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Research Article

The Reinforcement Bond Strength Behavior under Different Corrosion Condition

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Abstract: The main idea of this study is to evaluate the bond strength for reinforcing concrete with corrosion that it can damage the R.C bond. Pullout tests carried out to evaluate the effects of corrosion on bond, for that purpose a series of specimens with varying reinforcement corrosion levels tested. The acceleration steel corrosion was 4, 6 and 8 days corrosion. The aim of choosing 4, 6 and 8 days that are trying to reflect field condition on test. The test designed to provide the data required to assess the bond properties with different variables, bar diameter and concrete strength. The pullout test specimen was designed to can get best significant result by provided anchored length and avoid yield failure. The test result shows verity relation between the bond strength and corrosion. The percentage of steel metal loss was smaller for a large diameter bar compared to that for smaller diameter bar at a constant corrosion rate. For C30-10 results show there are reduction with bond strength around 22% for 4 days corrosion, 25% for 6 days corrosion and 31% for eight days corrosion. While for C30-14 results show there are reduction with bond strength around 19% for 4 days corrosion, 23% for 6 days corrosion and 28% for 8 days corrosion.

Keywords: Bond strength, pullout test, reinforcement corrosion

INTRODUCTION

In view of the fact that a large number of existing structures deteriorated with time by reinforcement corrosion due to environmental exposure, corrosion is one of the main causes for the limited durability of reinforced concrete (Fu and Chung, 1997). Bond strength is a measure of the transfer of load between the concrete and reinforcement. Bond strength influenced by bar geometries, concrete properties, the presence of confinement around the bar, as well as surface conditions of the bar (ACI, 2003).

The corrosion had a significant impact on the steel structure performance under static and dynamic load for different corrosion condition (AL-Hammoud *et al*., 2010). The interaction of reinforcing steel bars with concrete is a quite complex phenomenon that has important effects on the response characteristics of reinforced concrete elements and structures under static and dynamic loads (Tassios and Yannopoulos, 1981). There are number of research programmers have been carried out in the area of steel-concrete bond behavior, such as those by Tepfers (1973, 1980). Also, many researchers have conducted studies for the mechanism of bond failure. For example, and Jones proposed an approach for the relationship between bond strength and splitting, in which bond strength of ribbed bars is composed of non-splitting and splitting components (Tepfers, 1980; Cairns and Jones, 1995a, b).

Bala´zs (1993) developed a theory for crack formation in reinforced concrete based on an analysis of slip, bond stresses and steel stresses. The volume increase due to corrosion causes splitting and leads to weakening of the bond, which directly affects the serviceability and ultimate strength of reinforced concrete members within a structure (Cabrera, 1996). The non-uniformity in bond stress distribution causes difficulties in assessment of the effects of corrosion on bond and thus on the structures. Recently, a number of studies have been undertaken to evaluate the effects of corrosion on the bond strength (Lee *et al*., 2002; Lundgren, 2002; Cabrera, 1996).

Studies conducted by some researchers suggested that losses in the structural performance of reinforced concrete members with corroded reinforcements are caused by three factors (Morinaga, 1996; Okada *et al*., 1988; Katayama *et al*., 1995; Nakayama *et al*., 1995; Cabrera, 1996). Losses in the effective cross-sectional area of concrete due to cracking in the cover concrete, losses in the mechanical performance of reinforcing bars due to the losses in their cross-sectional area and losses in the bond performance of concrete with reinforcements. Although considerable research has been conducted on the bond behavior of specimens with different levels of corrosion, little has been done to improve the representativeness of the mechanical tests with regard to the actual bond behavior (Almusallam *et al*., 1996). Studies conducted by Auyeeung (2001)

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have confirmed that the loss of bond strength for unconfined reinforcement is much more critical than cross-section loss; that is, a low percent diameter loss could lead to 80% bond reduction. Auyeeung's study also showed that confinement provides excellent means to counteract the bond loss.

On the other hand according to the previous study by Kanakubo *et al*. (2008), bond behavior for the local area has been reported using test results of the specimen with a bond length of four times of the diameter of reinforcement, showing that the internal cracks of surrounding concrete occur by corrosion of reinforcement and the relationship between bond strength and weight reduction ratio of reinforcement up to 7% can be recognized.

