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EXPERIMENTAL STUDY ON THE EFFECT OF CONCRETE STRENGTH AND CORROSION LEVEL ON BOND BETWEEN STEEL BAR AND CONCRETE

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Abstract. Corrosion of the steel reinforcement bars reduces the area of the steel bar and the bond stress between the steel bars and around concrete that decreases the capacity of concrete structures. In this study, the bond stress between steel bar with a diameter of 12mm and concrete was examined with the effect of different corrosion levels and different concrete grades. A steel bar was inserted in a concrete block with a size of 20×20×20cm. The compressive strength of concrete was 25.6MPa, 35.1MPa, and 44.1MPa. These specimens were soaked into solution *NaCl* 3.5% to accelerate the corrosion process with different corrosion levels in the length of 60mm. The pull-out test was conducted. Results showed that the bond strength of the corroded steel bar was higher than that predicted from CEB-FIP. Slip displacement and the range of slip displacement at the bond strength were reduced when the concrete compressive strength was increased. The rate of bond stress degradation occurred faster with the increment of the corrosion level when the concrete compressive strength was increased.

Keywords: bond-slip relationship, concrete strength, corrosion level, corroded RC structure, pull-out.

1. INTRODUCTION

Reinforced concrete (RC) structures have been widely used in civil engineering because of their flexibility, durability, and economy [1]. After several years of service, RC structures are generally degraded. Many reasons cause the deterioration in RC structures. One of the reasons is steel corrosion, especially in concrete structures in the marine environment. In Japan, a study showed that 90% of the structures exposed to the marine environment with the protective concrete layer were not large enough. The structures that were only ten years old have been damaged in a large proportion. In the United States, based on the monitoring of 586,000 expressway bridges, 15% of the structures has deteriorated, mainly due to the strong development of corrosion. In Vietnam, the low quality of concrete in the corrosion environment causes steel corrosion in concrete structures that reduce its capacity. Many RC structures with corroded steel bars are shown in Fig. 1. 45% of steel bars in RC structures are seriously corroded. Many stirrups are destroyed and broken, the protective concrete layer is spalled and disappeared [2].

Generally, steel bars in RC structures are protected by concrete cover thickness. However, the deterioration of concrete as carbonation, shrinkage, cracks and so on makes water (H_2O) and oxygen (O_2) or ion chloride (Cl-) penetrate through a protective concrete layer and causing the corrosion of steel bars. In the non-corrosive environment, RC structures could be operated sustainably for their service time. However, in hot and humid climate conditions containing high ionic content, the RC structures show different corrosion levels. Therefore, corroded concrete structures do not save the life of the project [3,4]. In an aggressive environment as a marine environment, the RC structures with corroded steel bars only operate within 10 to 30 years. Corrosion of the steel reinforcement bars reduces the area of the steel bar and the bond stress between the steel bars and around concrete. It affects the anchorage of straight reinforcing bars, cracking control, and section stiffness [5]. That then reduces the capacity of concrete structures [6-8]. Collected data show that the effect and cost to repair for deterioration caused by corrosion was quite large [9].

Corrosion protection of concrete layer in RC structures depends on the level of environmental cavitation and the quality of materials such as concrete strength, types of cement, type reinforcement, design, construction quality, maintenance, and so on. The pull-out test of the steel bar inserted in a concrete block was carried out. The concrete block size was 20×20×20cm. Design compressive strength was 25MPa, 35MPa, and 45MPa. A steel bar

(a) Cua Cam Port after 30 years

(b) Trade Port after 15 years

Figure 1. Current status of reinforcement corrosion on some real projects [2].

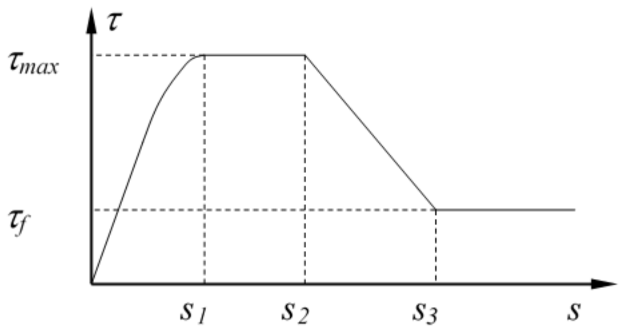

Figure 2. Bond stress and slip relationship by CEB-FIP [10].

with a diameter of 12 mm inserted in the concrete block was corroded in the laboratory in a short time using the electrochemical corrosion acceleration method. In this study, the bond stress between steel bar and concrete was examined with the effect of different corrosion levels and different concrete grades.

