



Experimental Study on Bond Performance of Reinforced Bars in Concrete

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ABSTRACT

This paper studied the effects of reinforcement corrosion on bond performance between G-35 concrete and 16mm reinforcing steel for different corrosion levels. The steel rebar embedded in concrete specimens were corroded using an electrochemical accelerated corrosion technique by impressing current to the specimens to develop the different mass losses of reinforcement bars after corrosion. Then, monolithic pull-out loading tests were carried out on the specimens to develop the bond strength which is an important property in concrete construction as it determines the amount of tensile stress a concrete member is able to withstand safely. Bond-slip relationships for the different corrosion levels were compared. The achieved mass losses of rebar were compared with theoretical mass losses obtained by Faraday's law.

KEY WORDS: *accelerated corrosion, mass loss, bond strength, bond-slip, corrosion level, Faraday's law*

I. INTRODUCTION

Reinforced concrete is utilized as a structural material derived from the combination of concrete that is strong and relatively durable in compression and reinforcing steel that is strong and ductile in tension. Maintaining composite action requires transfer of load between the concrete and steel. This load transfer is referred to as bond. Bond stress is the tangential shear of friction developed between the reinforcement and the surrounding concrete that transfers the force onto the reinforcement. Moreover it is also crucial for the overall strength and serviceability of RC members.

Corrosion of steel reinforcement is a major problem influencing the long-term performance of reinforced concrete infrastructures (Duan, Dai, & Jin, 2015). It

normally occurs due to attack by aggressive agents, such as chloride ions, from the marine environment.

The corrosion of steel bars in concrete is an electrochemical process that; involves both chemical reaction and current flow with anode and cathode occurring simultaneously on the reinforcement surface. A series of subsequent oxidation reactions converts the ferrous hydroxide into hydrated ferric oxide (rust).

In natural condition the steel corrosion is a very slow process; needs number of years to cause reasonable structural damage. Therefore, accelerated corrosion tests become in use to solve this problem.

Bonding behaviors primarily dependent on three factors: the compressive strength of concrete, confinement and the surface of the rebar (deformed or round) (Wu & Zhao, 2013). Bond deterioration is caused by corrosion-induced sectional decrease, weakening of layers by corrosion products, decrease of bearing load due to rib loss, and concrete surface cracking (Fédération Internationale du Béton 2000).

II. EXPERIMENTAL PROGRAM AND TEST SPECIMENS

A. Material properties and mix proportions

Properties of cement, sand and gravel are tested at Irrigation Technological Center in Bago. And concrete mix design is done according to ACI 211 to get the required strength.

B. Mixing, casting and curing (Specimen preparation)

For determining the 28 day compressive strength of the concrete mix, cube specimens of size 150mm x 150mm x 150mm were prepared.

Before mixing the concrete, the reinforcement bars were carefully cleaned. The mass of the reinforcement bars in each specimen was recorded, and the bars were aligned and fastened to the moulds. A mould-releasing compound was applied to the inside surfaces of the specimen moulds. Compaction was performed with a table vibrator. After pouring and compacting the concrete, the specimen surface was smoothed with a steel trowel. The concrete specimens were kept in a curing room maintained at 22 °C (± 2 °C) and 90% relative humidity for 24 h. Demoulding and transportation of the specimens were conducted with great care to avoid any disturbance of the reinforcement bars. After demoulding, the specimens were cured in a water tank at 22 °C (± 2 °C) for 28 days. Each rebar sample was weighed prior to casting using an analytical balance with precision of 0.01 g. After which they were subjected to accelerated corrosion test; whereas the concrete cubes were tested for compressive strength at the age of 28 days.

C. Accelerated corrosion test

The known methods to accelerate corrosion are the following: (i) acceleration by a cyclic test with fog; (ii) acceleration by cycles wetting and drying, (iii) acceleration by electric current (electrochemical method): an intense electrical current is applied between the reinforcement (anode) and the counter-electrode (cathode). The last method seems to be the one most often adopted to this study because it is the fastest method.