In this study the effect of reinforcement corrosion on bond investigated by using the analysis of tests carried out. The research program conducted for reinforcing bars of different corrosion levels. Specimens were first investigated under pullout loads.

EXPERIMENTAL PROGRAM

Experimental methods: The main test for experimental that is pullout test which used to get the bond strength and slip for various corrosion duration time. To can be corroded steel bar, the specimens were submersions in a 5% NaCl solution after 28 day curing. All corroded specimens would be corroded for different designed corrosion levels under direct electric current. The specimens tested for bond strength and slip under pullout loading. Electrolytic chemical corrosion method used to accelerate the corrosion. In the procedure of reinforcement corrosion, electric current and corrosion time used as the indications for the designed corrosion levels. The 4 days duration would be taken as light corrosion condition while the 6 days refer to the medium corrosion condition and 8 days corresponding to heavy corrosion condition.

Test specimens: The design of the specimen conformed to standard (China Standard, 2002a). The steel properties showed in Table 1. The reinforcement had a 14, 10 mm bar diameter (Fig. 1). For those specimens with stirrups, steel with a diameter of 8 mm selected as stirrups as shown in Fig. 2. To avoid corrosion of the stirrups, they isolated from the main bar. The bars cleaned before casting into the concrete specimens. The embedment length chosen was four times the bar diameter, to avoid yielding of the steel bar under pullout load. The concrete mixture parameter such as cement, sand, aggregate, water to cement ratio, were same for all the concrete mixtures. The Table 2 shows the mix proportions used for concrete casting.

The concrete mix was then pouring into 150×150×150 wooden molds. Three concrete cubes with a dimension of 100×100×100 mm^3 were also casting for testing the compressive strength of the specimens. For corroded specimen the 5% Nacl from cement weight added to mixture for acceleration corrosion. After casting, the concrete specimens, both pullout specimens and cubes for compressive strength, kept and covered with plastic sheet with standard curing for 28 days. The 28-day cured specimens had an average measured strength of 26 and 32 MPa. The 42 samples classified into the many groups, according to the bar diameter and concrete strength. The Table 3 shows designation of the control samples while the Table 4 shows the corroded sample.

Corrosion acceleration: After curing, the specimens prepared to accelerated corrosion by applying anodic current of specified intensities and for specified time periods (4, 6 and 8 days). This achieved through DC power supply with a built-in ammeter to monitor the current and a potentiometer to control the current intensity which it was 2 ma/cm^2. The concrete specimens were partially immersing in 5% sodium chloride solution in a tank such that the base of the specimen was just in contact with water. The direction of the current adjusted so that the reinforcing steel became an anode and a stainless steel plate placed on

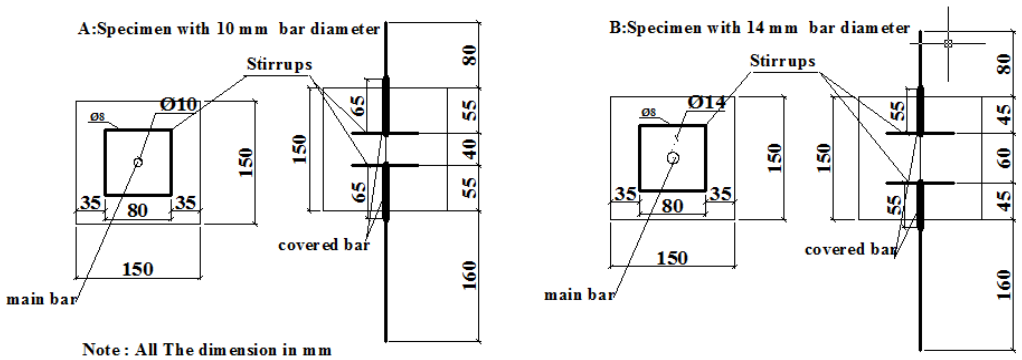


Fig. 1: The pullout reinforced casting specimen details

Table 1: Properties of steel material (China Standard, 2002b)

Steel bar type	D (mm)	Yield stress (n/mm^2)	Tensile strength (N/mm^2)	Elastic modulus ($X10^5 N/mm^2$)
HRB 335 (20 MnSI)	10-14	305-312	365-370	2.0-2.1