2. GENERAL BOND BEHAVIOUR

The relationship between bond stress and slip displacement of a steel bar around concrete according to the CEB-FIP model [10] is shown in (Fig. 2). The maximum bond stress, $\cdot_{max}$ is calculated as follows Eq. (1):

$$\tau_{max} = k\sqrt{f_c'} \tag{1}$$

Where k is a factor taken by 2.5, f'_c is the compressive strength of concrete (MPa). Bamonte và Gambarova [11] proposed the maximum bond stress of $0.45f'_c$. Using Eq (1), k value suggested by Bamonte và Gambarova to predict the maximum bond stress is 3.74. It means that the maximum bond stress has been predicted with the different value from other researchers. The maximum bond stress between steel bar and concrete by CEB-FIP [10] is accepted as constant within slip from s_1 to s_2. The value of s_1 and s_2 for pull-out failure mode is 1mm and 2mm, respectively. The bond stress from an experiment is calculated by Eq. (2):

$$\tau = \frac{P}{\pi d l} \tag{2}$$

Where P is the load from the experiment, d is the nominal diameter of the steel bar, and l is the anchorage length of steel bars.

3. MATERIALS AND TEST PROGRAM

3.1. Steel bars

Normal reinforcement bar using in this study is a deformed bar with a diameter of 12mm. The length of bars of 600 mm was prepared (Fig. 3). A segment was about 6cm accelerated corrosion was embedded in the concrete block. Other parts of the embedded bar in the concrete block were protected by plastic tubes. Concrete blocks with embedded bar were soaked into the corrosion environment *NaCl* soluble. The end of the steel bar was set out of concrete block about 5cm to measure the displacement of steel bar in pull-out test. This end of bar was also soaked under the corrosion environment. Therefore, this end of bar was protected

Figure 3. Preparing steel bars.

Figure 4. Coarse and fine aggregates.

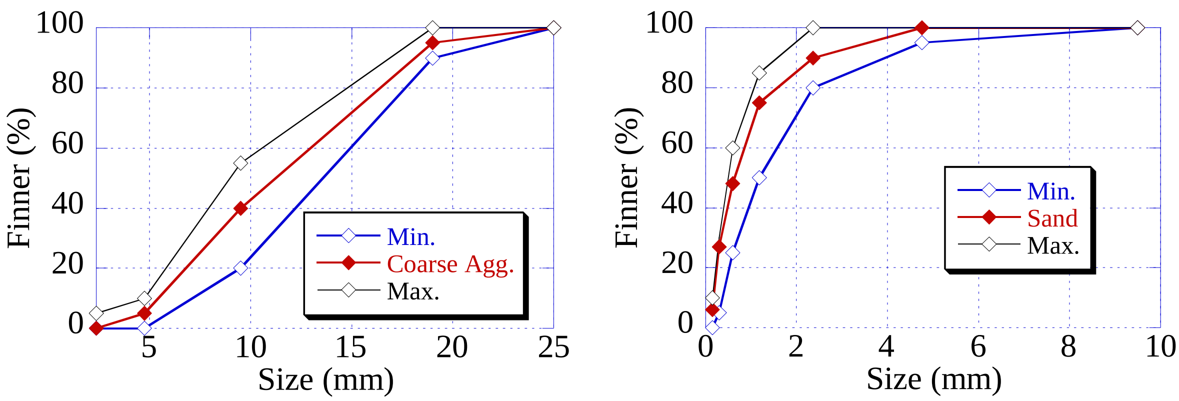

Figure 5. Size distribution curves of coarse and fine aggregates.

carefully to avoid corrosion [Fig. 3(b)]. Its yield and tensile strengths were 400MPa and 570MPa, respectively. Its elongation is about 14%.

