論文

EXPERIMENTAL STUDY ON CORROSION EFFECT ON TIME DEPENDENCE OF BOND

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ABSTRACT: In this study the effect of corrosion on time dependent bond behavior was investigated experimentally. Reinforced concrete prism specimens were made of concrete with 0.60 water cement ratio (w/c) and were provided with two separate reinforcement steel bars arranged along their longitudinal axis. One of the steel bars with shorter embedded length was corroded electrolytically before performing pull out test. Bond stress level was chosen as a major factor for a corrosion of 5.5% percentage of mass loss. The results show that if bond stress level exceeds 62%, remarkable creep of bond takes place. Moreover, load history may have some effect on slip creep in presence of corrosion.

KEYWORDS: Bond, Slip, Creep, Corrosion, Bond stress level.

1. INTRODUCTION

Vast amount of data was accumulated for the effect of corrosion on bond behavior between steel reinforcement and concrete under instantaneous load. This data is very important for safety assessment of the constructions suffering from reinforcement corrosion. However, most of the structures are subjected to long-time load, and very few studies were conducted on corrosion under sustained load. In addition, the influence of corrosion on long-term bond behavior still needs more explanation. Therefore, the present experimental study is a part of a project dedicated to study the effect of corrosion on bond characteristics between reinforcement steel bar and surround concrete under sustained load. The target of this study is to provide bond stress levels limits that should not be exceeded in presence of corrosion, in order to prevent deterioration due to large creep.

In this study the effect of corrosion on time dependent bond behavior was investigated experimentally, Reinforced concrete prism specimens were made of concrete with 0.60 water cement ratio (w/c) ratio and were provided with two separate reinforcement steel bars arranged along their longitudinal axis. One of the steel bars with shorter embedded length (4.0D,D: diameter of RB) was corroded electrolytically before performing pullout test. Based on bond strength under instantaneous pull out tests, bond stress levels as well as corrosion degree (5.5%) was adopted for the sustained load test. The results show that if bond stress level exceeds 62%, remarkable creep of bond takes place. Moreover, load history may have some effect on slip creep in presence of corrosion.

2. OUTLINE OF EXPERIMENT

2.1. MATERIALS AND CONCRETE MIX

Table 1 Mix. Proportions

w/c	Proportions (kg/m^3)				AE Agent (kg/m^3)
	Water	Cement	Aggregate		
			Fine	Coarse	
60%	180	300	790	1015	0.075

Ordinary Portland cement was used to make concrete of 60% water-cement ratio (W/C), which has been used widely. The concrete mix

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proportions are tabulated in **Table 1**. The coarse aggregate was a crushed stone with maximum nominal size of 20mm, specific gravity of 2.74 and fineness modulus of 6.35. The fine aggregate was crushed sand with specific gravity of 2.66 and fineness modulus of 2.88. The concrete compression, splitting tension strength and modulus of elasticity at age of 28 days were 36.0, 3.29 N/mm^2 and 30.0 kN/mm^2, respectively.

The used reinforcement was of deformed steel bar of 16 mm in nominal diameter and 295 N/mm^2 in nominal yield strength. The chemical composition percentages of the used steel were 0.19%, 0.12%, 0.52%, 0.028% and 0.039% in mass of Carbon, Silicon, Manganese, Phosphorus and Sulfur, respectively.

2.2 TEST SPECIMENS

As shown in **Fig. 1**, the specimens were reinforced concrete prism of dimensions 150x150x400 mm provided with two separate steel bars along their longitudinal axes. One steel bar with short embedded length equal to four times the nominal diameter (D) was to be corroded and the other one was with longer embedded of 9D in length was not corroded. Therefore, even in case of conducting pullout test for the intact specimens, bond failure will be in the short embedded steel bar side. In addition, to ensure bond failure, the dimensions of the concrete cross section were chosen to prevent the axial tension failure of concrete. Unbonded portion near the loaded end was installed equal to nominal diameter of the steel bar (16 mm) to prevent the premature cracking at low levels of loading.

