The influence of main bar corrosion on bond strength in self-compacting concrete

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Abstract. The experimental study was conducted to determine the influence of main bar corrosion on bond strength in self-compacting concrete (SCC). A total 16 tension pullout tests specimens reinforced with 10 mm and 14 mm diameter bar were used for the bond strength test. The properties of SCC were determined from the slump flow, Ti50cm, V-funnel and L box test. Reinforcing bars in the concrete were submitted to impressed current to accelerate the corrosion of the bar. It was found that the relationship between bond strength and concrete strength in un-corroded specimens differed from that of corroded specimens set in high-strength concrete because of brittleness in the corroded specimens, which caused a sudden loss of bond strength. The results revealed that specimens of un-corroded and corroded showed a higher percentage of bond strength degradation during the pullout tests.

1. Introduction
Corrosion of steel reinforcement continues to pose threats to the performance and integrity of reinforced concrete structures. Steel bar corrosion affects the reinforcement itself, the surrounding concrete and the composite action between the steel and concrete. The most obvious effect is the reduction in cross sectional area of the affected steel bars [1]. The corrosion of embedded reinforcement is one of the major problems that contribute to the deterioration of structural concrete. The direct effects of the reinforced corrosion are a loss of bar cross section; an increase in bar diameter resulting from the volumetric expansion of the corrosion products; a change in the characteristics of the bar/concrete interface upon the formation of corrosion product; and reduction of the concrete section [2]. The loss of bar section may reduce the ductility of the steel reinforcing bar. With insignificant ductility, a structure might fail and collapse in a brittle fashion without warning.

Self compacting concrete is a latest innovation in concrete technology is being regarded as one of the most promising developments in the construction industry due to numerous advantages of it over conventional concrete [3]. In construction industry, SCC is easier to handle than the normal concrete due its ability to consolidate or self-levelled without any internal or external compaction.

Many experimental works have been conducted previously to study the effects of steel bar corrosion in normal concrete [4, 5, 6] while less available data in self compacting concrete. In normal concrete, the general trend of changes in the bond strength after corrosion has been initiated is presented in figure 1 [7], although there are exceptions in certain circumstances that will be described later. Initially, the bond strength is increased by a small amount of corrosion but starts to decrease with a further increase in the corrosion level.
2. Experimental program

2.1 Specimen
A total of 16 specimens were tested in the study. The specimens were subdivided into four groups that reinforced with 10 mm and 14 mm diameter of the bar with two different concrete cover thicknesses (figure 2). Each sample was then subjected to corrosion using an accelerated corrosion method. The crack width ($W_{cr}$) of the specimens was visually observed and measured with “Crack Detection Pocket Microscope”. After the corrosion conditioning, tension pullout test was conducted to determine its bond strength. The length of embedment was limited to $12\varnothing_b$. Transverse reinforcement was provided to study the influence of confinement on the bond strength.

![Figure 2. Tension pull out test specimen.](image-url)
2.2 Materials properties

Table 1 shows materials the mixture proportions of concrete. Table 2 shows workability, compressive and tensile results. After pouring the concrete specimens were kept outside in normal temperature for 28 days. Before mixing the concrete and casting the reinforcement bars were carefully cleaned then mass of the reinforcement bar in each specimen were recorded.

**Table 1. Mix proportions for self-compacting concrete.**

| Material          | Water (kg/m³) | Cement (kg/m³) | Fly ash (kg/m³) | Fine aggregate (kg/m³) | Coarse aggregate (kg/m³) | Admixtures-20% (SP 800) (ml) | Water-cement ratio |
|-------------------|---------------|----------------|-----------------|------------------------|------------------------|----------------------------|-------------------|
| Quantity          | 180           | 420            | 180             | 853                    | 698                    | 8400                       | 0.43              |

**Table 2. Workability, compressive and tensile results.**

| Mix            | Slump flow (mm) | T₅₀cmᵃ (sec) | V-funnel Tᵇ (sec) | L-box bloking ratio (H₁/H₂)ᵇ | 7 day (MPa) | 28 day (MPa) | Tensile (MPa) |
|----------------|-----------------|--------------|-------------------|-------------------------------|-------------|--------------|--------------|
| 1              | 710             | 3            | 8                 | 0.85                          | -           | -            | -            |
| Cubic          | -               | -            | -                 | -                             | -           | -            | -            |
| Cylinder       | -               | -            | -                 | -                             | 23          | 36           | 2.67         |

T₅₀cmᵃ: Time taken for concrete to reach the 500 mm spread circle.
Tᵇ: V-funnel flow after keeping the concrete in funnel.
H₁/H₂: Heights of the concrete at both ends of horizontal section of L-box after allowing the concrete to flow.

2.3 Accelerated corrosion method

Acceleration corrosion was carried out by impressing an electric current using “ATTEN APS3005” power supply as in figure 3. Where the reinforcement bars were served as an anode and stainless steel plate at the concrete surface served as a cathodes. A total of 360 mA current, which corresponds to approximate current density (i_corr) of 0.09 mA/cm² was impressed to the main bar. The wet sponges were placed between the stainless steel plates and the concrete surface to provide an adequate current contact during corrosion conditioning process.