The electrochemical corrosion technique was used to induce accelerated corrosion of the reinforcement bar embedded in the concrete. The steel bar acted as the anode as it was connected to the positive terminal of the external power supply, while a stainless steel plate was placed in the tank acted as the cathode. Reinforcement bar was protruded 40 mm from the bottom of the concrete specimens. The embedded length was set at 50 mm to ensure bond failure. To prevent contact between the concrete and the reinforcement bars while maintaining the required concrete cover on the surface of the concrete specimen, 50 mm lengths of the reinforcement bars were placed inside polyvinyl chloride (PVC) pipes.

The specimens were fully immersed in plastic tanks with an aqueous solution of 3.5% sodium chloride by weight for four days before being subjected to the accelerated corrosion procedure. After that the specimens were placed in the container which was

filled with a 5% NaCl solution. The specimens were connected in parallel to a DC power supply of constant 60 V and the current passing through each specimen was daily recorded. Using Faraday's Law, the corrosion of the bars was monitored (Stanish et al 1999). Two specimens were not subjected to corrosion in order to serve as a control. [5][6][7]



Fig.1 Electrochemical corrosion technique set-up

The designed (theoretical) mass loss of the reinforcement bars due to corrosion was calculated according to Faraday's law:

$$\text{Mass Loss} = \frac{\text{time} \times \text{current} \times 55.847}{2 \times 96487} \quad \text{Eq. (1):}$$

Where, t is the time (s), I is the current (A), 55.847 (g/mol) is the molar mass for iron and 96,487 (coulomb) is the Faraday's constant. The actual corrosion level or percentage mass loss of each specimen was calculated by Eq. (2):

$$\text{Corrosion Level, } C_L = \frac{G_0 - G}{g_0 l} \times 100 \% \quad \text{Eq. (2):}$$

where, G_0 is the initial weight of the reinforcement bar before corrosion, G is the final weight of the steel bar after removal of the corrosion, g_0 is the weight per unit length of the reinforcement bar and l is the bond length. [5]

D. Pull-out test

A loading frame was designed and fabricated to perform the pulled tests, as shown in fig.3. The upper rod of the frame was fixed to the upper jaw of the machine to lift the weight of specimens. Two linear variable differential transformers (LVDTs) were

applied to monitor the free-end slip. The data from the LVDT was collected through the datalogger TC-32 K and the pullout load was collected by a computer. Load was applied at a rate of 4.4 kN per minute, up to failure. Pullout tests were performed for both corroded and uncorroded specimens based on ASTM C 234-91a.[15] The bond tests were performed with a Shimadzu universal testing machine with a capacity of 1000 kN. This apparatus was especially designed and adapted to avoid any changes in bond strength during the pullout test. None of the reinforcement bars reached the yield point during the pullout tests, and the maximum pullout forces were recorded to calculate the ultimate bond strength (τ) according to Eq.(3):

$$\text{Measured bond strength, } \tau = \frac{F}{\pi d_b l_e} \quad \text{Eq. (3)}$$

where, F is the ultimate pullout load and d_b and l_e are the diameter and bond length of the reinforcement bars, respectively.



Fig.2 Pull-out test arrangement

E. Chemical cleaning procedure for removal of corrosion products

Corrosion products on corroded specimens were removed by chemical procedure. Chemical procedures involve immersion of corroded test specimen in a chemical solution which is specially designed to

remove the corrosion products with minimal dissolution of any base metal.



Fig.3 Cleaning and weighing of rebar

According to ASTM-G1-03, table (A 1.1). The solution contained 500ml hydrochloric acid ($\rho = 1.18 \text{ g/m}^3$) and 3.5g hexamethylenetetramine was freshly prepared with distilled water to make 1000ml. After cleaning, the metal specimen should be thoroughly rinsed, first with tap water and finally with distilled water. Then the specimen was dried in an oven and allowed to cool in a desiccator to the balanced room temperature before reweighing to the nearest 0.1mg. [16]

III. Results and Discussions

A. Material properties and mix proportions

Properties of cement, sand and gravel were tested at Irrigation Technological Center in Bago.

