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Chloride induced corrosion and bond strength in relation to concrete cover and bar diameter

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ABSTRACT: This study investigates the effect of different concrete cover thickness and bar diameter on chloride induced corrosion rate and the effect of different corrosion levels (i.e. 1%, 2%, 4% and 6% steel mass loss) on the bond strength. The parameters investigated includes bar diameter (13mm and 18mm), and different cover to bar diameter ratio (*C/D*) = 1, 2 and 3. It was found that (*C/D*) ratio doesn't have a significant effect on the bond strength at different corrosion levels. Also, it was found that (*C/D*) ratio has significant impact on the corrosion rate and the protection provided. It is concluded that practice codes should relate the cover thickness not only to the exposure environment but also to the used bar diameter by specifying a minimum (*C/D*) ratio to control the corrosion rate as it will affect the intended structure's service life.

1 INTRODUCTION

The corrosion of steel reinforcement in concrete structures is an international problem that leads to extensive damage to various types of structures. It is considered to be the number one cause of RC structure deterioration and cause of failure. Researchers conducted in that field could be subdivided under 3 main categories; the first group dealt with the effect of corrosion on RC structures (Lee et al. 2002, Carins et al 2007, and Ahmed et al. 2007), the second group dealt on evaluating the corrosion process and how to mitigate reinforcement corrosion (Okba et al. 2003, and Ha et al. 2007), while the third group of studies focused on how to repair corrosion damaged structural elements (El-Dieb et al. 2002 and 2012).

Corrosion of steel reinforcement in concrete is an electrochemical process, where anode and cathode cells are formed on the reinforcement steel which is electrically connected through the body of the metal in the presence of an aqueous medium. The corrosion process needs moisture and oxygen to continue. The lack of either will result in reducing the corrosion process. Concrete cover is considered one of the main defense lines in protecting reinforcement against corrosion as it will affect the water, oxygen, carbon dioxide and chlorides accessibility. Minimum values for concrete cover are specified in codes of practice for different exposure conditions (ACI 305M-2005). In previous studies, Al-Sulaimani et al. (1990) and El-Dieb and Reda Taha (2000) examined the effect of concrete quality and cover thickness on reinforcement corrosion, it was concluded that the concrete quality and cover thickness are important in protecting reinforcement against corrosion.

2 RESEARCH SIGNIFICANCE

Codes of practice specify minimum concrete cover for different exposure conditions especially when structures are exposed to corrosive environment in addition to the minimum requirements to produce good quality concrete. Preceded by the concrete quality, the concrete cover is considered the second line of defense for protecting reinforcement against corrosion. It will reduce the corrosion rate and increase the service life of structures. The minimum concrete cover specified by codes of practice is not related to the reinforcing bar diameter used. Also, under the same exposure conditions, concrete quality and concrete cover the corrosion rate of different bar diameters is expected to differ.

The aim of this study is to investigate the effect of concrete cover to bar diameter ratio and bar diameter on chloride induced corrosion rate. The effect of different corrosion levels on the bond strength is also investigated. The study outcomes are expected to help improve design and construction guidelines in order to extend the expected service life time of structures in aggressive environment.

The parameters investigated includes bar diameter (13mm and 18mm), different cover to bar diameter ratio (*C/D*) = 1, 2 and 3 and different corrosion levels (1%, 2%, 4% and 6% steel mass loss).

3 EXPERIMENTAL WORK

3.1 Specimens, test setup and text matrix

In this study concrete prism specimens of cross sectional dimensions of 130x130mm and length of 260mm were cast. A reinforcing steel bar with different diameters (*D*) and length 360mm is embedded in the specimen at different cover to bar diameter (*C/D*) ratio, as shown in Figure 1. The specimens were moist cured for 28 days before being subjected to corrosion.