3.2. Concrete

Concrete includes aggregate, sand, cement, and water. Coarse and fine aggregates (Fig. 4) are in the local market. It was evaluated by sieving analysis based on ASTM C136-01 [12]. The maximum size of the coarse and fine aggregates was 25mm and 4.75mm, respectively. Size distribution curves of coarse and fine aggregates satisfied ASTM C33M-18 [13] (Fig. 5). Cement is PCB40 in the market with a density was 3.11 ton/m^3. Concrete mixtures were designed based on ACI [14]. Its desired compressive strength at 28 days was 25MPa, 35MPa,

Table 1. Concrete mix proportions.

Design strength (MPa)	Cement (kg)	Sand (kg)	Aggregate (kg)	Water (l)	Compressive strength at 28 days (MPa)
25	350	660	1200	170	24.6
35	465	650	1150	186	35.1
45	550	645	1100	210	44.1

Figure 6. Determining compressive strength of concrete at 28 days.

and 45MPa. The mix proportions were tabulated in Table 1. Each compressive strength at 28 days predicted by an average of three-cylinder specimens (Fig. 6) was also shown in Table 1.

3.3. Specimens and corrosion process

Prismatic specimens with the size of 200×200×200mm were cast according to ACI 440.3R-04 [15]. Formwork for specimens was made from wooden plates. The steel bar was located in the center of the formwork. It was fixed carefully to ensure perpendicularly to the surface of the concrete block. Concrete was cast on the formwork (Fig. 7). The top surface of specimens was made as flat as possible because this top surface will be placed on the bottom plate of the jig on testing. After casting, concrete blocks were cured by covering wet clothes for six days. Water was provided three times a day. After one week, the formwork was removed. The specimens were then put in laboratory conditions.

Figure 7. Casting specimens.

Figure 8. DC power for corrosion test.

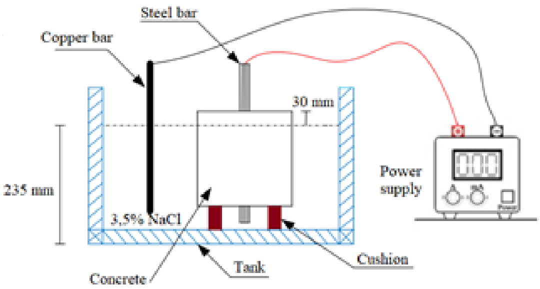

Figure 9. Experiment of corrosion acceleration.

At 28 days, all specimens were soaked in solution *NalCl* 3.5% (35*g*/*l*) within seven days to be fully saturated by chloride ions before connecting to the transformer (Fig. 8). The setting of a specimen to accelerate the corrosion process is illustrated in Fig. 9. The samples are connected simultaneously with the terminals of the transformer according to a parallel circuit diagram. The negative pole of the transformer is connected to a copper rod placed in the solution *NalCl* 3.5%. The top of the surface solution *NalCl* 3.5% was far from the top of concrete blocks around 3cm [Fig. 9(a)]. Saltwater has a salinity equivalent to seawater in Vietnam and around the world, and in the experiment acts as a liquid solution. Transformer allows to convert alternating current to direct current (Fig. 10). Amperage can be fixed in advance. During the soaking, the amperage was adjusted and recorded every 12 hours. The steel bars were controlled to corrode up to 3%, 6%, and 10% to investigate bond behaviour between a corroded steel bar and concrete. Electrolysis time is predicted simply according to Faraday's law Eq. (3):

$$M_{th} = \frac{W \times T \times I_{app}}{F} \tag{3}$$

Where M_{th} is a theoretical mass of rust per unit surface area of the bar (*g*), *W* is the equivalent weight of steel which is taken as the ratio of the atomic weight of iron to the valency of iron 27.925 (*g*), I_{aap} is applied current density (*Amp*), *T* is the duration of induced corrosion (*second*), *F* is Faraday's constant 96487 (*Amp*/*second*). Based on equation Eq. (3), the time to soak specimens to corrode steel bars of 5%, 15%, and 25% was soaked in solution *NalCl* 3.5% within 51hours, 154 hours, and 255 hours, respectively. When the soaking was finished, specimens were taken out of solution *NalCl* 3.5% for pulling out tests.