1. Cement

Ordinary portland cement (Double Rhinos) was used in this research. Specific gravity test, consistency test, setting time test and compressive strength of cement mortar test were carried out according to ASTM C 188[8], ASTM C 187[9], ASTM C 191[10] and ASTM C 109[11] respectively.

TABLE 1 Properties of Cement

Test No.	Specific gravity	Consistency (%)	Setting Time (min)		Compressive Strength (kg/cm ²)	
			Initial	Final	3 Days	7 Days
1	3.13	29.88	1:55	3:50	374.15	448.18
2	3.15	30.38	1:55	3:55	436.17	488.2
3	3.14	30.38	1:45	3:55	320.13	390.16
Avg.	3.14	30.21	1:51	3:53	376.82	442.18

2. Fine aggregate

In this study, sand from Pyinbongyi in Bago region was chosen as fine aggregate. The specific gravity, absorption percentage, finite modulus, unit weight and salt percent were done and the average values was shown in table 2. All values were allowable limit according to ASTM. And sieve analysis was done according to ASTM C 136[12] and the grading curve was constructed and this curve lies between upper and lower grading curves.

TABLE 2 Physical properties of fine aggregate

Sp.Gr	Absorption (%)	F.M	Unit Weight (gm/cc)	Salt Content
2.59	1.44	2.36	1.46	0.005

3. Coarse Aggregate

River Shingle from North Dagon was used as coarse aggregate and its maximum size was 19 mm. The sieve analysis was done according to ASTM C 117 and the grading curve was constructed. [13] The grading curve of aggregate lies a little above the standard upper curve. The required properties were tested and the average properties of coarse aggregates are described in table 3.

TABLE 3 Properties of Coarse aggregates

Sp.Gr.	2.61
Absorption (%)	0.7
F.M	6
Unit weight (gm/cc)	1.77
Abrasion (%)	33.2
A.M.F (%)	0.72
5 cycle soundness (%)	9.83
Flakiness index (%)	8.87
Elongation index (%)	14.72

4. Mixing water

Mixing water for concrete was used from YTU campus. The following tests were performed to detect the impurities, sulfate and chloride in the mix water because these may affect setting time, drying shrinkage, or durability and ultimate strength. [4]

TABLE 4 Water quality test results

Water Tests	Results	Maximum Concentrations (mg/l)
pH	6	6~8
Total Alkalinity	67 mg/l as CaCO ₃	600
Chloride (as Cl ⁻)	149.17 mg/l	20,000~50,000
Sulphate (as SO ₄ ⁻)	97 mg/l	10,000~40,000
Total Solids	598 mg/l	2,000

5. Concrete mix design

In this research, 35 MPa compressive strength was chosen and some trial tests were done to get target strength of 43.3 MPa based on ACI 211 mix design method. Some trials were done and the optimal design was chosen to get the target strength. The final composition of concrete mixture is shown in table 4 and the concrete samples are shown in figure 2.

TABLE 5 Composition of concrete ingredients and its compressive strength

Test No.	Test 1	Test 2	Test 3	Avg.
w/c	0.42	0.42	0.42	0.42
Cement (kg/m ³)	488.1	488.1	488.1	488.1
Water (kg/m ³)	205	205	205	205
Fine aggregate (kg/m ³)	440.3	440.3	440.3	440.3
Coarse aggregate (kg/m ³)	1175	1175	1175	1175
Slump (mm)	80	89	86	85
7 days comp: (MPa)	40.99	38.37	40.55	39.97
28 days comp: (MPa)	47.93	43.34	46.49	45.92