Figure 2 shows the accelerated corrosion setup used in the study. The setup consists of a direct current (DC) power supply with a constant potential difference of 12V, a 100 Ohm resistance, a voltmeter, a steel cathode and a plastic dam filled with 5% NaCl solution. A fixed length of 160 mm of the reinforcing bar was exposed to corrosion, and the rest of the bar was epoxy coated to protect it from corrosion, which performed well as it prevented the unexposed parts of the bar from corrosion. The electric current in the circuit (i.e. corrosion current I_{corr}) was recorded at 24 hours intervals. The amount of corrosion was related to the electrical energy consumed using Faraday's relation, Equation (1):

$$MassLoss = \sum \frac{time\ (s) \times corroion \quad current\ (A) \times E}{2 \times 96487} \tag{1}$$

Where; E is the atomic weight of $Fe = 55.847$. After reaching the required corrosion level (i.e. percentage of mass loss) the accelerated corrosion process was stopped and the concrete prism was tested in pull-out test to determine the bond strength.

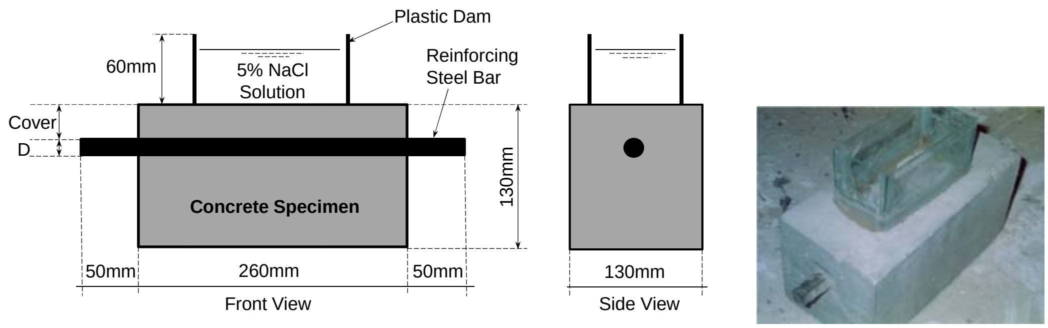

Figure 1. Specimens' details.

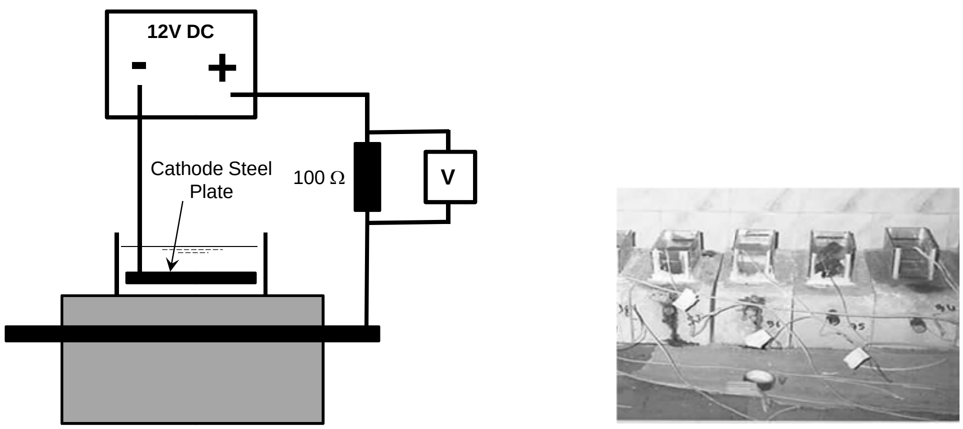

Figure 2. Accelerated corrosion test setup.

In order to evaluate the corrosion level reached by the accelerated corrosion set up, preliminary tests were conducted on control specimens with different reinforcing bar diameters (i.e. 13mm and 18mm) and *C/D* ratios (1, 2 and 3) in order to study the relation between the calculated corrosion level (i.e. mass loss %) and the actual measured mass loss. This investigation resulted in determining the time needed to reach the required corrosion level. Figure 3 shows schematic diagram of the experimental test matrix and parameters included in the investigation.

