EARLY DETECTION OF CORROSION ACTIVITY IN REINFORCED CONCRETE SLAB BY AE TECHNIQUE

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ABSTRACT: Chloride induced corrosion of steel reinforcement in concrete is the main cause of damage to concrete structures in marine, or structures exposed to de-icing salt environments. The need for early detection of corrosion in reinforced concrete structures is widely acknowledged in corrosion health monitoring for strategic civil engineering projects. This paper summarizes results from a laboratory experiment, using Acoustic Emission (AE) technique, regarding early detection of corrosion in reinforced concrete slabs that are exposed to chloride. The Results showed that while AE was able to determine the initiation of corrosion in reinforced concrete slab, Half-cell potential (HCP) was not able to detect it at the early stage of corrosion.

Keywords: Corrosion; Acoustic Emission; Half-cell potential; Non-destructive techniques.

1. INTRODUCTION

It is well recognized that the corrosion of steel in reinforced concrete is one of the main reasons of deterioration of civil engineering concrete infrastructures. The principal cause of the degradation of concrete structures, such as parking garages, bridges, transit system tunnels, piers and residential buildings, is corrosion damage to the concrete reinforcement. Corrosion damage is largely related to concrete being exposed to de-icing or to the presence of chloride in concrete mixture ingredients. The corrosion phenomenon of the steel reinforcement has been widely studied by various electrochemical methods, stationary and non-stationary, such as the reinforcement electrode potential measurement in different places of the concrete surface, determination of polarization resistance, the measurement of electrochemical impedance (Idrissi et al 2003, Videm and Myrdal 1998, Dubravka et al 2000, Elesner 2003, Law et al 2000, Andrade and Alonso 2001). However, these methods are sensitive to environmental conditions, which often give misleading results (Kyung and Ohtsu 2001).

Half-cell potential measurements can be used to determine the probability of corrosion activity taking place at the time of the reading. Using ASTM Test Method C876, the corrosion potential of the rebar is measured using a grid pattern over the concrete surface. However, the interpretation of the potential mapping is often inconclusive because the measurements depend on the condition of the concrete. Moisture level and the amount of carbonation and salt concentration can affect the reading and give erroneous readings. In addition, half-cell potential measurements do not provide information on the rate of corrosion.

According to the Japanese Society of civil Engineering (JSCE) standard, the critical threshold for onset of corrosion is suggested to be about $0.3 \sim 0.6$ kg/m^3 chloride concentration of concrete volume. When the chloride concentration becomes over $1.2 \sim 2.4$ kg/m^3, corrosion cracking could be nucleated in concrete.

More advanced methods such as radiography and ultrasonic, have been used to detect rebar corrosion. However, they have met with limited success due to the skill needed to

analyze the data, as well as the expense of the equipment. In addition, radiography uses X-ray or gamma rays require extensive safety precautions. Recently, Acoustic Emission (AE) technique has been applied to detect initiation of corrosion in concrete (Hearn and Shield 1997, Tanaka and Ohtsu 2003). Elastic waves, due to micro cracks on the surface of rebar or in the interface of steel/concrete, could be detected by AE sensor placed on the top of concrete. These waves could be considered as an indicator of early corrosion activity in concrete.

AE technique has been used in some industrial applications; however, there are few studies that have evaluated the use of this technique in civil engineering applications. It seems that AE has the potential for detecting of early corrosion, film cracking, and micro-cracking in concrete structures.

In addition, it is also possible to use the AE signal to calculate and specifically locate steel corrosion, allowing structure inspectors to determine the extent of corrosion damage.

2. SCOPE AND OBJECTIVES

This paper evaluates the potential application of AE technique in the early detection of corrosion activity in a reinforced concrete slab. A laboratory experiment was performed to study the corrosion process due to chloride attack under dry and wet cyclic conditions.
The two most common of concrete corrosion monitoring methods, half cell potential and chloride content, were used to compare and evaluate corrosion activity with AE method.