Because the pullout test was conducted by applying tensile forces to long and short bars, they were concentrically aligned at the center of the cross section as precisely as possible to obtain accurate results. Therefore, for each specimen, one end of each of the two steel bars was grinding to become round bars with diameter of 12.95 mm and length of 85 mm. The grinding ends were inserted into the two ends of a polyvinyl pipe (PVC) of internal diameter of 13mm, to coincide the axes of the two steel bars. This arrangement ensured location alignment of both bars. The outer diameter of the PVC pipe was 16 mm equal to nominal diameter to avoid stress concentration on concrete at the interface between the steel bar and the PVC pipe as much as possible. The inner surface of the PVC pipe was covered by oil to confirm no such effect of bond stress between steel bar and the PVC pipe. Inserting a butyl rubber into the interface between the pipe and the steel bar prevented leakage of water inside the PVC pipe.

The surface layer of the steel bar was removed by 10% HCl solution. In addition to the prism specimens, cylinders with a dimension 100x200 mm and that with 150x200 mm were cast to obtain compressive and tensile behavior of concrete. Twenty-four hours after casting, the specimens were demolded and immediately placed in curing water for one weak. Hereafter, specimens were kept in the curing room (20 °C and 100% R.H.) up to age of 28 days old before starting of the electrolytic corrosion. The results of only fifteen specimens will be presented in this study.

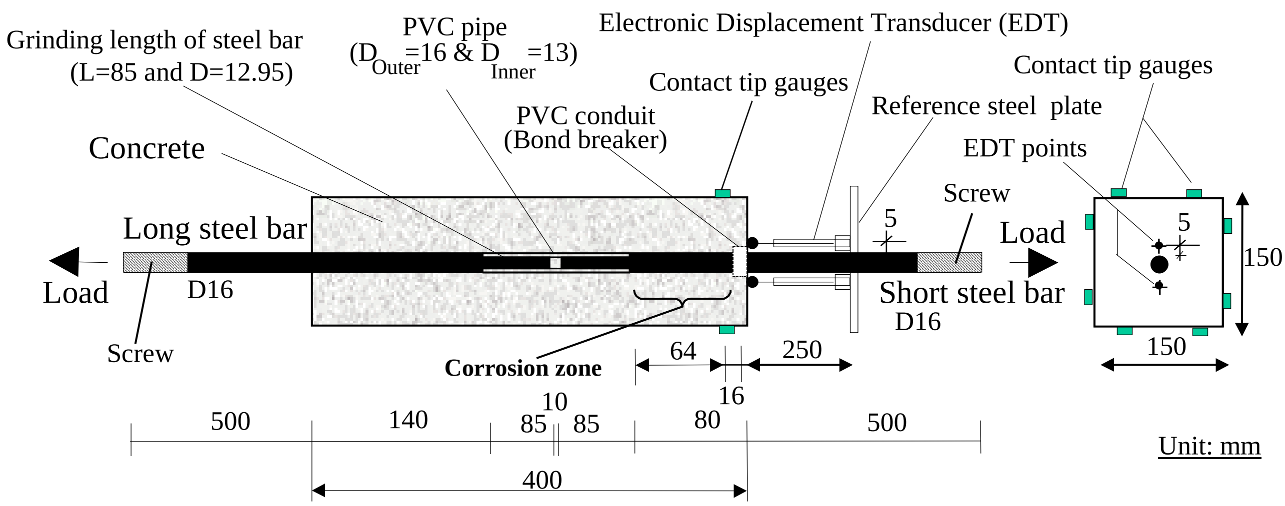

Fig. 1 Specimen specifications

2.3 ACCELERATED CORROSION

Electrolytic corrosion technique was used to accelerate corrosion of the shorter embedded reinforcement. **Fig. 2** shows a schematic accelerated corrosion setup.

The prism specimens for bond test were soaked in solution containing 3% Sodium Chloride (NaCl) by the weight of water. A constant electric potential of 72 volt was applied to each specimen for different controlled period to get various corrosion degrees in range of 0 to 10% of mass loss. The direction of the current was arranged so that the reinforcing bar served as the anode where mass reduction takes place, and a metallic ring was setting to the short embedded reinforcement bar acted as cathode. After the power supply was turned on, the anodic current (corrosion current) flowing through each specimen was recorded every one minutes using data logger. The amount of corrosion was calculated according to Faraday's law given by Eq. (1).