3.2 Materials and concrete mixture

Ordinary Portland cement (OPC) which conforms to (ASTM Type I) and (BS EN 197 CEM I) was used in this study. Natural crushed stone consisting of two sizes, S1 (5 to 20 mm) and S2 (10 to 28 mm) were used as coarse aggregate. Table 1 shows different properties of the used crushed stone. Natural siliceous sand with specific gravity 2.65 and bulk density of 1680 kg/m3 and fineness modulus of 2.54 was used as fine aggregate.

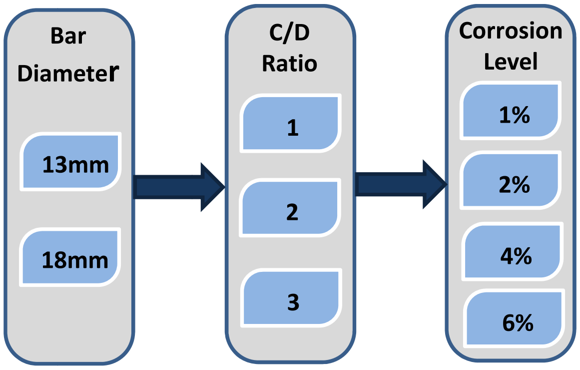

Figure 3. Experimental test matrix and parameters.

High tensile deformed reinforcing steel bars with nominal diameters 13mm and 18mm were used in the study. The average yield and ultimate strength of the steel bars was 435 and 690 MPa respectively.

The concrete mixture was designed to have a slump range of 40mm to 60mm. The mixture consisted of 350 kg/m^3 OPC, 475 kg/m^3 of crushed stone size S1, 710 kg/m^3 of crushed stone size S2, 585 kg/m^3 of natural siliceous sand and 210 lit/m^3 of water (i.e. w/c ratio of 0.6). The average 28 days cube compressive strength of the mix was 34 MPa ± 1.5 MPa.

4 RESULTS AND DISCUSSIONS

4.1 Time and corrosion level

The preliminary investigation conducted to evaluate the corrosion level reached by the accelerated corrosion, showed very good agreement between the calculated corrosion mass loss and the measured mass loss, according to ASTM G1-90; procedure C 3.5, by using diluted solution of hydrochloric acid (HCL) and hexamethyline tetramine. Figure 4 shows the measurement of corrosion level of corroded reinforcement. The deviation between the calculated and the measured mass loss was less than ±15%. The time needed to reach required corrosion level is shown in Table 3.

Table 1 physical and chemical properties of the used crushed stone

Property	S1 (5-20mm)	S2 (10-28mm)
Bulk density (t/m^3)	1.640	1.590
Specific gravity	2.63	2.56
Los Angles Hardness	26.9	27.4
Absorption %	1.1	1.3
Fine Materials (weight %)	0.9	0.7
Free Cl^- ion %*	0.021	0.030
Total SO_3 ion %*	0.2	0.17

* Mass % of dry aggregate mass

Table 2. Corrosion time to reach required corrosion level for different bar diameter and C/D ratio

Corrosion level	Corrosion Time (hrs)					
	Bar diameter 13mm			Bar diameter 18mm		
	C/D = 1	2	3	C/D = 1	2	3
1%	50	70	100	115	165	220
2%	105	140	185	215	300	345
4%	230	290	360	430	540	585
6%	360	410	520	645	760	825

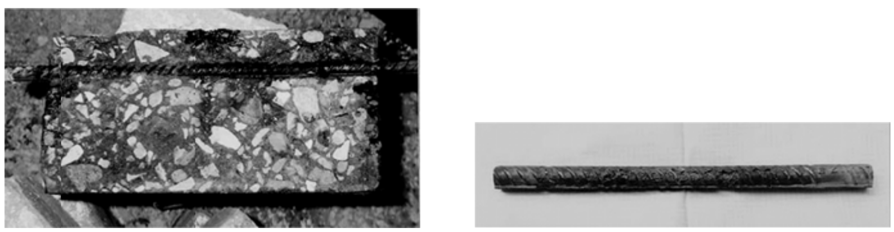

Figure 4. Measurement of corrosion level.

