

Influence of Crack Spacing on Corrosion Rate in Reinforced Concrete

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Abstract. The presence of cracks may significantly reduce the service life of a RC structure, by acting as pathways for chloride to the reinforcement steel. This leads to the initiation and propagation of corrosion. Whilst corrosion initiation marks the end of service life in a conservative durability design approach, knowledge and predictability of the propagating corrosion rate may improve durability design procedures. This paper reports the chloride-induced corrosion rate in cracked RC beams subjected to cyclic ponding of salt aqueous solution. The role of crack spacing on corrosion rate is reported. Although the investigation is ongoing, the preliminary indications are that a reduced crack spacing leads to a reduction in the corrosion rate.

Keywords: Corrosion · Corrosion rate · Cracked concrete

1 Introduction

Durability of cracked reinforced concrete (RC) structures within coastal regions is a major concern both locally and globally. The service life of a RC structure may be drastically reduced by the presence of cracks whereby the reinforcement steel is exposed to the corrosive external environment. The corrosion process involves corrosion initiation once de-passivation has occurred, followed by corrosion propagation (e.g. Tuutti 1982). Service life of a structure is directly affected by the corrosion rate in the propagation phase. The research program on which this paper reports, focuses on chloride-induced corrosion rate in cracked RC structures or structural elements in the corrosion propagation phase, with the dual intention of establishing reliable non-destructive test methods for condition assessment, and sound intervention strategies towards reaching intended service life, or to extend service life.

Corrosion in RC is a complex process, and typically, standardized durability control in RC is typically by limiting crack width, supported by studies for instance by Schiessl and Raupach (1997). The influence of crack spacing on corrosion in RC elements was reported by Arya and Ofori-darko (1996), and more recently in reinforced strain-hardening cement-based composites (R/SHCC) by Paul and van Zijl (2016). They postulated that the reduced anode to cathode ratio associated with reduced crack spacing, leads to a reduced corrosion rate. The corrosion rate within the propagation phase is effected by multiple factors, however this paper focusses on the crack spacing and the amount of reinforcement within the concrete cross section. These factors were

chosen to investigate the effect of macro-cell corrosion versus micro-cell corrosion and the interaction on the electrochemical process between multiple reinforcement bars in the corrosion state within a RC structure.

The program is ongoing, and the first results are reported on a laboratory study of chloride-induced corrosion rate in $150 \times 150 \times 700$ mm long pre-cracked RC beams subjected to cyclic salt aqueous solution. The corrosion rate is measured with a GECOR 10 (2015) device, which uses a polarisation resistivity technique. Particular test parameters reported on here are crack spacing and amount of reinforcement, but verification of non-destructive corrosion rate measurements with actual corrosion damage to reinforcement embedded in the RC beams in the form of mass loss and/or pitting corrosion is a final objective.

2 Experimental Program

This research project is conducted in the Concrete materials and Structural Laboratories of Stellenbosch University. Phase one of the research comprises the design of a suitable setup to measure and monitor corrosion rate in RC to best predict real life conditions. Two parameters, namely amount of reinforcement and crack spacing, were varied in this investigation, while other parameters like concrete class, cover depth and crack width were kept constant. The mix, test parameters and test setup are described in the next subsections.

2.1 Mix Design and Concrete Class

A mix design similar to current coastal structures was then chosen, while ensuring that the mix design would conform to both the mechanical and durability performance requirements set out in the investigation. To achieve the durability requirements for concrete in corrosive environments, it is important to limit the water-cement (w/c) ratio as well as the extenders (cement replacements materials such as fly ash, slag, etc.) within the mix (Owens 2009). In this research the w/c ratio was limited to 0.45 as per SANS 10100-2: (1992). While it is known that partial cement replacement with extenders influences concrete resistivity, which in turn influences the corrosion rate (Otieno 2014), an unblended CEM I 52.5 cement containing less than 5% of extenders was used for consistency. Table 1 shows the material proportions used in this study.