3.4. Experimental method

A specimen was set on a jig [Fig. 10(a)]. There is a hole in the bottom plate of the jig. Therefore, a steel bar was put through to connect to the loading machine. The top plate of the jig is connected to a bolt with thread to create a high bond to the jig and the loading machine. To measure slip between the steel bar and the concrete block in each specimen, two transducers type of CDP25 were set up at two locations on the steel bar close to the top and bottom surfaces of the concrete block. One transducer type of CDP25 was measured displacement of concrete block at the bottom surface. A K-gauge and pi-gauge were pasted on concrete at the middle of a side of the concrete block to detect crack and crack width. All measurement devices were connected to Data Logger TDS630 (Fig. 11). The loading machine was controlled with a load speed of 0.1kN/s.

3. RESULTS AND DISCUSSION

Tested compressive strengths of concrete were approximate the designed values. The relationships between bond stress and slip of steel bar were expressed in Fig. 12, Fig. 13, and Fig. 14. The bond strength reduced when the corrosion level increased in each compressive strength. The corrosion level was also evaluated after testing by losing weight. The corrosion level was not the same as the designed values. The higher compressive strength it was, the lower the corrosion level it was. The same design corrosion level of 3%, compressive strength

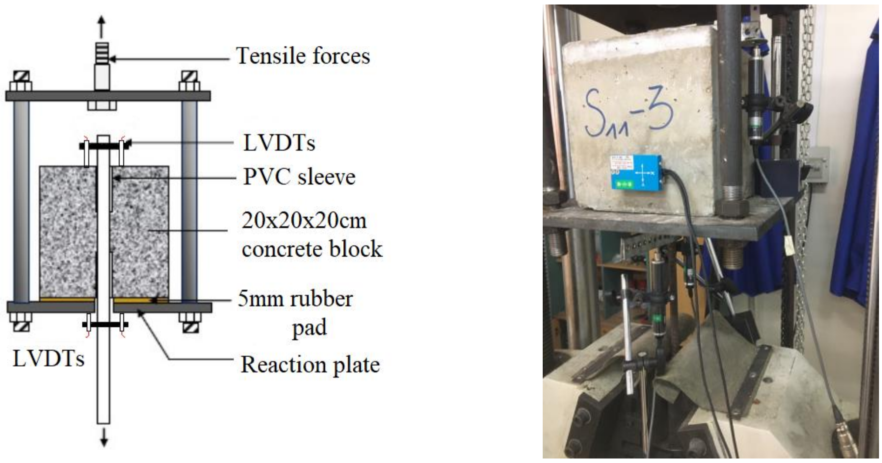

Figure 10. Layout of test samples on tractors and support devices.

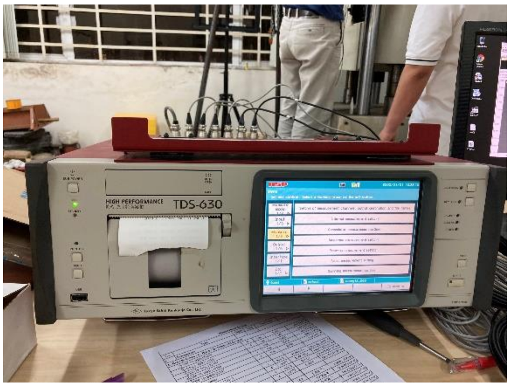

Figure 11. Data Logger TDS630.

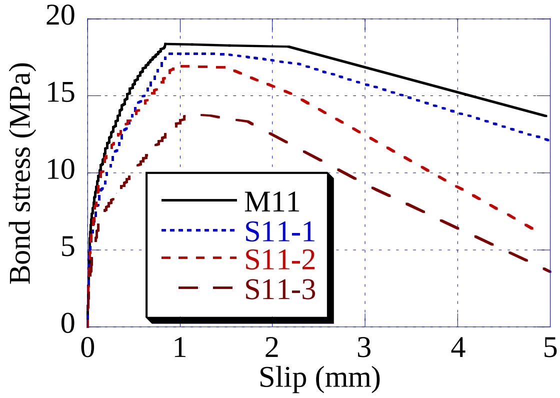

Figure 12. Bond stress and sliping curve in concrete of 24.6 MPa.