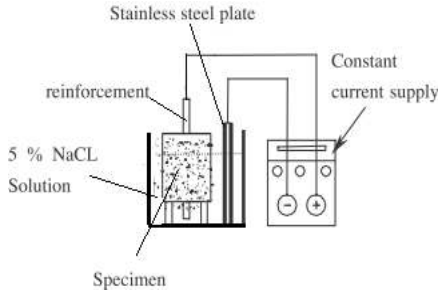


Fig. 2: The electrochemical acceleration system

Table 2: Mixture proportion

Concrete strength	Cement (gm)	Sand (gm)	Aggregate (gm)	w/c
C30*	309	824	1048	0.45
C25	274	833	1061	0.48

*: The quantity for 1 m^3 concrete

Table 3: Designation of control sample

Bar diameter (mm)	Concrete strength (mpa)	Designation
10	C30	C30-10- (1, 2, 3)
14	C30	C30-14- (1, 2, 3)
10	C25	C25-10- (1, 2, 3)
14	C25	C25-14- (1, 2, 3)

Table 4: Designation of corroded sample

Bar diameter (mm)	Concrete strength (mpa)	Time days	Designation
10	C30	4	C30-10- (4, 5, 6)
10	C30	6	C30-10- (7, 8, 9)
10	C30	8	C30-10- (10, 11, 12)
14	C30	4	C30-14- (4, 5, 6)
14	C30	6	C30-14- (7, 8, 9)
14	C30	8	C30-14- (10, 11, 12)
10	C25	4	C25-10- (4, 5, 6)
10	C25	6	C25-10- (7, 8, 9)
10	C25	8	C25-10- (10, 11, 12)
14	C25	4	C25-14- (4, 5, 6)
14	C25	6	C25-14- (7, 8, 9)
14	C25	8	C25-14- (10, 11, 12)

the concrete specimen served as a cathode as show in Fig. 2.

Corrosion rate test: To get the significant corrosion level (corrosion current density Icorr.) with time for all specimens, the Linear Polarization Resistance Measurement (LPRM) technique will use for all specimen Stern *et al*. (1957) and IJsseling (1986).

The LPRM idea constructed according to the stern-Geary characterization of typical polarization curve for the corroding metal. In other words, if a large current required changing the potentials by a given amount, the corrosion rate is high and on the other hand, if only a small current is requiring, the corrosion rate is low.

The corrosion cell consisted of a reference electrode, a working electrode which was the reinforcing steel embedded in the concrete specimen and a counter electrode which was placing in the salt solution around the concrete specimen as shown in Fig. 3. The reinforcing steel bar polarized by applying a small potential shift to it (ΔE (mV)) and the resultant current (ΔI) between the working electrode and the counter electrode measured.

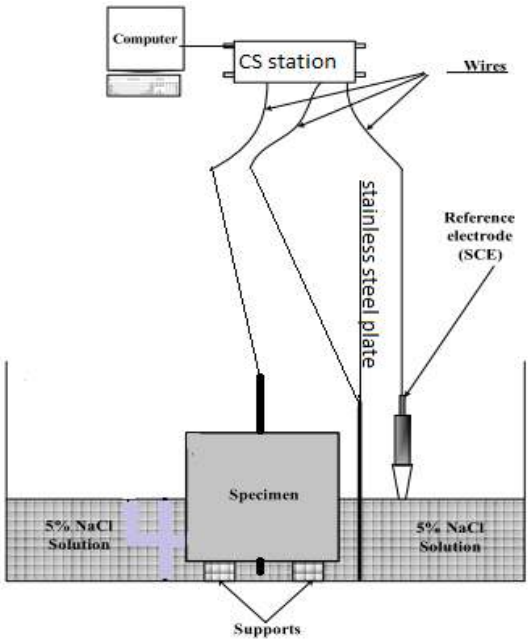


Fig. 3: The corrosion rate measure detail

The linear polarization resistance, R_p, determined from the slope of the plot of applied potential versus the measured current. The corrosion current density was then calculating by using the Stern-Geary formula (IJsseling, 1986):