Table 1. Selected concrete mix proportions (kg/m^3)

Cement	Water	Fine aggregate*	Coarse aggregate**
467	210	425	1326

* Local Malmesbury river sand

** Local 19 mm Greywacke stone

Compressive strength tests were performed on 100 mm cubes specimens, to characterise the concrete class. All specimens were stripped after one day, water cured at 23 ± 2 °C for 7 days, and thereafter kept in a laboratory conditions at 25 ± 2 °C and relative humidity of $65 \pm 5\%$ until the testing date. The average 28-day compressive strength achieved was 59.1 MPa, with a coefficient of variation (CoV) of 2.8%.

2.2 Experimental Variables

The two experimental variables considered in this study are *crack spacing*, and the *amount of reinforcement*. A single crack might lead to significantly localised (pitting) corrosion, which can be more dangerous than multiple cracks which can lead to general corrosion over a widespread length of reinforcement (Arya and Ofori-Darko 1996). An attempt was made to enforce predetermined crack spacing in RC beams by cutting notches in the tensile faces of the beams before mechanical loading. Three notch spacings were used; (i) a single, central notch, (ii) 3 notches (denoted by N3) at 50 mm spacing, and 5 notches (N5) 30 mm apart. This was not successful in enforcing these selected crack patterns. Two cracks at most formed in beams with multiple notches. The actual crack spacing was noted for interpretation of the corrosion rate results.

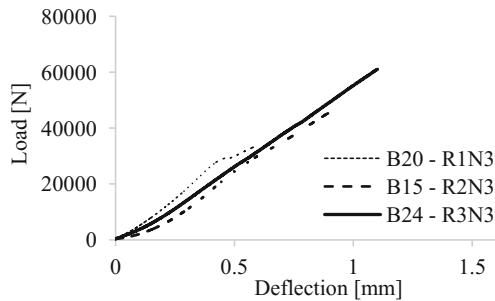
The second parameter, namely the amount of reinforcement was chosen to study the possible influence of multiple reinforcement bars on the electrochemical process and how this might influence the corrosion rate (Paul 2015). Three amounts of reinforcement, namely (i) a single, centrally placed Y10 bar, i.e. a high strength (450 MPa yield strength) ribbed bar of 10 mm diameter, (ii) two Y10 bars and (iii) three Y10 bars. In case of multiple bars, they were electronically interconnected with copper wire. In all cases a cover depth of 40 mm was maintained in the beams with cross section of 150×150 mm, and 700 mm length. In total, 27 beams were prepared, given the three realisations of each of two parameters, and three specimens of each type.

2.3 Pre-cracking

All 27 RC beam specimens were pre-cracked in flexure and subjected to chloride- induce corrosion. Nine specimens containing a single central notch were pre-cracked in three-point bending, whilst the remaining 18 specimens containing multiple notches were pre-cracked in four-point bending. Table 2 summarises the flexural pre-cracking forces, and Fig. 1 shows typical beam responses of beams with a single reinforcing bar (R1), two bars (R2) and three bars (R3). The pre-cracking was performed in an Instron materials testing machine, at a constant cross-head rate of 0.05 mm/min. The load was terminated once either a load drop of 250 N was detected, or a crack width of 0.2 ± 0.1 mm crack was observed. The pre-cracking in the MTM was to initiate cracks, with the intention to subsequently widen the cracks to a required 0.4 mm width in simple frames for chloride ponding exposure, which is discussed in the next section.

Table 2. Flexural pre-cracking responses

Reinforcement	Notch spacing (mm)	Avg. load (kN)	CoV (%)
R1	1 N – Central single crack	24.3	4.74
	3 N – 50	30.4	10.6
	5 N – 30	31.3	9.75
R2	1 N – Central single crack	40.1	5.00
	3 N – 50	46.3	3.29
	5 N – 30	49.0	1.22
R3	1 N – Central single crack	55.1	1.81
	3 N - 50	60.1	3.45
	5 N - 30	62.3	0.92

**Fig. 1.** Typical specimen response in pre-cracking flexure.

2.4 Test Setup for Chloride-Induced Corrosion

After the flexural pre-cracking, each beam was unloaded and reloaded in a steel loading frame until a crack width of 0.4 ± 0.1 mm was observed on the crack face. The frame setup is shown in Fig. 2, consisting of an angle sectioned structural steel beam. Two bolts through the upper flange pass through the RC specimen, to allow mechanical loading by tightening nuts onto the bolts at the beam ends, while a central steel cylinder obstruction forms the third point in three-point flexure in the frame. On the upper, tensile face of each beam, a 250 mm long central Perspex pond was built as shown in the figure, to contain the aqueous solution above the central, cracked face of the beams.