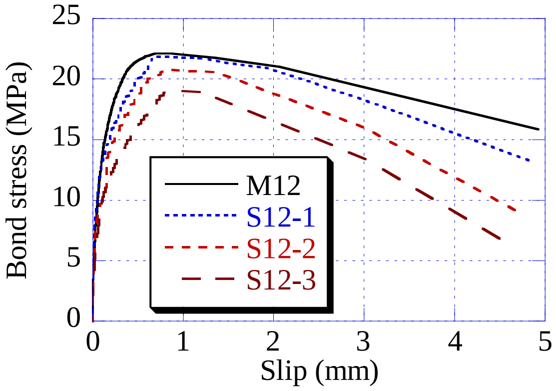

Figure 13. Bond stress and sliping curve in concrete of 35.1 MPa.

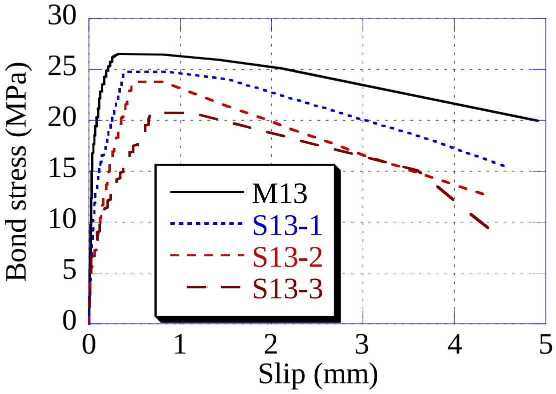

Figure 14. Bond stress and sliping curve in concrete of 44.1 MPa.

of concrete of 24.6MPa, 35.1MPa, and 44.1MPa, the corrosion level in the experiment showed 1.76%, 0.55%, and 1.11%, respectively. Table 2 shows all testing results of specimens.

Fig. 15 showed that compressive strength was affected bond stress between steel bar and around concrete. The bond stress increased when compressive strength increased. Bond strength from this experiment was about 50% higher than that was predicted from CEB-FIP MC2020. Based on the compressive strength of concrete of 24.6MPa, 35.1MPa, and

44.1MPa, the maximum bond strength based on Eq. (1) was 12.4MPa, 14.8MPa, and 16.6MPa, respectively. However, the maximum bond strength from the experiment was calculated as 18.4 MPa, 22.1MPa, and 26.5MPa, respectively. Based on the experimental results, the *k* value to predict the maximum bond stress in Eq. (1) was approximately 3.8. This value was closer to the *k* value proposed by Bamonte và Gambarova [11].

Table 2. Test results.

Specimens	***f'c*** **(MPa)**	**Corrosion level (%)**	***P*** **(kN)**	**τ_{max} (MPa)**	**s_1 (mm)**	**s_2 (mm)**	**Failure type**
M_{11}	24.6	0	41.55	18.37	0.838	2.168	Pull out
S_{11}-1		1.76	40.15	17.75	0.863	1.512	
S_{11}-2		4.14	38.25	16.91	0.930	1.502	
S_{11}-3		12.93	31.25	13.81	1.070	1.728	
M_{12}	35.1	0	50.05	22.13	0.688	1.353	
S_{12}-1		0.51	49.35	21.82	0.671	1.256	
S_{12}-2		3.36	47.05	20.08	0.814	1.354	
S_{13}-3		5.05	43.10	19.05	0.872	1.202	
M_{13}	44.1	0	60.15	26.51	0.326	0.805	
S_{13}-1		1.11	58.95	24.82	0.406	0.849	
S_{13}-2		2.05	53.80	23.79	0.482	0.821	
S_{13}-3		4.79	46.95	20.76	0.702	1.125	

Note: f'_c: compressive strength; *P*: peak load; τ_{max}: bond strength; s_1 and s_2: slip at bond strength

The values s_1 and s_2 in the experimental results were not the same as the slip values in the bond-slip model proposed by CEB-FIP [10]. The experimental results showed that s_1 and s_2 were lower than those suggested CEB-FIP [10]. The compressive strength affected the values s_1 and s_2 (Fig. 16). The range between s_1 and s_2 was also reduced when compressive strength was increased. At the failure stage, concrete around the steel bar on the top of the concrete block was spalled. No crack propagated to the edges of concrete blocks in all specimens. Therefore, specimens were considered as pull-out failure modes (Fig. 17).

