

Phenomenological Model of Corrosion Process in Reinforced Concrete identified by AE

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Abstract

Corrosion of reinforcing steel is modelled phenomenologically as corrosion losses of three phases. In order to identify the corrosion process in reinforced concrete based on the model, continuous AE monitoring in reinforced concrete specimens was conducted in an accelerated corrosion test and a cyclic wet and dry test. It is demonstrated that two periods of high AE activities are observed. The 1st AE activity corresponds to the onset of the corrosion in rebar of the 1st phase in the phenomenological model. At the 2nd period of high activity AE events result from concrete cracking, corresponding to the 3rd phase in the model.

Keywords: Acoustic emission; Corrosion; Reinforced concrete; Half-cell potential; Chloride concentration.

1. Introduction

Corrosion of a reinforcing steel bar (rebar) is known to be critical in reinforced concrete. By applying acoustic emission (AE) techniques, it has been reported that concrete cracking due to rebar corrosion is effectively detected [1-3]. According to a phenomenological model [4], a typical corrosion loss is postulated as four phases as shown in Fig. 1 (a). At phase 1, the corrosion is initiated. As the corrosion products build up on the corroding surface of rebar, the flow of oxygen is eventually inhibited and the rate of the corrosion loss decreases at phase 2. The corrosion process involves further corrosion loss as phases 3 and 4 due to anaerobic corrosion. Based on the model, continuous AE measurement was conducted to monitor the corrosion process in reinforced concrete [5].

2. Experiment

2.1. Specimens

Reinforced concrete specimens tested were of dimensions 300 mm× 300 mm × 100 mm. Deformed rebars of 13 mm nominal diameter were embedded with 15 mm cover-thickness for axial

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reinforcement. When making specimens, concrete was mixed with NaCl solution. In order to investigate the threshold limit of chloride concentration for the corrosion, the lower-bound threshold value (chloride amount 0.093% mass of cement) was taken into account. After the standard curing for 28 days in 20°C water, chloride content was measured by employing a standard cylindrical sample of 10 cm diameter and 20 cm height and found to be 0.039% mass of cement as lower than 0.3 kg/m³ in volume. The maximum size of gravel was 10 mm, and the slump value and air content were controlled by using air-entrained admixture. A compressive strength at 28 days of the standard curing was 35.0 MPa. Following the standard curing, all surfaces of the specimen were coated by epoxy, except the bottom surface for one-directional diffusion.

2.2. Corrosion test

An accelerated corrosion test and a cyclic wet-dry test were conducted. In the accelerated corrosion test, the specimen was placed on a copper plate in a container filled with 3% NaCl solution. Between rebars and the copper plate, 100 mA electric current (0.754 mA/mm²) was continuously charged. In the cyclic wet-dry test, the specimens were cyclically put into the container in the figure without charge for a week and subsequently dried under ambient temperature for another week.

AE measurement was continuously conducted, by using AE analyzer (LOCAN 320, PAC). Two broadband-type AE sensors (UT1000, PAC) of 1 MHz resonance were attached to the upper surface of the specimen. Frequency range of the measurement was 10 kHz - 1 MHz and total amplification was 60 dB gain. For event counting, the dead-time was set to 2 msec and the threshold level was 40 dB gain.

Half-cell potentials at the surface of the specimen were measured by a portable corrosion-meter (SRI-CM-II, Shikoku-Soken). In the accelerated corrosion test, the measurement was conducted twice a day, right after discontinuing the current. When the average potentials reached to -350 mV (C.S.E.), the test was terminated. In the cyclic test, the specimen was weekly measured until the average potentials in dry condition reached to -350 mV (C.S.E.). During the half-cell potential measurement, AE measurement was discontinued in both tests.

2.3. Chloride concentration and micrograph observation

Chloride concentrations were measured at several periods. At first, the initial concentration was measured by using a standard cylinder sample after 28-day moisture-curing as an initial value. At other periods, two core samples of 5 cm diameter were taken from the specimens. Slicing the core into 5 mm-thick disks and crushing them, concentrations of total chloride ions were determined by the potentiometric titration method. At two stages during the cyclic test, rebars were taken out of the specimen. Then, they were cut into 10 mm portions, and then ferrous ions on their surface-layers were examined by the scanning electron microscope (JSM-5600, Nippon-Denshi).