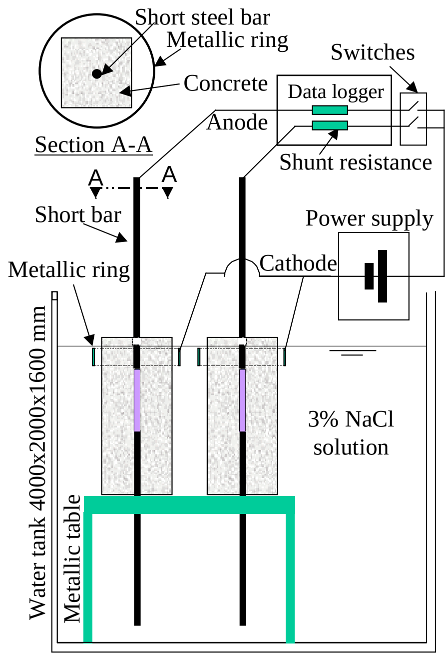

Fig.2 A schematic accelerated corrosion setup

$$\Delta\omega = \frac{A \cdot I \cdot t}{Z \cdot F} = \frac{A}{Z \cdot F}\int I\,dt \qquad (1)$$

Where: $\Delta\omega$ is metal weight loss due to corrosion (g), A is atomic weight of iron (55.847g), I is corrosion current (amp), t is time elapsed (sec), Z is valence of the reacting electrode of iron (2) and F is Faraday's constant (96487 amp sec).

Preliminary test was carried out to confirm the reliability of using Faraday's law, in the used galvanic corrosion arrangements and conditions, to get accurately predefined percentage degree of corrosion. The actual mass losses that measured by gravimetric method were always larger than the computed values with differences less than 5% of the measured ones; thus, the correlation between actual and predicted mass loss was almost perfect. Consequently, in this study, the reported degrees of corrosion are only based on that predicted by Faraday's law.

2.4 LOADING TEST

Figs. 3 shows the arrangement of the specimen in loading apparatus for tension creep frame with capacity of 80kN. The specimen is fixed to the frame through coupler using screwed ends of the specimen's steel bars. The pull out force was applied to the specimen by a system of lever arms that transmit and magnify (50 times) the weights that were stacked through chain and hanged freely to the end of the upper lever arm. The specimen was fixed to the both the lower lever arm and screw jack fixed on the base of the frame. Using this loading method, the load was kept constant throughout the creep experiment period. Short-term tests were performed in the same creep frame by controlling the tension displacement of the full length of the specimen through controlling the upper lever arm level in the hanged free weight sides, regardless of the magnitude of the hanged weights.

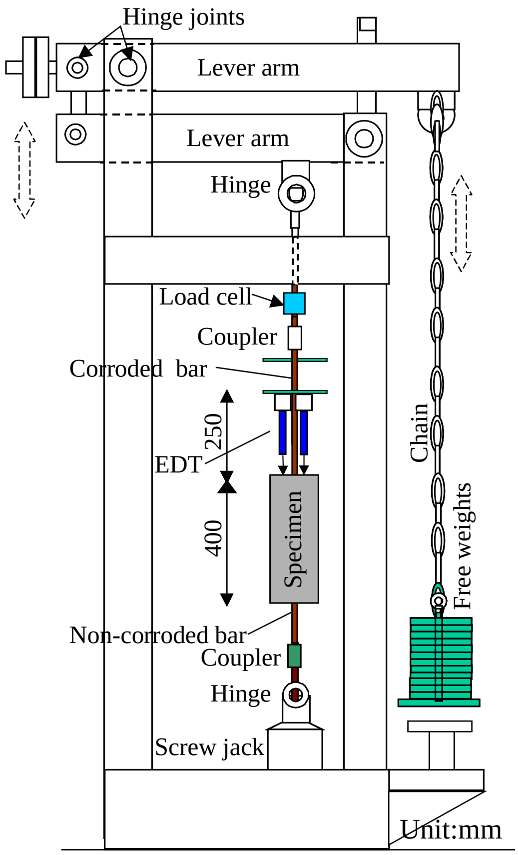

Fig. 3 Loading setup

Load was measured by means of tension load cells. The bond slip response between the concrete and the reinforcing bars was measured using two electrical displacement transducers (EDT) (of 1/1000mm accuracy) mounted to a reference steel plate fixed on the external extension of the steel with the tested bond zone. The displacement measured between the concrete surface and the reference plate was adjusted by subtracting the elongation of the bar to obtain the slip.