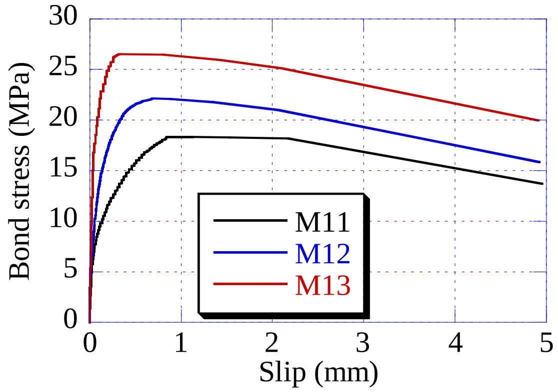

Figure 15. Effect of compress strength on bond stress without corrosion.

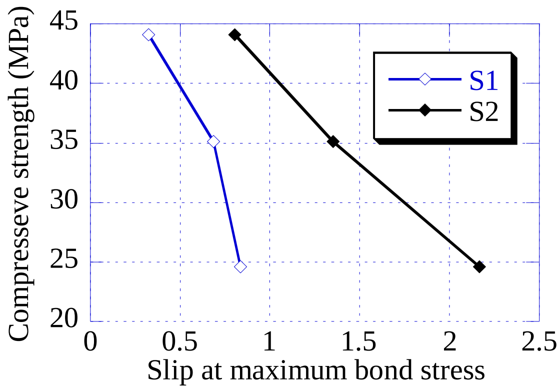

Figure 16. Effect of compressive strength on value of s_1 and s_2.

Figure 17. Failure of specimens in pull-out test.

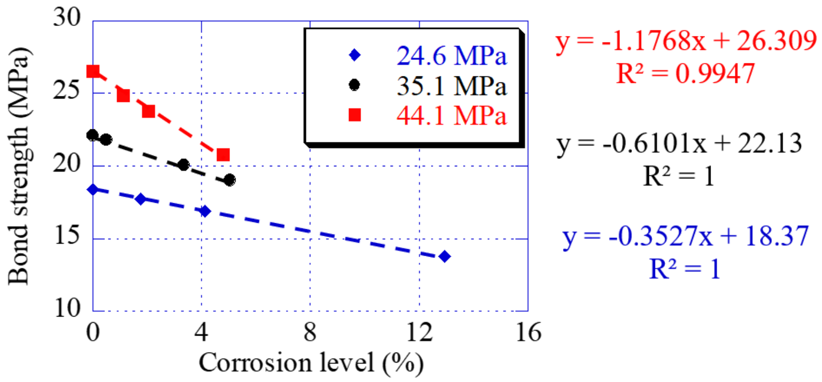

Figure 18. Effect of corrosion level on bond stress.

Based on the experiment results, the change of the bond strength was different with the different concrete compressive strength (Fig. 18). The relationships between bond strength and corrosion levels were linear, the coefficient of determination close to 1. The results showed that the rate of bond stress degradation occurred faster with the increment of the corrosion level when the concrete compressive strength was increased. In the corrosion environment, concrete compressive strength is required to be not smaller than 31MPa [14]. In the case of concrete compressive strength of 35.1MPa and 44.1 MPa, the bond strength of the steel bar and concrete would be reduced by 50% when the corrosion level was around 18% and 11%, respectively. The reduction of the bond stress decreases the capacity of concrete structures. Therefore, in concrete structures with higher compressive strength, the capacity of the corroded RC structure degraded faster when the corrosion level increased. In another word, in higher concrete strength, a lower corrosion level of steel bar it was the higher capacity of corroded RC structures decreased.

4. CONCLUSIONS

In this research, bond stress between a steel bar and concrete was investigated from pull-out tests with the effect of concrete grades and corrosion levels. Steel bars were electrochemical corrosion acceleration method. The following conclusions can be taken from the findings of this paper:

- The *k* value to predict the maximum bond strength between corroded steel bar and around concrete in the pull-out test was approximately 3.8. The bond strength from this experiment was about 50% higher than that was predicted from CEB-FIP [10].
- Slip displacement and the range of slip displacement at the maximum bond stress were reduced when the concrete compressive strength was increased.
- The rate of bond stress degradation occurred faster with the increment of the corrosion level when the concrete compressive strength was increased.

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