Fig.4 Concrete mix samples

6. Reinforcing Steel

Deformed steel bars 16 mm in diameter (HRB-400C) and 450 mm long were used for all specimens. Tensile tests were performed on three randomly selected reinforcement bars and tested at MES in accordance with a ASTM- A 615/A. The tested values are shown in table 6. [14]

TABLE 6 Properties of reinforcement bars

Sr No	Nominal diameter of bar (mm)	Yield Strength (MPa)	Ultimate Strength (MPa)	Elongation (%)
1	16	592.3	717	13.2
2	16	603.5	721.8	11.2
3	16	614	738.8	11.7
Avg	16	603.3	725.9	12.03

B. Pull out Test Results

The pull out test was done with Universal Testing Machine and the results are shown in Table 7. Most specimens occur split failure because grade 35 concrete is used in this study.

TABLE 7 Experimental test results of pull-out test

Specimen No.	Max. Force (kN)	Ultimate bond strength (MPa)	Max. Slip (mm)	Failure mode
S-16-1	36.19	14.4	0.36	Split
S-16-2	40.66	16.18	0.27	Split
S-16-3	65.62	26.11	0.31	Split
S-16-4	61.51	24.47	0.41	Split
S-16-5	31.16	12.4	0.28	Split
S-16-6	16.54	6.58	0.45	Split
S-16-7	23.71	9.43	0.20	Split
S-16-8	41.46	16.5	0.03	Split
S-16-9	67.69	26.93	0.13	Split
S-16-10	17.97	7.15	0.22	Split
S-16-11	26.93	10.72	0.33	Split
S-16-12	47.32	18.83	0.25	Split
S-16-13	65.88	26.21	0.12	Split
S-16-14	71.94	28.62	0.58	Split
S-16-15	65.23	25.95	0.50	Split
S-16-16	66.07	26.09	0.45	Split
S-16-17	70.53	28.06	0.74	Split
S-16-18	78.87	31.38	1.99	Pull-out
S-16-19	62.93	25.04	2.09	Pull-out
S-16-20	70.21	27.93	0.56	Split
S-16-21	73.76	29.35	0.9	Pull-out

TABLE 8 Corrosion Level and Mass Loss

Specimen No.	Corrosion Level (%)	Theo; mass loss (g)	Actual mass loss (g)
S-16-1	2.12	1.59	1.41
S-16-2	2.22	1.53	1.48
S-16-3	1.73	1.18	1.17
S-16-4	2.28	1.32	1.52
S-16-5	2.82	1.64	1.91
S-16-6	5.83	2.05	3.94
S-16-7	3.97	2.08	2.64
S-16-8	1.57	3.36	1.09
S-16-9	0	0	0
S-16-10	4.71	0.86	3.13
S-16-11	2.63	0.47	1.75
S-16-12	2.2	0.61	1.48
S-16-13	1.39	1.78	0.94
S-16-14	1.03	1.50	0.69
S-16-15	0.91	1.31	0.62
S-16-16	1.04	1.47	0.7
S-16-17	0.8	0.22	0.55
S-16-18	0.88	0.24	0.6
S-16-19	0	0	0
S-16-20	0.93	0.89	0.63
S-16-21	0.85	0.82	0.57

TABLE 9 Decreased Bond Strength with Different Corrosion Levels

Corrosion Level (%)	Decreased Bond Strength (%)
0.93	-3.72
2.12	47
3.97	65
4.71	73
5.83	75

The decreased bond strength is calculated based on zero percentage corrosion level. When corrosion increased to about 1%, the bond strength increased to about 4% and when corrosion increased to 5.83%, the bond strength decreased to about 75%. It is found that the bond strength decreased gradually when the corrosion level is higher.

C. Influence of corrosion levels on the bond strength

For low levels of corrosion, the bond strength increased due to the increased roughness of the steel bar caused by the confined corrosion products and then decreased for a given corrosion level.