$$I_{corr} = \frac{\Delta E}{\Delta I} = \frac{B}{R_p} \quad (1)$$

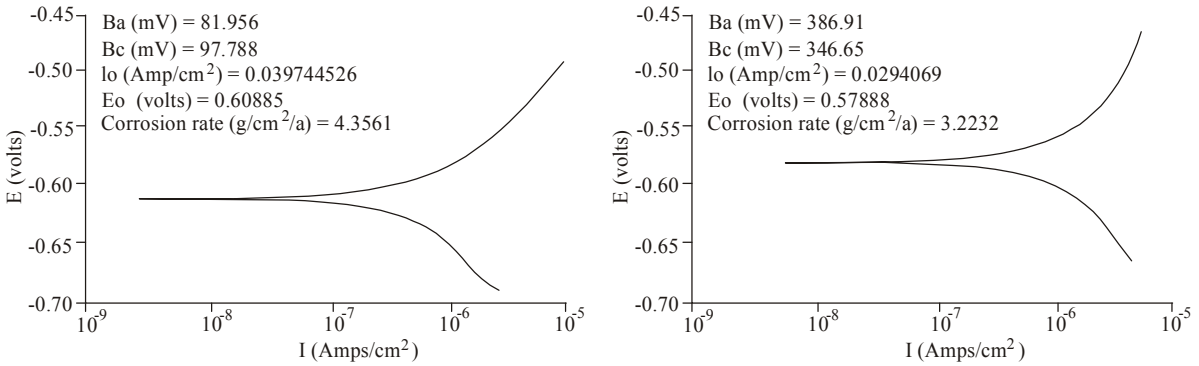
where,
I_{corr} : The corrosion current density (μA/cm^2)
R_p : The polarization resistance (kΩ.cm^2)

To measure the weight loss was used to calculate the instantaneous Corrosion rate (J_r) as follows (China Standard, 2002b):

$$J_r = (\frac{W}{F})I_{corr} \quad (2)$$

where,
W = Equivalent weight of steel
F = Faraday's constant
I_{corr} = In mA/cm^2
J_r = In g/cm^2/year

For corrosion rate measure, the Corrosion test electrochemical measurement System (CS) that used in this study. The electrochemical measurement system is an integrated set of full automatic electrochemical measurement and analysis that controlled by microcomputer. The system includes electrochemical work station, corrosion test control and data analysis



(a) Corrosion rate for specimen C25-10-1 (b) Corrosion rate for specimen C30-10-9

Fig. 4: The corrosion test result by using electrochemical measurement system (CS)

software, which can use for measuring corrosion rate Jr as shown in Fig. 4.

Pullout tests: A pullout test is one method for measuring the bond strength between the reinforcing steel and concrete. In a pullout test, a bar embedded in a block of concrete. The bar pulled out of the block in load control. The load at which the bar pulls out taken as the bond strength as shown in Fig. 5 The pullout test is widely using to test the reinforcement concrete bond and bond-slip. The KB-150 models (China Standard, 2002a) used in this study for pullout test.

TEST RESULTS

To can evaluate the strength bond properties between corroded steel and concrete, the test results would analyze to the following items:

- Comparison between corroded and control specimen
- Load-displacement behavior at failure for different corrosion levels
- Effects of corrosion level on the bond strength

The average failure load, corrosion rate and corresponding displacement for the specimens obtained by averaging the results of three specimens that tested in each case, they are presenting in Fig. 5 and 6 for control and the corroded specimen, respectively. All specimens failed in pullout with the exception three of specimen, which failed in yielding.

The bond strength calculated corresponding to load and embedded length as the following (China Standard, 2002c):

$$T = \frac{P}{Lx\alpha} \quad (3)$$

where,

T : Bond strength (MPa)
P : Max. load (n)

Fig. 5: Pullout test machines

(a) Corroded specimen crack (b) Control specimen crack

Fig. 6: Corroded and control specimen crack after pullout test

α : Steel bar circumference (Π d) (mm)
L : Embedded length bar (mm)

From Table 5 and 6, it can be seen that the measured failure load and bond strength was generally lower than the control ones. The difference in results indicates that the corrosion rate reduced the bond strength for steel bar with concrete. The 4 days corrosion recorded less reduction in bond strength from the other corrosion of duration.

In the beginning period of corrosion acceleration, it observed that the electrical intensity was slowly and then increased slowly for a relatively long time. The Surface fine cracks could observe a time after the electrical intensity began to decrease. The Fig. 6 showed the different crack for corroded and control specimen after pullout test.