4.2 *Effect of corrosion level on bond strength*

Figure 5 shows the effect of corrosion level on the bond strength, measured by pull-out test, of 18mm reinforcing bar with different *C/D* ratios. It could be seen that the bond strength increased as the corrosion level increases and up to 2% corrosion level after that the bond strength started to decrease. At 2% corrosion level, the increase in bond strength ranged from 13% to 24% for different *C/D* ratios. The reduction ranged from 6% to 17% for corrosion level 4% and from 49% to 58% for corrosion level 6% for different *C/D* ratios. Similar results were obtained for 13mm reinforcing bar. Fang et al. (2004 and 2006), and Wang and Liu (2004 and 2006) reported similar results and observations and found that bond strength started to decrease beyond corrosion levels of 2-4%.

The increase in bond strength at 2% corrosion level could be attributed to the fact that the friction between the reinforcing steel bar and the concrete increases due to the formation of a rough thin layer of corrosion products on the reinforcing steel bar surface. Cairns et al. (2007) investigated the effect of corrosion on the friction characteristics of the steel/concrete interface and concluded that low corrosion levels which did not cause surface cracks did not impair the friction characteristics of steel bar/concrete interface. Corrosion levels beyond 2% will result in significant reduction in bond strength due to the formation of cracks in the interface between the steel bar and concrete due to the increase in the volume of corrosion products (Lee et al. (2002) and Ahmed et al. (2007)). Figure 6 shows the correlation between corrosion level and normalized bond strength with respect to original bond strength for different *C/D* ratios for reinforcing bar 18mm. Comparable behavior and observations were noticed for steel reinforcement with diameter 13mm.

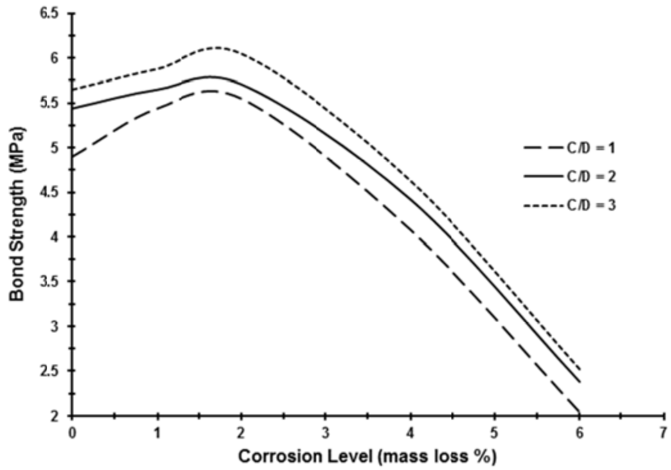

Figure 5. Effect of corrosion level on bond strength for bar diameter 18mm.

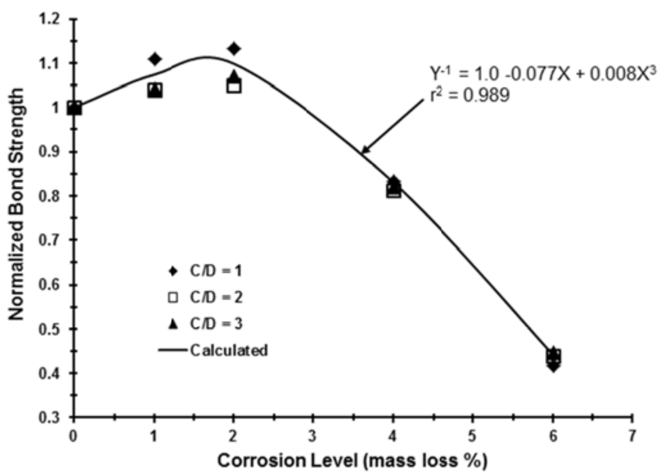

Figure 6. Correlation between corrosion level and normalized bond strength for bar diameter 18mm.