For the short embedded length used, as the bond stress variation along the axis could be negligible. Therefore, the assumption of uniform bond stress distribution along the embedded length of the bar should be accepted, thus average bond stress was computed using the equation $\tau = P/(u\,.l)$ where: τ is the bond stress, P is the applied pullout load, u is the nominal perimeter of the steel bar and l is the length of the bond part (4.0D,D: diameter of RB).

Based on the effect of corrosion on bond strength resulted from the instantaneous pullout test, the degree of corrosion and bond creep stress levels were determined. Data logger recorded all the measurements at pre-set intervals. The loading age of the sustained load specimens was 150 days. The results shown in the current study cover 125 days of loading (four months).

3. RESULTS AND DISCUSSIONS

3.1 EFFECT OF CORROSION ON BOND STRENGTH

Fig. 4 shows the effect of corrosion on the bond strength resulted from instantaneous pullout test. As shown in the figure, in the absence of corrosion cracks before loading, for corrosion degrees less than 5.3%, bond strength increased slightly with increasing corrosion degree, while, bond strength increased more from 10.4 to 12.6 N/mm^2. The bond strength was obtained at corrosion degree of 5.3%, and was almost 20% over than that of the intact specimen. This can be attributed to an increase in the reactionary confinement and the mechanical interlock of concrete around bar against axial direction. Failure occurred due to sudden splitting of the concrete cover followed by tension concrete failure.

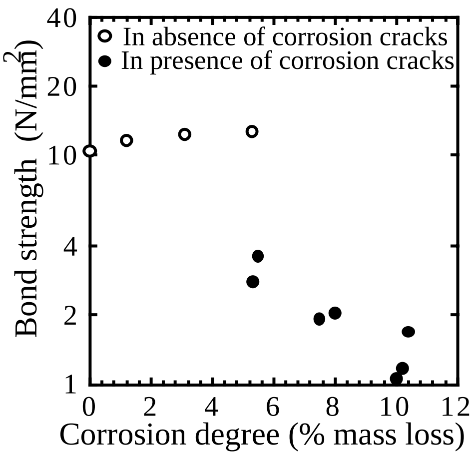

Fig. 4 Effect of corrosion on bond strength

In the presence of corrosion cracks before loading, bond strength decreased significantly. For corrosion degrees from 5.5% to 10.5%, the bond strength reduced from 38% to 11% of the bond strength (10.4 N/mm^2) obtained from the intact specimen. For these specimens, failure occurred due to complete sliding of the concrete key over the bar ribs with/without crushing of the concrete key's tip.

3.2 ADOPTING OF CORROSION DEGREE AND BOND STRESS LEVELES

Table 2 represents the specimens' specifications for the sustained load test. From **Fig. 4**, for the long-term test, corrosion degree was adopted to be the percentage of reinforcement mass loss at which bond strength dropped suddenly due to the formation of corrosion cracks. Consequently, 5.5% of mass loss was considered, where its bond strength is about 3.9 N/mm^2 corresponding to 38% of the bond strength of the intact specimen. The applied bond stress level was taken as the ratio between applied bond stress and the bond strength associated with the specimen corrosion degree. **Fig. 5** shows corrosion cracks patterns of the

Table 2 Specifications of creep specimens

Symbol	Corrosion degree	Loading periods			
		Stage 1 From 0 to 2500 hours		Stage 2 After 2500 hours	
		Bond stress (N/mm^2)	Bond stress level	Bond stress (N/mm^2)	Bond stress level
S0	0.0%	2.69	26%	3.67	35%
S1	5.5%	2.69	69%	3.76	96%
S2	5.5%	2.40	62%	3.49	89%
S3	5.5%	2.07	53%	3.48	89%

specimens selected to the sustained load test. In the figure, crack widths are presented, and both the upper and lower surfaces during the casting are mentioned. The sustained loads were divided into two parts. The first part (stage 1) was applied for a period of 105 days (3.5 months) till slip creep became nearly constant. Thereafter, the second part (stage 2) of the sustained load was added. The load stress levels given in stage 1 usually, in practice, resulted from degradation of bond strength due to the presence of corrosion cracks along the reinforcement. For example bond stress level for intact specimen (0% corrosion degree) is taken in the table as 26%, and due to corrosion induced cracks of 5.5% mass loss, the bond stress level became 69% that is represented by specimen S1.