Table 5: Control specimen pullout test results

Sample	Max. displacement (mm)	Max. load (kn)	Min. load (kn)	Max. bond strength (mpa)
C30-10	0.45	60.62500	1.240	12.85985
C30-14	0.42	72.75000	5.400	11.02273
C25-10	0.47	57.59375	1.178	12.21686
C25-14	0.41	69.11250	5.130	10.47159

Table 6 corroded specimen pullout test results

	4 days corrosion			6 days corrosion			8 days corrosion		
Sample	Avg. corrosion rate (j_r)	Max. displacement (mm)	Max. bond strength	Avg. corrosion rate (j_r)	Max. displacement (mm)	Max. bond strength	Avg. corrosion rate (j_r)	Max. displacement (mm)	Max. bond strength
C30-10	2.147	0.512	10.031	2.773	0.520	9.520	3.3778	0.530	8.881
C30-14	1.931	0.491	8.923	2.041	0.541	8.380	2.6430	0.541	7.940
C25-10	2.213	0.521	12.001	3.321	0.551	11.778	4.3467	0.571	8.180
C25-14	1.023	0.533	10.320	1.980	0.561	10.169	2.6227	0.581	7.420

Avg.: Average; Max.: Maximum

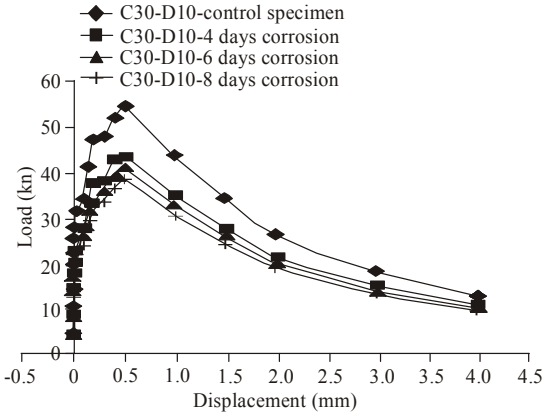


Fig. 7: Load and displacement relationship for C30-D10 specimen with different corrosion duration

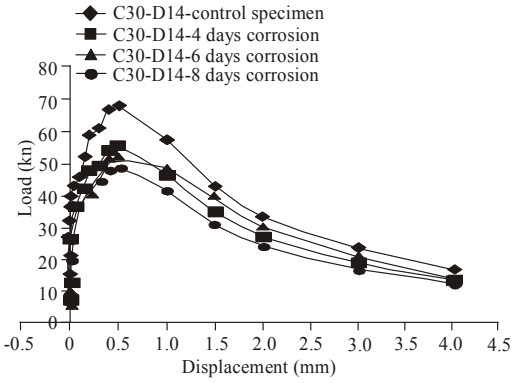


Fig. 8: Load and displacement relationship for C30-D14 specimen with different corrosion duration

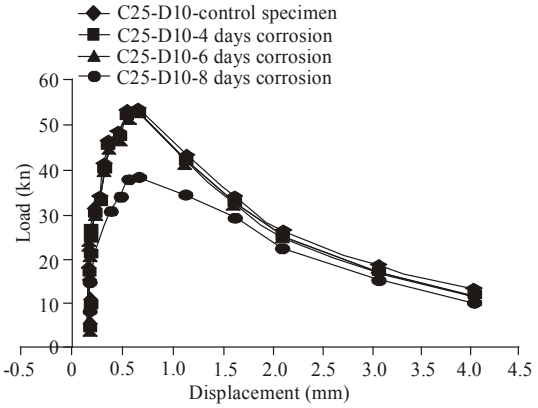


Fig. 9: Load and displacement relationship for C25-D10 specimen with different corrosion duration

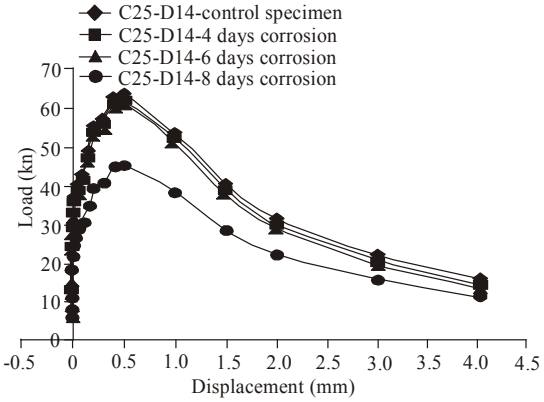


Fig. 10: Load and displacement relationship for C25-D14 specimen with different corrosion duration