3. EXPERIMENTAL PROGRAM

3.1 Materials and Specimens

Ordinary Portland cement (OPC) was used in this laboratory experiments. As for concrete mixture proportion, weight ratios of water, cement, sand, and gravel were 0.55, 1.0, 2.35, and 3.67 per unit volume, respectively. The maximum gravel size was 20 mm. The slump value and air content of the fresh concrete were 80 mm and 6%, respectively. Compressive strength and Young's modulus of concrete at 28 days were 28.6 MPa and 25 GPa, respectively. Mixture proportion and properties of concrete is given in Table 1.

Table 1. Concrete mix. proportion

| W/C (%)	Weight of unit volume (Kg/m³)				NaCl (g)	AE (g/m³)	Slump (mm)	Air (%)	Comp. strength (MPa)	Young's Modulus (GPa)
	W	C	S	G						
0.55	175	318	746	1168	494	95.4	80	6	28.6	25

AE = Air entraining admixture.

A reinforced concrete slab was made of with dimensions of 1000 x 570 x 100 mm. Steel reinforcement rebars with 13 mm diameter were embedded at 20 mm and 33 mm from the surface for transverse and longitudinal orientations, respectively.

All slab sides were coated by epoxy except the bottom side, which was left uncoated to allow ingress of chloride. Configuration of a specimen, as well as rebars arrangement, is shown in Fig 1. The amount of mixed NaCl in concrete mix was equivalent to the chloride concentration of 0.2 kg/m³ in concrete volume.

Six AE sensors of type R-15 (150 kHz resonance; Physical Acoustics Corporation PAC) were attached to the top surface of concrete specimen. The arrangements of AE sensors are also shown in Fig 1. Frequency range of the measurement was 10 kHz ~ 1 MHz and total

gain was 40 dB. To determine chloride concentration profiles, concrete specimens of dimensions 300x250x100 mm were made with the same concrete mix ingredients and conditional condition as the slab specimen. As similar to the slab specimen, only the bottom surface of the specimens was not coated. The chloride concentrations, as a destructive test, were measured at four periods. The initial concentration was measured by using a concrete cylinder after 28 days of standard curing. On the second and third periods, cores were taken from two of small slabs, expecting the chloride concentration to be higher than 0.3 kg/cm^3 and 1.2 kg/cm^3, respectively. On the forth period, after the test was over, it was taken from the large slab.
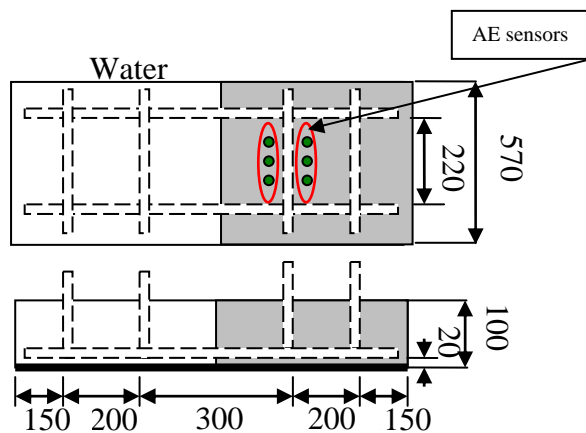
All dimensions in mm
Fig 1. Rebars and Acoustic Emission Sensors Arrangement in Concrete Specimen.

4.   ANALAYTICAL PROCEDURE

4.1 AE Parameter Analysis

Acoustic Emission (AE) is a non-destructive technique that detects and characterizes micro-cracking inside solid materials (Ohtsu 1996, Ohtsu 1998). AE events are associated with cracking and are detected by AE sensors as electrical signals, which are amplified, filtered, and processed as shown in Fig 2.

In the case of reinforced concrete, AE sources are caused by thermal cracking, freezing and thawing, corrosion of reinforcing steel (Ohtsu 1998). An AE signal is characterized by employing AE parameters such as count, event, amplitude, rise-time and duration as illustrated in Fig 3.