3. Data analysis

3.1. Chloride content

Ingress of chloride ions into concrete is normally simplified as diffusional flow. For one-dimensional diffusion, it is postulated that chloride ions penetrate through concrete cover to rebar, following Fick's second law. In the present study, an effective diffusion coefficient was determined from the water-to-cement ratio based on statistical data in Japan [6]. Surface

concentration was estimated from chloride concentrations at 0.5 cm - 1.5 cm depths as an averaged value, when core-drilled samples were obtained.

3.2. *AE parameters*

Characteristics of AE signals were estimated by using two indices of RA value and average frequency. These are defined from such waveform parameters as rise time, maximum amplitude, counts and duration. According to the recommendation [7], AE sources of active cracks are classified, based on the relationship between the RA values and the average frequencies.

To evaluate the size distribution of AE sources, the amplitude distribution of AE events was analysed. The gradient of the distribution is called the *b*-value, and is applied to estimate the size distribution of AE sources. In the case that the *b*-value is large, small AE events are mostly generated. In contrast, the case where the *b*-values become small implies nucleation of large AE events.

4. Results and discussion

4.1. *Accelerated corrosion test*

From a relation between AE activity and half-cell potentials, two periods of high AE activities are clearly observed around at 3 days elapsed and at 7 days elapsed. The activity at the 1st period is even higher than the 2nd. It is noted that the half-cell potentials start to decrease after the 1st high activity. This may suggest the onset of corrosion in rebars, although the potential are still less negative than -350 mV (ASTM criterion denoted in the graph) at the 2nd high activity.

Following two periods of high AE activities and at the final stage, cores were taken. Total chloride ions were determined in depths. Based on chloride concentrations at the initial and after the 1st high AE activity, chloride concentration at the cover thickness was analytically estimated. Results are plotted in Fig. 1 (b). A broken curve shows analytical values, which are compared with measured values (open circles in the figure) at the cover thickness in the tests. Agreement between analyzed and measured values after the 2nd high activity and at the final stage is reasonable. In the figure, two horizontal lines are denoted. One is the lower bound of threshold value for onset of corrosion (0.3 kg/m³ in volume) and the other is the threshold value (1.2 kg/m³ in volume). It is interesting that the curve of the total number of AE hits is in remarkable agreement with the typical corrosion loss in the phenomenological model in Fig. 1 (a). This could suggest that AE activity observed could phenomenologically corresponds to the corrosion activity in rebar.

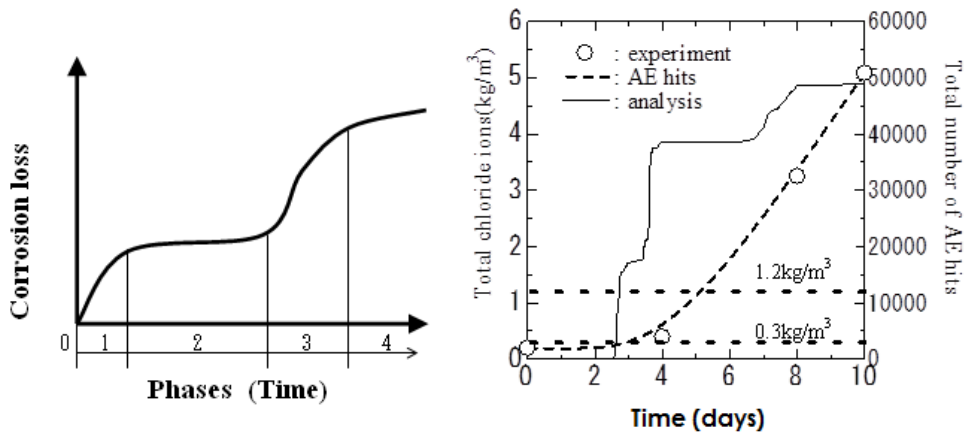


Figure 1. (a) Phenomenological model and (b) AE activity with chloride concentration.

4.2. Cyclic corrosion test

In order to classify AE sources, the RA values and the average frequency were determined, averaging the data in two weeks of wet and dry. Results are shown in Fig. 2. Corresponding to the 1st period, the RA value becomes large and the average frequency is low. This implies that AE sources are classified as other-type cracks than tensile. After 100 days elapsed, a slight increase of the RA values is observed. Identification of the 2nd high activity seems to be difficult. According to the decrease in the half-cell potentials around at 100 days elapsed, the 2nd period was identified. Thus, the RA values are low and the average frequencies are fairly high. It is suggested that tensile cracks were nucleated at this period. In addition, the b -values were determined during each wet-dry cycle as the average values. b -value becomes high at the 1st period and then b -values keep fairly low. Results suggest generation of small other-type cracks at the 1st period and nucleation of fairly large tensile cracks at the 2nd period. Combining the results of the accelerated test, it may be concluded that the 1st high AE activity is associated with generation of small other-type cracks and could be related with the onset of corrosion in reinforcement. The 2nd high AE activity results from the nucleation of fairly large tensile cracks, which could be generated due to the expansion of rebar caused by corrosion product.