Three failure types observed in the experimental program: A pullout failure occurs when the test bar reaches a peak load and then proceeds to pull out from the block without splitting any face of the concrete. A splitting failure is occurring when the bar reaches a maximum load and then a crack opens parallel to the applied force on the front face of the block as the bar pulls out. This splitting can happen suddenly or gradually (both were observed). The last type of failure is bar yielding, when the bar reaches a load higher than the load required to cause yielding. While technically a yielding bar is not a failing specimen, in most cases if a bar was visibly yielding the test would cut off to prevent damage to the system that was possible with bar fracture. Because of this, the peak load must consider separately from splitting or pullout type failures.

The Fig. 7, 8, 9 and 10 showed the load, displacement behavior under different condition. The results show the steel bar diameter have linear impact

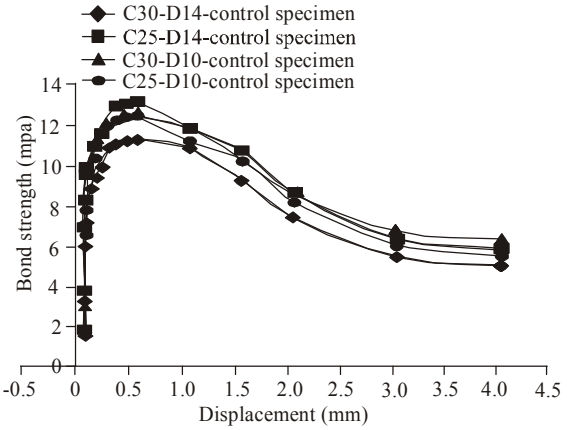


Fig. 11: Relationship between bond strength and displacement for control specimen

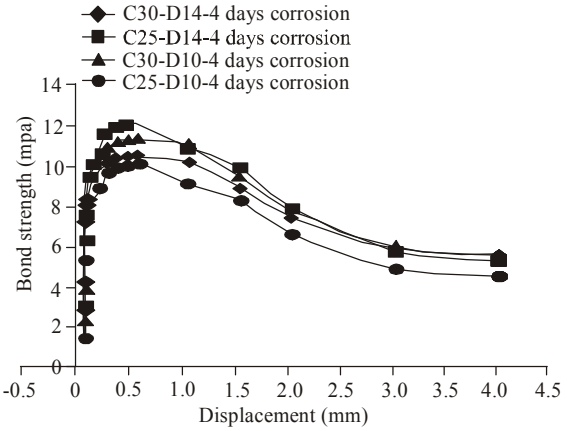


Fig. 12: Relationship between bond strength and displacement for 4 days corrosion specimen

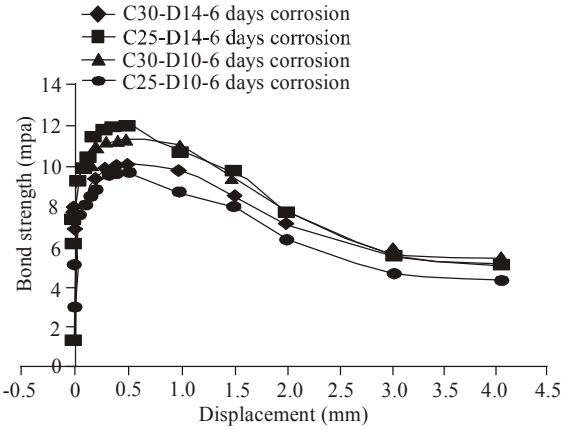


Fig. 13: Relationship between bond strength and displacement 6 days corrosion specimen

on the load displacement behavior with different corrosion duration. The corrosion rate has a different effect on strength of concrete.