3.2 SUSTAINED PULL OUT TEST

Fig. 6 represents the slip creep along the test period of four months. The figure shows the increase in slip due to creep only and no slip increase due to loading is represented in this figure. During the first 105 days, as illustrated in **Table 2**, the applied bond stresses on specimens S0, S1, S2 and S3 were 2.69, 2.69, 2.4 and 2.07 N/mm^2, corresponding to bond stress levels of 26%, 69%, 62% and 53%, respectively.

From **Fig. 6**, it is shown that slip of specimen S1 increased remarkably with time and reached to 0.25mm at about 105 days of loading time, on the other hand creep of the other specimens S0, S2 and S3 were 0.06, 0.10 and 0.07 mm. This means that slip for 69% load stress level was 2.5 times slip of 62% bond stress level. As a result, if bond-stress level increased due to corrosion of 5.5% mass loss and reached to 69%, slip increased significantly. **Fig.7** represents the relation between bond stress level and creep of slip at 105 days. From regression, the exponential equation Eq.2 governs the relation between bond stress level and creep of slip. It is obvious that bond stress level 62% could be considered as an upper limit for bond stress levels to prevent large slip creep, in case of corrosion degree of 5.5%.

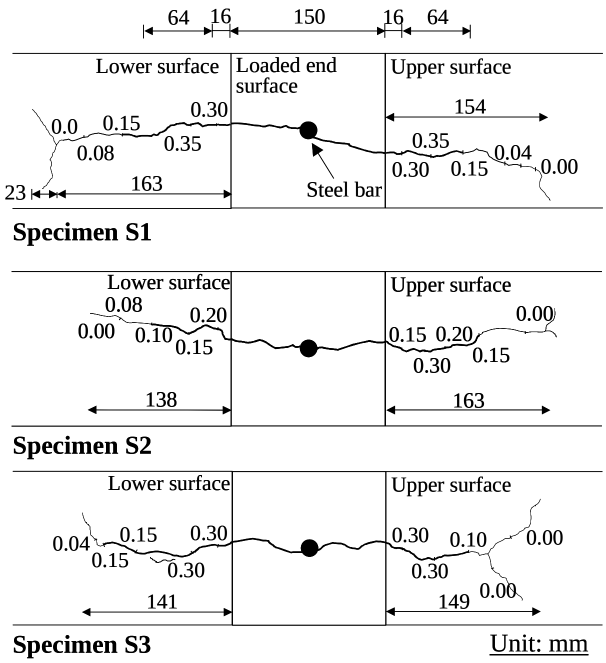

Fig.5. Corrosion crack patterns and widths of the sustained load specimens

$$\text{Slip} = e^{-8.42 + 0.102\ \text{Bond stress level}} \tag{2}$$

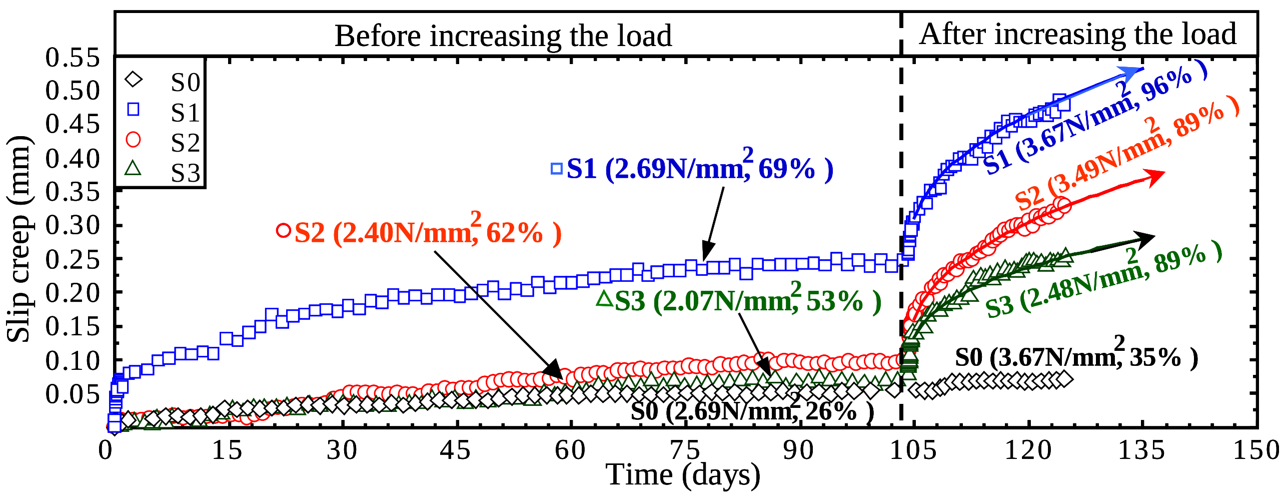

Fig.6 Creep of slip

From **Fig. 6**, after about 105 days, creep rates for all corroded specimens became almost stable. Thereafter, as illustrated in **Table 2**, the applied bond stresses for specimens S0, S1, S2 and S3 were increased to 3.67,3.76, 3.49 and 3.48N/mm^2, hence, bond stress levels became 35%, 96%, 89% and 89%. All corroded specimens exhibited very high rate of creep, where the minimum bond stress level was 89%. Within 20 days after the increasing load, creep for S1, S2 and S3 increased by 0.25, 0.25 and 0.18 mm attaining total slip of 0.50, 0.35, 0.25mm at 125 days of starting the sustained load test, respectively. Which means, both of S1 and S2 have the same creep increase (0.25mm) regardless of the applied load stress