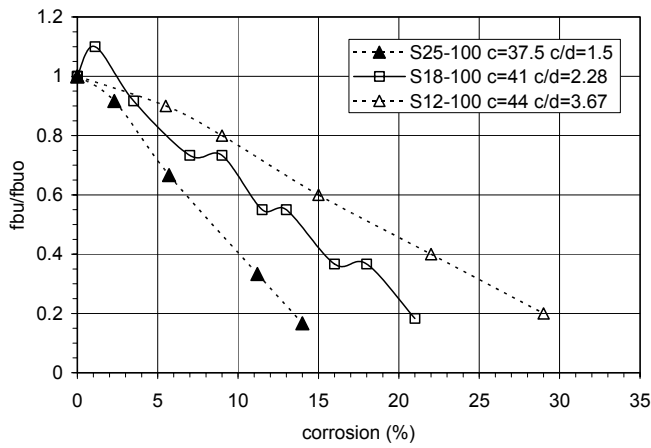
(B)

(C)

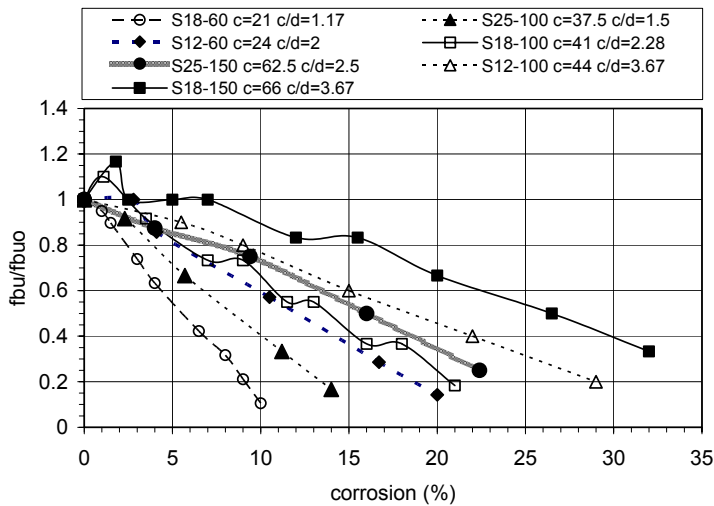**Fig. 11.** Effect of rate of corrosion on bond strength, constant reinforcement diameter (d=18 mm) (Fig. 12A) constant specimen diameter (D=100 mm) (Fig. 12B) all specimens (Fig. 12C).

By studying these curves for all specimens, three states can be distinguished: firstly, elastic behavior up to first cracking point in which perfect bond between concrete and steel can be assumed namely "non-cracking state". Secondly, "multiple cracking state" in which increases in bond stress and slip are observable and finally, thirst phase which represents stable crack state in which bond stress is maximum, uniform and constant (final cracking state). Also, tensile behavior curve shows c/d ratio plays a key role in ultimate bond stress. By the way, this formula is proposed by means of mean square curve fitting technique:

$$f_{bu} = 0.4c\sqrt{f_c}/d \ (MPa)$$

(11)

In comparison with similar formulas proposed by elders [3, 4, 5]' equation (10) has better agreement with experimental results [6].

From equation (8), it can be seen that f_{bu} is related to adverse of average crack spacing which leads us to:

$$f_{bu}/f_{bu0} = S_{m0}/S_m$$

(12)

In above equation ultimate bond stress after first crack could be calculated easily. Graph of f_{bu}/f_{bu0} against C_w is shown in Fig. 11. As it can be observed firstly bond strength, a little bit increased; but after first longitudinal crack corrosion level (C_{cr}) with increasing corrosion rate, bond strength diminishes.

Experimental Investigation: Effect of corrosion on cross section of reinforcement

An experimental relation shall be constructed to modify the cross section due to corrosion, so this formula is proposed by means of mean square curve fitting technique:

$$A_s/A_{s0} = 1.2 - 0.08c/d - 0.35 C_w/C_u$$

(13)

CONCLUSIONS

In this paper result of 54 direct tension tests is presented. 40 specimens have low, mediocre or severe corrosion problem. Using this data, a new relation is proposed for ultimate bond strength and crack spacing. For modifying some parameters due to corrosion such as reinforcement cross section and other bond-slip related parameters is represented. In all of this relations beside rate of corrosion, concrete cover and rebar diameter play a key role. The tensile behavior of RC specimens shows rate of corrosion leads to tension stiffening behavior of RC elements. high rate of corrosion completely destroys bond-slip behavior which leads to brittle fracture of RC element especially flexural dominant one.

NOTATIONS

a	= half of spacing betweem two subsequent crack
A_c	= net concrete cross-section
A_s	= reinforcement cross-section
A_{s0}	= reinforcement cross-section without considering corrosion effect
c	= concrete cover
C_0	= corrosion level corrosponding to first bond strength increase
C_{cr}	= corrosion level corrosponding to first longitudinal crack
C_u	= ultimate corrosion level
C_w	= corrosion rate
d	= reinforcement diameter
D	= specimen diameter
E_c	= concrete intial modulus of elasticity
E_s	= renforcement steel intial modulus of elasticity
f_{bm}	= mean bond strength
f_{bu}	= ultimate bond strength
f_{bu0}	= ultimate bond strength without corrosion effect consideration
f_c	= concrete compressive strength

f_t = comcrete tensile strength
F_c = concrete force contribution
F_s = reinforcement steel force contribution
l = specimen length
S_m =ultimate average crack spacing between two adjacent crack
S_{m0} =ultimate crack spacing between two adjacent crack without considering corrosion
S_{max} =ultimate maximum crack spacing between two adjacent crack
S_{min} =ultimate minimum crack spacing between two adjacent crack
T =Apllied tensile load
T_y =Apllied tensile load corresponding to yield strength
T_{y0} =Apllied tensile load corresponding to yield strength without considering corrosion
u_c = concrete end deformation
u_s = reinforcement steel end deformation
Δ_s =end net slip
ε_{cm} =concrete average strain
ε_{sm} =reinforcement steel average strain
ρ =reinforcement ratio
σ_{cm} =concrete average stress

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