4.3 Effect of bar diameter and C/D ratio on corrosion rate

As the *C/D* ratio increases the time needed to reach a certain corrosion level increases. Also, the reinforcing bar diameter affects the time needed to reach required corrosion level. As seen in Figures 7 for bar diameters 13mm and 18mm respectively. The corrosion rate (i.e. slope of the curve) decreases as *C/D* increases. Also, corrosion rate is affect by the reinforcing bar diameter; the larger the diameter the lower the corrosion rate which means it needs more time to reach the same corrosion level. As seen in Figure 8 which shows the effect of bar diameter on corrosion time of different bar diameters and the same concrete cover thickness. This could be attributed to the fact that the larger the diameter the more charge required to corrode to a certain level.

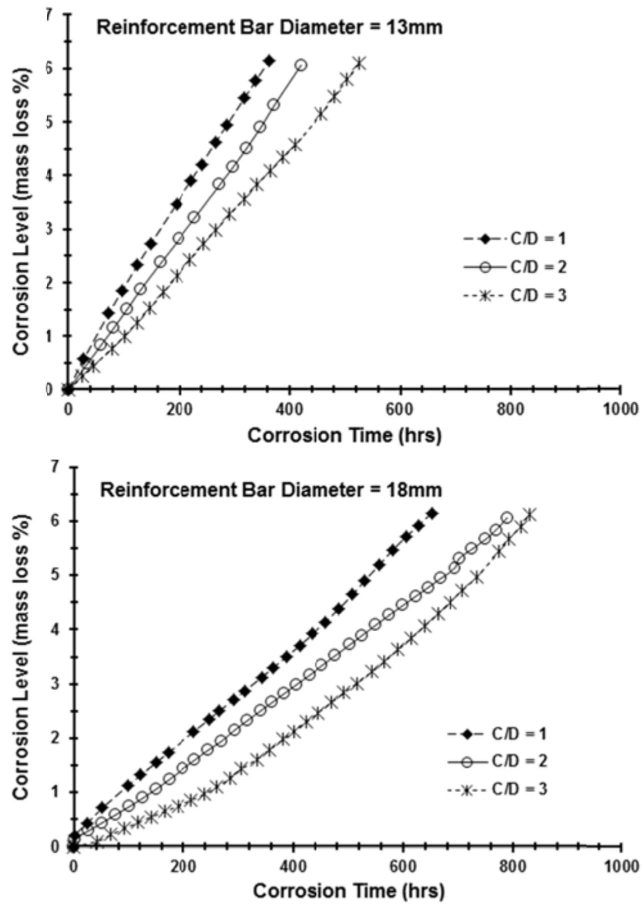

Figure 7. Corrosion level versus corrosion time.

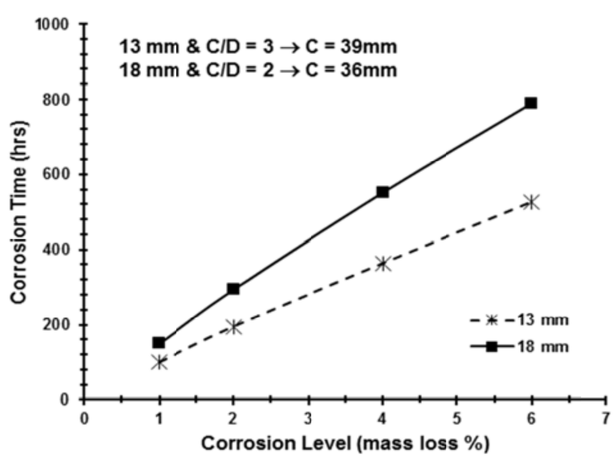

Figure 8. Corrosion time for different bar diameter and the same concrete cover.

5 CONCLUSIONS

The main findings of this study could be summarized in the following:

- The concrete cover plays a very important role in delaying the initiation of the corrosion process.
- Corrosion rate is mainly affected by reinforcing bar diameter and *C/D* ratio which should be used as guideline in codes of practice rather than specifying a minimum concrete cover thickness regardless the bar diameter.
- The diameter of the reinforcing bars is proportionally to the electric charge needed for its corrosion to certain level, i.e. the larger the diameter the more charge required to corrode to a certain level and therefore requires more time.

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