level value. According to a previous study [1], when bond stress level for corroded specimen was 95%, the specimen exhibited a high and steady rate of creep (secondary creep) that eventually may lead to creep failure in bond. Therefore, since S1 and S2 got similar creep behaviour for stress level 96% and 89%, as a result, it could be said that when stress level exceeds 88% due to corrosion, bond creep failure is potential. However, for specimen S3 that has bond stress level of 89% like S2, it showed smaller creep. This may be owned to the influence of the former load stress level before increasing the applied bond stress, where the former load stress levels for S2 and S3 were 62% and 53%, respectively.

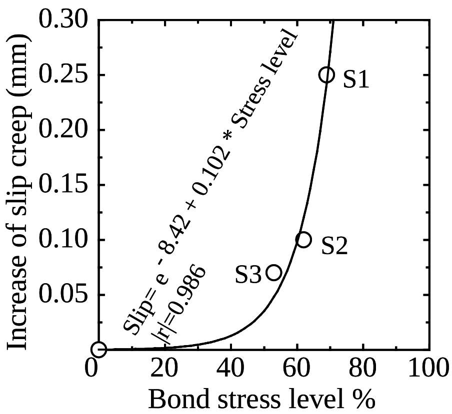

Fig. 7 Effect of bond stress level on slip at 105 days of loading time

In the present study it was focused on corrosion degree of 5.5%, as the degree, which is responsible to form corrosion cracks enough to reduce significantly the bond strength. However, in nature, corrosion degree, which causes cover cracking depends on corrosion rate, concrete strength, ratio between bar diameter and concrete cover thickness, … etc. Therefore the results of this study should be calibrated to be applicable in other conditions. In addition, corrosion degree needed to crack the cover should be smaller, when corrosion process takes place under loading. The burst pressure that is required to crack the concrete cover would be the summation of expansion corrosion pressure as well as vertical component of bond stress acting in the same direction of corrosion pressure.

4. CONCLUSIONS

Within the limits of the results obtained in this study, for specimens with corrosion degree of 5.5%, the following points could be drawn:

(1) Bond stress level of 62% could be considered as safety limit to avoid large bond creep in case of corrosion degree of 5.5%, where after this level creep of slip increased aggressively.

(2) In case of increasing the applied load, if bond stress level exceeds 89%, and the former bond stress level was larger than 53%, rate of creep will be approximately similar regardless of the magnitude of the applied bond stress level.

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