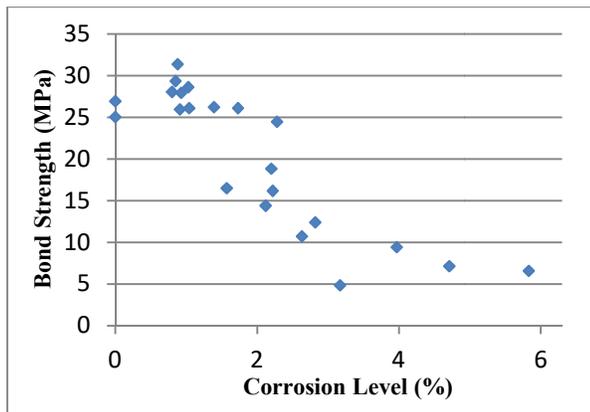


Fig.5 Bond strength versus achieved corrosion level

D. Influence of corrosion levels on slip

The slip of the control specimens was higher than that of the corroded specimens. The slip corresponding to the maximum bond strength decreased with an increasing corrosion level within the range considered.

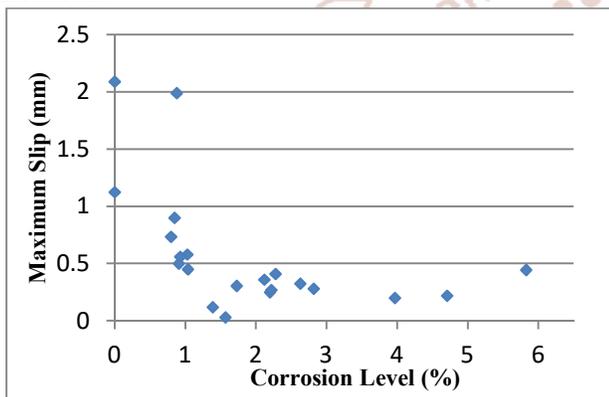


Fig.6 Slip at bond strength versus achieved corrosion level

E. Slip properties with corrosion of the rebar

The values of load-slip show higher trends for control specimens than other specimens with different corrosion levels. The more corroded the specimen is, the lower the trend is except for a very small amount corrosion.

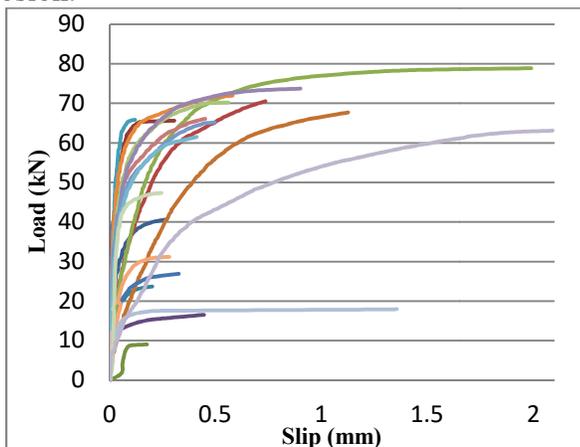


Fig.7 Load – slip curves with different corrosion level

IV. CONCLUSIONS

In this study grade 35 concrete with HRB-400C 16 mm rebar is used to study corrosion effect on bond strength. The electrochemical corrosion technique is applied to obtain the corroded rebar. Most corroded specimens failed by splitting the concrete as grade 35 concrete is more brittle than the low strength concrete. When the corrosion level is increased and the bond strength is decreased and slip is increased. According to test results, when the corrosion is started, the bond strength increased due to the increased roughness of the steel bar caused by the confined corrosion products. However the corrosion level is increased about 5%, the bond strength decreases 75%. The maximum mass losses between actual and theory is about 2g for bonded length 50 mm. Based on the experimental result of the study, it was found that reinforcement corrosion levels have significant effects on bond performance of reinforcing bars in concrete.

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