Once fixed and kept under deformation control mechanically in the frame, the total number of cracks and crack spacing were recorded. A crack width (w_c) of 0.4 mm was considered as a threshold crack width (*fip*/CEB model code 2010). Cracks are monitored bi-monthly, and the bolts tightened if necessary to maintain this crack width for the test duration. For all three cases of amounts of reinforcement, all of the cracks were found to be perpendicular to the steel bar and no parallel cracks were observed. Cracks did not form at all the notches. The actual crack spacing (S_c) was measured, and is summarised in Table 3.

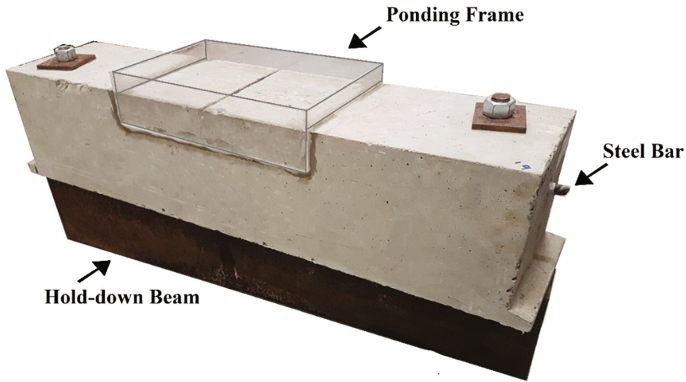


Fig. 2. Specimen fixed in steel frame, showing pond on the tensile face.

Table 3. Corrosion rate and number of cracks in the beams at final reading

S_c [mm]	w_c [mm]	Nr of cracks	Nr of specimens	I_{corr} [$\mu\text{A}/\text{cm}^2$]			Cov [%]
				Avg	Min	Max	
90	0.4 ± 0.1	2	6: 1R1 + 2R2 + 3R3	0.22	0.12	0.38	40.3
100	0.4 ± 0.1	2	5: 1R1 + 1R2 + 3R3	0.24	0.14	0.28	23.4
110	0.4 ± 0.1	2	1: 1R2	0.27	–	–	–
120	0.4 ± 0.1	2	3: 1R1 + 2R2	0.25	0.19	0.30	21.8
Single crack	0.4 ± 0.1	1	12: 6R1 + 3R2 + 3R3	0.32	0.16	0.65	46.7

Pre-cracking was done to accelerate corrosion initiation to occur immediately upon chloride ingress. The propagation phase can take several years to propagate, so accelerated corrosion rate was envisaged by cyclic ponding of NaCl aqueous solution (5% wt) on the cracked face of each RC beam. A two week cycle was used, consisting of three days of wetting, after which the solution was removed from each beam pond for 11 days. The beam faces were sealed to prevent leakage through cracks from the beam sides. The longer period of drying was to allow sufficient oxygen penetration to the steel bars to maintain the electrochemical corrosion reaction. Corrosion rate (I_{corr}) measurements were taken on the cracked face of each beam using a GECOR 10 (2015) device. For each measurement the average of three I_{corr} readings of 45 s duration was taken, using the advanced modulated confinement method. Note that corrosion rate readings were taken weekly, falling in a wet part of the cycle (after 3 days wetting), and one week later in the drying period.

Specimens were kept in ambient laboratory conditions (temperature 25 ± 2 °C, relative humidity $65 \pm 5\%$) for the remainder of the test period where all corrosion rate measurements were taken. I_{corr} readings were taken on the beam specimens in the un-cracked state as reference readings, thereafter in the cracked state and then repeated once a week between the ponding cycle. The exposure condition used in this study is not a standard method but rather a modified cycle of previous studies to obtain the best possible condition of corrosion propagation (Paul 2015).