Here, characteristics of AE signals are estimated by using two indices of RA value and average frequency, which are defined from wave parameters as:

RA value = Rise Time/Amplitude   (1)

Average frequency = Counts/Duration   (2)

According to the JCMS-III B5796 standard 2003, a crack type is classified from the relationship between RA value and average frequency as shown in Fig 4. A tensile -type crack is referred to as an AE signal with high average frequency and low RA value. In the opposite way a shear-type crack is identified.
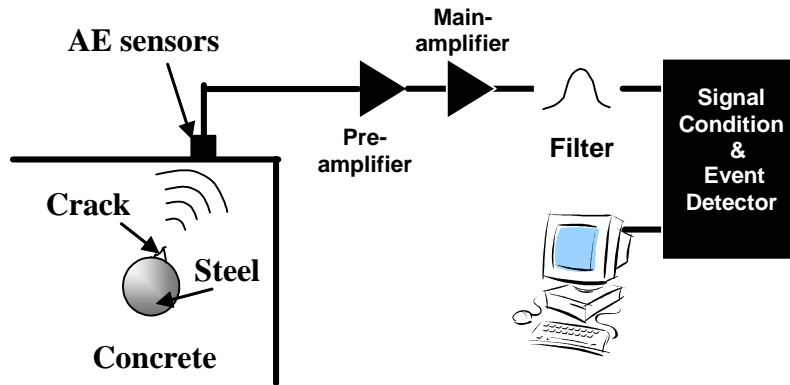
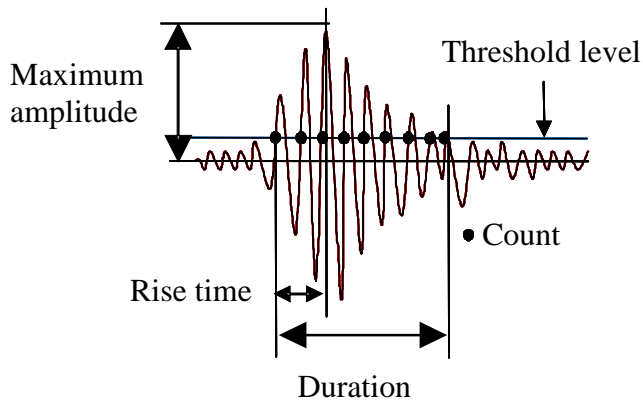*Fig 2. AE Measurement (Leelalerkiet et al, 2005).*

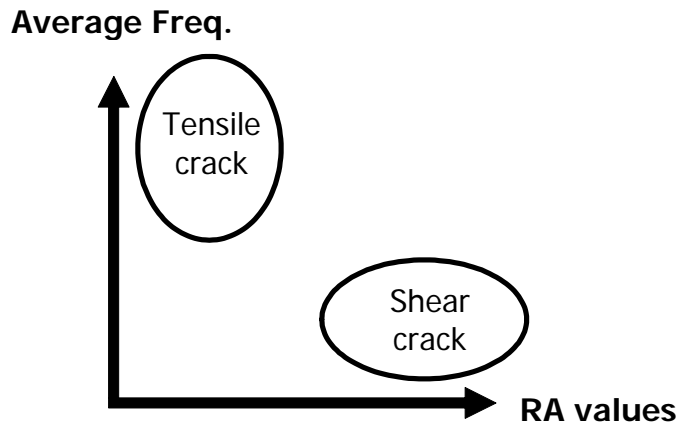*Fig 3. AE Signal Parameters (Leelalerkiet et al, 2005).*

Fig 4. Classification of Crack Type.

4.2 Ingress of Chloride Ions

Chloride ions penetrate from the environment and/or contaminate concrete-mixed materials to the reinforcement surface. A one-dimensional, diffusion is governed by Fick's second law as in Equation (3).

$$\frac{\partial C(x,t)}{\partial t} = D\frac{\partial^2 C(x,t)}{\partial x^2} \tag{3}$$

Where $C(x, t)$ is concentration of chloride ions (kg/m^3) at a distance x (cm) from the surface and time of exposure t (second). D is the diffusion coefficient of chloride (cm^2/s).