All the corroded specimens' results showed in Fig. 11 to 14 reveal that as the corrosion level increased

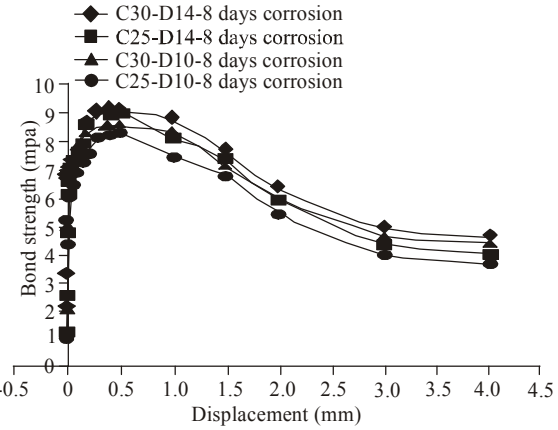


Fig. 14: Relationship between bond strength and displacement for 8 days corrosion specimen

bond strength of deformed reinforcing bar specimens decreased. In terms of bond strength of corroded specimens when compared to bond strength of no corroding specimens, when the corrosion was 2.0%, the bond strength only decreased 16%. An explanation may be that corrosion had caused fine cracks in the specimen, the stirrups provided enough confinement.

When a pullout load applied to the specimen, the bearing action of the ribs of the deformed sled bars against the concrete caused horizontal bearing stresses as well as hoop stresses. Due to the corrosion cracks, the tension in the specimen reduced therefore the confinement reduced and the slip increased which finally resulted in bond failure of the specimen. For the corrosion levels in this range, bond failure usually was the result of splitting of the specimen along the corrosion cracks. For this type of failure, the corrosion-induced cracks had already weakened the concrete. The Fig. 11 to 14 also comprised between concrete strength and bar diameter. The strength of concrete had a positive impact effect on the pullout test results. The mechanical bond slope affected by the elastic modulus and post yield behavior of the reinforcement. The decreased elastic modulus of stainless steel bars result in lower mechanical bond slopes and higher slip values at the peak load. Relative rib area did not have a significant effect on the slope of the mechanical bond.

At higher levels of corrosion, residual bond strength observed for deformed reinforcing bar specimens with stirrups. For the control specimen (no corrosion) with deformed bar, the load-slip curve usually had a sharp decrease. For samples with higher corrosion levels, this decrease was more gradual. A possible explanation is that corrosion-induced cracks on the specimen had already released some energy before loading. For deformed bar specimens, slip at ultimate bond load tended to decrease as the corrosion level increased.

CONCLUSION

From these tests, where splitting curves observed for all corroded specimens, the following conclusions can be drawn:

- The shape of bond strength curves for both corroded and control specimens are similar: the bond strength initially increases up to a maximum value, but eventually decreases for greater levels of corrosion. Also, the bond strengths of corroded specimens are less than those of post-corroded specimens.
- For deformed bars, bond strength was very sensitive to corrosion levels and generally decreased with the corrosion level. Bond strength decreased rapidly as the corrosion level increased; bond strength at 2% corrosion was only one third of that of control specimens. The exception is that when the corrosion level was very low, when bond strength increased as the corrosion level increased.
- For deformed bars with confinement, corrosion had no substantial influence on the bond strength.
- For steel bar, bond strength increased as corrosion level increased, up to a relatively high degree of corrosion. The increase in bond strength could be observed even at a corrosion level of more than 5%.
- For C30-10 results show there are reduction with bond strength around 22% for 4 days corrosion, 25% for 6 days corrosion and 31% for 8 days corrosion. While for C30-14 results show there are reduction with bond strength around 19% for 4 days corrosion, 23% for 6 days corrosion and 28% for 8 days corrosion.
- The measured failure load was generally lower than the control ones. The difference in results indicates that the corrosion rate reduced the bond strength for steel bar with concrete.
- There are three failure types observed in a pullout test. The first failure occurred when the test bar reaches a peak load and then proceeds to pull out from the block without splitting any face of the concrete. Second failure, a splitting failure was occurring when the bar reaches a maximum load, and then a crack opens parallel to the applied force on the front face of the block as the bar pulls out. This splitting can happen suddenly or gradually (both observed). The last type of failure is bar yielding, when the bar reaches a load higher than the load required to cause yielding. While technically a yielding bar is not a failed specimen, in most cases if a bar was visibly yielding the test would be cut off to prevent damage to the system that was possible with bar fracture. Because of this, the peak load must be considered separately from splitting or pullout type failures. The results show the steel bar diameter had linear impact on the load displacement behavior with different corrosion duration.
- Corrosion can reduce both the elongation and the ratio of yield to ultimate strength of the reinforcement at maximum load. These reductions can be leaded to premature fracture of the bar before yield is reached for that there are no general relationships for this situation.

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