3 Experimental Outcome

3.1 Corrosion Rate

The corrosion rate results after 10 weeks are shown in Figs. 3, 4 and 5 for single reinforcing bar (R1), two bars (R2) and three bars (R3). In Figs. 3a, 4a, 5a, the results are distinguished by the number of notches seen in the specimens, namely a single (N1), three (N3) spaced 50 mm apart and five (N5) spaced 30 mm apart. However, it must be noted that the notches were not successful in forcing cracks to form in the region of each notch. Instead, at most two cracks formed, as summarised in Table 3. The corrosion current results shown in Figs. 3b, 4b and 5b distinguish the actual crack spacing. Notably, more than one crack formed in only three R1 specimens, but in six R2 and R3 specimens respectively, meaning that in six R1 specimens, and three

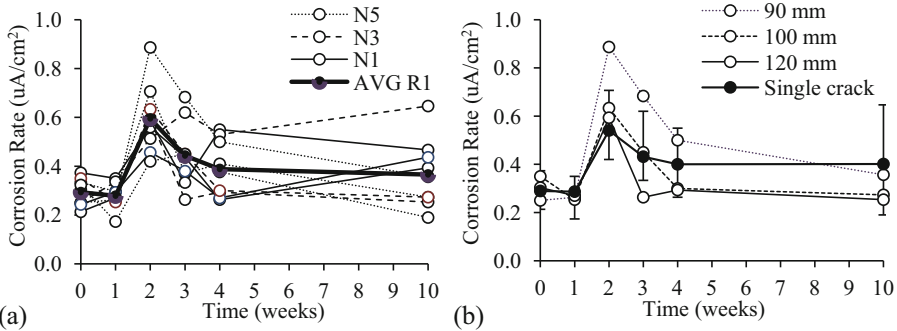


Fig. 3. Corrosion rate of R1 (single steel bar) beams, for (a) all specimens, (b) specimens distinguished in terms of crack spacing

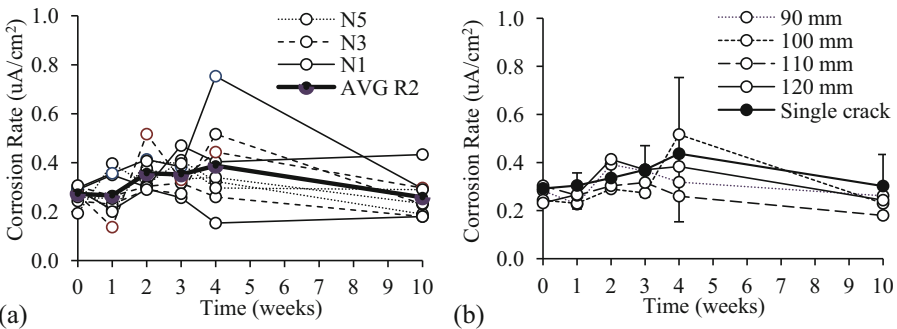


Fig. 4. Corrosion rate of R2 (double steel bar) beams, for (a) all specimens, (b) specimens distinguished in terms of crack spacing

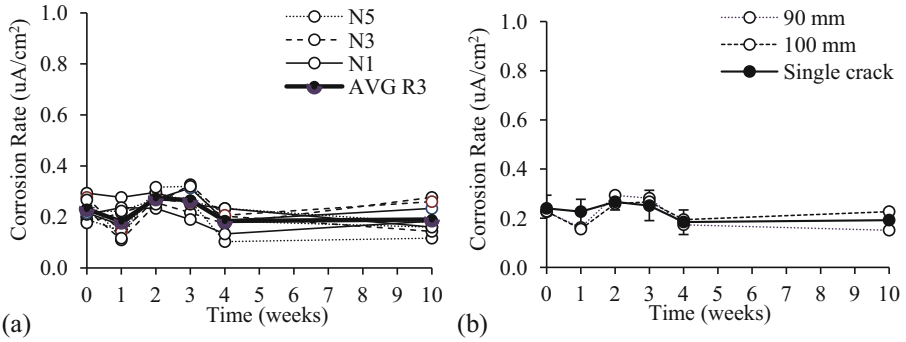


Fig. 5. Corrosion rate of R3 (triple steel bar) beams, for (a) all specimens, (b) specimens distinguished in terms of crack spacing

R2 and R3 specimens each only a single crack formed. In Figs. 4b and 5b the average corrosion current values are plotted. In each case (Figs. 3b, 4b, 5b) the error bars are used to show the minimum and maximum values of the single crack specimens.