In the case that the initial surface concentration C_o is known, a solution of Equation (3) is obtained as the following error-function:

$$C(x,t) = C_o(1 - erf\frac{x}{2\sqrt{Dt}}) \tag{4}$$

Where C_o is concentration of chloride at the surface of steel and *erf* is error function. In this study, the diffusion coefficient (D) was determined from JSCE standard (2002):

$$\log D = -3.9(W/C)^2 + 7.2(W/C) - 2.5 - \log(3.15x10^7) \tag{5}$$

Where *W/C* is the water-cement ratio. The surface concentration C_o is estimated form chloride concentrations at 1.5 cm – 2.5 cm depths as the averaged value.

5. CORROSION DETECTION MEASUREMENT

In order to accelerate the corrosion process, concrete specimen was cyclically dried under ambient temperature for a week and subsequently put into 3% NaCl solution in a tub for another week. Half-cell potentials were measured weekly by using a portable corrosion meter SRI-CM-IV with a silver/silver chloride reference electrode (SCE), which is illustrated in Fig 5 (Yokota 1999).

The surface of the specimens was divided into 50 meshes as illustrated in Fig 6. The CSE measurements were conducted at the center of each mesh.

The corrosion meter works on AC Impedance principle. It measures with 3 electrode system, which has a reinforcing steel bar connection, a reference electrode and a counter electrode. It applies a small sinusoidal voltage and the amplitude of the sinusoidal current response, and the phase difference between the two signals, are measured.
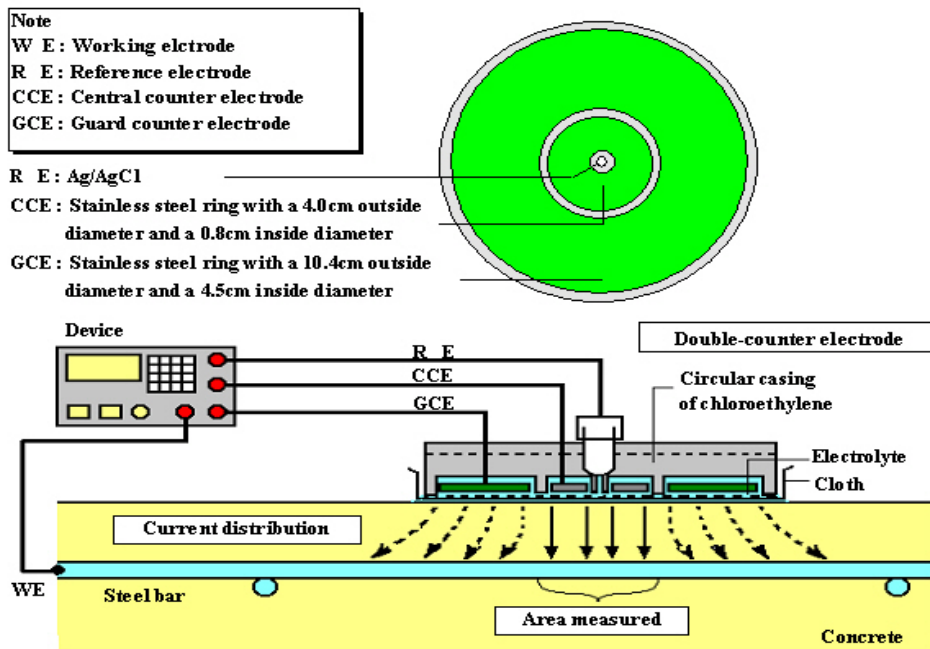
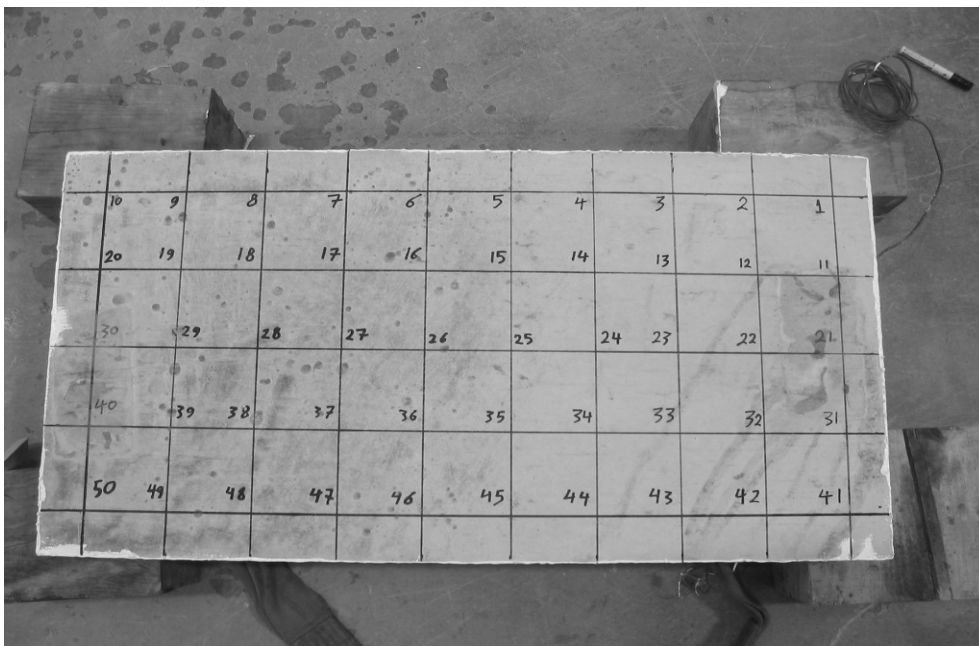*Fig 5. Portable corrosion meter SRI-CM-IV (Leelalerkiet et al, 2005).*