4.3. Visual and SEM observations

In the cyclic wet-dry test, it is found that chloride concentration at rebar reaches to the lower-bound threshold of 0.3 kg/m^3 after 40 days. At around 100 days elapsed, the concentration becomes higher than 1.2 kg/m^3 . Accordingly, at 42 days elapsed and 126 days elapsed, rebars were removed and visually inspected. No corrosion was observed on rebar surface after 42 days, while rebar was fully corroded after 126 days. These results imply that rebars could corrode after chloride concentration reaches over 1.2 kg/m^3 in concrete. AE activities after 100 days could reasonably result from concrete cracking due to the expansion of corrosive products in rebars.

In order to investigate the condition of rebar at the 1st AE activity, the surface of rebar was examined by the scanning electron micrograph (SEM). Distributions of ferrous ions were estimated at the initial of as-received condition and at 42 days elapsed. In the as-received condition, homogeneous distribution of ferrous ions is observed at the surface as the gray zone. At 42 days elapsed, rebars removed were cut into 10 mm fragments, and the circumferential surfaces were examined. In Fig. 3, it is shown that at some portions of the surface layer, ferrous ions (grey) vanish and black areas appear as non-ferrous zones. This demonstrates that the

onset of corrosion occurs in rebars at the 1st period of AE activities. Although no corrosion was observed visually, rebars were actually corroded as found in the SEM observation.

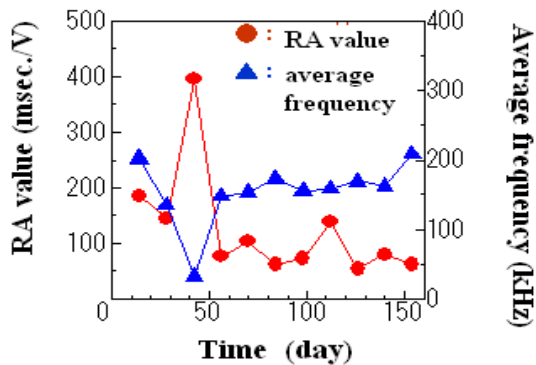


Figure 2. The RA values and the average frequencies in the cyclic wet-dry test

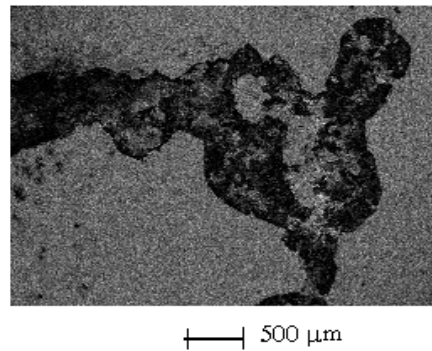


Figure 3. Distribution of ferrous ions after the 1st period.

5. Conclusion

Continuous acoustic emission (AE) monitoring in reinforced concrete specimens was performed during the corrosion tests. In an accelerated corrosion test, high AE activities were twice observed, while the 1st activity was clearly observed during a cyclic wet-dry test. Two indices of AE waveform parameters were adopted for classifying AE sources into tensile-type and other-type of cracks.

(1) At the 1st high AE activity, AE sources were of small amplitudes and classified as other-type cracks. At this stage, chloride concentration at the level of rebar was just higher than the lower-bound level for the initiation of corrosion. Although rebars were removed, no corrosion products were visually observed. According to examination of rebar surfaces by the SEM observation, ferrous ions on the rebar surface are found to vanish at some areas, which could be the reason for the 1st high AE activity due to generation of small other-type cracks.

(2) At the 2nd high AE activity, chloride concentration was already higher than the upper-bound level for corrosion in the code. When rebars were removed, corrosion products were visually observed at the surface. Here, AE events were associated with fairly large tensile cracks and thus could result from concrete cracking due to rebar expansion caused by corrosion product. In the tests, the half-cell potentials were also measured. It was confirmed that both AE high activities were observed earlier than the stage where the potentials became more negative than -350 mV.

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