![Figure 3](image-url)

(a) (b)

**Figure 3.** Connection setup for the accelerated corrosion process.

2.4 Calculation corrosion level and mass loss

The gravimetric approach is used to determine the percentage of mass loss on each corroded bar using equation (1) based on the weight of the steel bar before and after corrosion conditioning [8].
where $G_0$ is the initial weight of the steel bar before corrosion (gram), $G_f$ is the final weight of the steel bar after removal of the corrosion products (gram), $g_0$ is the weight per unit length of the steel bar (gram/mm) and $l$ is the corroded length (mm).

2.5 Tension pull-out test

Pull-out tests were conducted for both corroded and un-corroded specimens. The bond tests were performed using an Instron universal testing machine with a capacity of 50kN. The applied loads were controlled via computer using displacement control at a rate of 10 mm/min. The setup of the pull-out testing system is shown in figure 4. The maximum pull-out force was recorded and used to calculate the ultimate bond strength ($f_b$) according to equation (2).

$$f_b = \frac{P_{\text{max}}}{\phi_b L}$$

where $P_{\text{max}}$ is the maximum pull-out load, $\phi_b$ is diameter of the reinforcing bar and $L$ is the bonded length of the reinforcement bar in concrete.

3. Test results and discussion

3.1 Control bond strength

The average bond strengths for control un-corroded specimens are plotted in figure 5. The trend shows that the linear increment on bond strength with increasing $C/\phi_b$ ratio. Furthermore higher bond strength is observed on the specimen with stirrup compared to non-stirrup specimens. This condition should be expected since the presence of stirrups has increased the confinement around the steel reinforcing bars, thus increased the bond strength. The difference between these two measurements ranges from 3% to 32%. Based on the regression line, the following equation (3) and (4) are developed to predict the bond strength ($f_b$) of un-corroded specimen:

$$f_b = -1.85 + 1.9 C/\phi_b \text{ for specimen with stirrup}$$

$$f_b = -0.96 + 1.23 C/\phi_b \text{ for specimen without stirrup}$$
3.2 Corroded bond strength
The influence of corrosion on bond strength is shown in figure 6. The level of corrosion in this study is up to 2% mass loss and for both bar diameters. The trend shows that the bond strength is decreased with increasing mass loss. This trend is consistent for both bar diameters and confinement conditions. Since thin concrete cover was used in this study, the bond reduction is more critical on bigger 14 mm bar diameter where its corrosion penetration is higher than the 10 mm bar diameter.

Figure 6. Bond strength versus mass loss.
The effects of corrosion on bond strength are depicted in figure 7 and 8 for specimens with and without stirrups. The presence of corrosion on both bar diameters had significantly reduced the bond strength where the ratio between corroded to control specimens between 0.6 to 0.8 for specimens with and without stirrups and 10 mm bar diameter had higher ratio than 14 mm bar diameter.

**Figure 7.** Control and corroded bond strength of specimens with stirrups.

**Figure 8.** Control and corroded bond strength of specimens without stirrups.

4. Conclusion
Tension pull-out test method was used to study the influence of corrosion on self compacting concrete. The results showed a linear relationship was found between bond strength and cover-to-diameter ratio for both confined and unconfined specimens. Furthermore, higher bond strength was observed on confined specimen compared to unconfined ones as similar as observed in normal concrete. Corroded specimens had lower bond strength and this value was decreased with an increasing in mass loss. This trend was similar as observed in normal concrete.
5. References

[1] Sather I 2011 Bond deterioration of corroded steel bars in concrete, *Structure and Infrastructure Engineering* 7 415–429

[2] Cairns J, Du Y and Law D W 2006 Residual bond strength of corroded plain round bars, *Magazine of Concrete Research* 58 221- 231

[3] Naik T R, Kumar R, Ramme B W and Canpolat F 2012 Development of high-strength, economical self-consolidating concrete, *Construction and Building Materials* 30 463–469

[4] Dahou Z, Castel A and Noushini A 2016 Prediction of the steel-concrete bond strength from the compressive strength of Portland cement and geopolymer concretes, *Construction and Building Materials* 119 329–342

[5] Ayop S S and Cairns J 2013 Critical study of corrosion damaged concrete structures, *International Journal of Integrated Engineering* 5 984- 989

[6] Rasheeduzzafar S, Al-Saadoun S and Gahtani A S 1992 Corrosion cracking in relation to bar diameter, cover and concrete quality, *Journal of Materials in Civil Engineering* 4 327-342

[7] fib 2000 *Bond of Reinforcement in Concrete fib* Bulletin 10 (Lausanne: The International Federation for Structural Concrete) pp 187-212

[8] Fang C, Lundgren K, Plos M, and Gylltoft K 2006 Bond behaviour of corroded reinforcing steel bars in concrete, *Cement and Concrete Research* 36 1931- 1938