Andrade and Alonso (1996) suggest that a corrosion rate of less than $0.1 \mu\text{A}/\text{cm}^2$ is negligible, whereas a rate of $1.0 \mu\text{A}/\text{cm}^2$ is considered high. The rates shown in Figs. 3, 4 and 5 are thus significant, approaching high. It was observed that for each drying exposure measurement, a lower corrosion rate was observed, and after each wetting cycle the corrosion rate readings were found to be higher. Although the external factors were controlled as far as possible, there may be other factors within the specimens such as moisture content, temperature and humidity (ASTM C876). During the period of 70 days (10 weeks) of corrosion rates reported here, only 6 readings were taken. The first 5 readings followed successively from day 1 to day 28, and thereafter a fifth reading on the 70th day of testing. Note that a period of drying was followed between week four reading, and the week 10 reading.

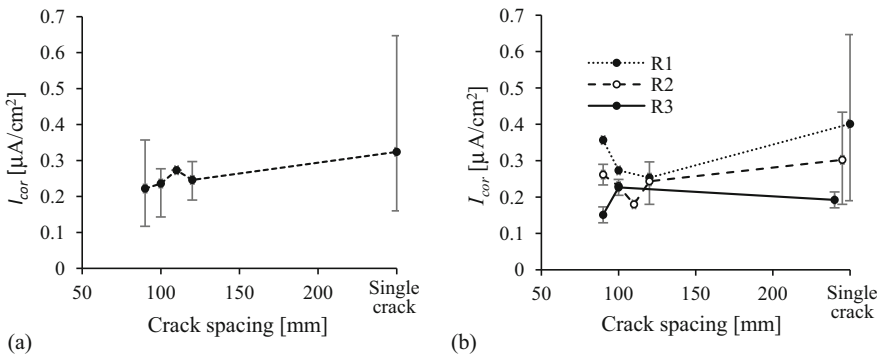


Fig. 6. Corrosion rate as function of crack spacing after 10 weeks of ponding, (a) for all specimens, and (b) distinguished by the number of steel bars.

Also shown in Table 3, are the corrosion current readings in the beams at the final reading (i.e. after 10 weeks of cyclic ponding). Recall that despite the cutting of up to 5 notches at a spacing of 30 mm, no more than 2 cracks were formed in the beams, with the smallest spacing of 90 mm. In Fig. 6 the corrosion current is shown as function of crack spacing, suggesting an increased corrosion current with increased crack spacing for beams reinforced with a single bar (R1) and two bars (R2). However, the variability in corrosion rate readings is significant, as indicated by the minimum, average and maximum values per crack spacing shown in the figure.

4 Conclusion

This paper presents preliminary results of cracked reinforced concrete subjected to chloride-induced corrosion. The following conclusions are suggested by the results:

- Corrosion rate appears to be higher in RC beams containing a single crack, than in beams with cracks spaced 90 to 120 mm apart. This may be explained by a smaller cathode to anode ratio in the electrochemical corrosion process. However, the variability in corrosion rate is significant. Continued cyclic ponding and corrosion rate measurement is required to verify a higher chloride-induced corrosion rate for larger crack spacing.
- An increased number of reinforcing bars as applied in this work, leads to a lower corrosion rate recorded.

The cyclic ponding and weekly corrosion rate measurements have been resumed and are planned to continue for a total of 245 days, where after the beam specimens will be destructed and visually observed for corrosion damage (mass loss, pitting). The actual corrosion that took place over the course of testing will then be compared to the predicted corrosion rate in the next phase of the investigation.

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