Fig 6. Concrete Surface Mesh Grids.

6. RESULTS AND DISCUSSION

6.1 AE Monitoring

AE activity was monitored and compared with the half-cell potentials. Results of averaged AE hits from 6 sensors and averaged half-cell potentials of all the mesh points are plotted in Fig 7. It is found that the first high AE activity observed approximately at 14 days after the

standard curing, when chloride concentration was at the critical level of 0.3 kg/m³ ~ 0.6 kg/m³. After 70 days, the second high activity of AE hits was recorded corresponding to the chloride concentration level of 1.2 kg/m³ ~ 2.4 kg/m³. Although a fair number of AE events are observed in Fig 7, the measured half-cell potentials were below, or almost equal to -200 mV at the early stage of monitoring. According to ASTM C876, these suggest 90% possibility of no corrosion status. Thus, the corrosion initiation was identified by AE technique much better than by the half-cell potential measurement.

To distinguish the two stages of corrosion, RA values and average frequencies Equations (1) and (2) were estimated by AE method. In Fig 8, after the first stage (14 days), RA values drastically increase and the average frequencies are getting smaller. This suggests the nucleation of AE events of the shear type. After 60 days, RA values decrease and the average frequencies slightly increase. This implies the generation of the tensile crack that followed by the second stage at age of 70 days.

6.2 SEM

After the first high AE activity, rebars were removed from small concrete specimen. No corrosion was visually detected. Then, the surface of reinforcing steel was examined by scanning electronic microscope (SEM). Fig 9 shows the distribution of ferrous ions before the test and after the first stage. Before the test, homogeneous distribution of ferrous ions is observed, while they disappear after the first stage. This implies that at the onset of corrosion, surface layer of ferrite could be broken, which possibly generate small AE events of shear type. This implies that the corrosion of rebar can be detected both at onset and at nucleation of concrete cracking by AE.
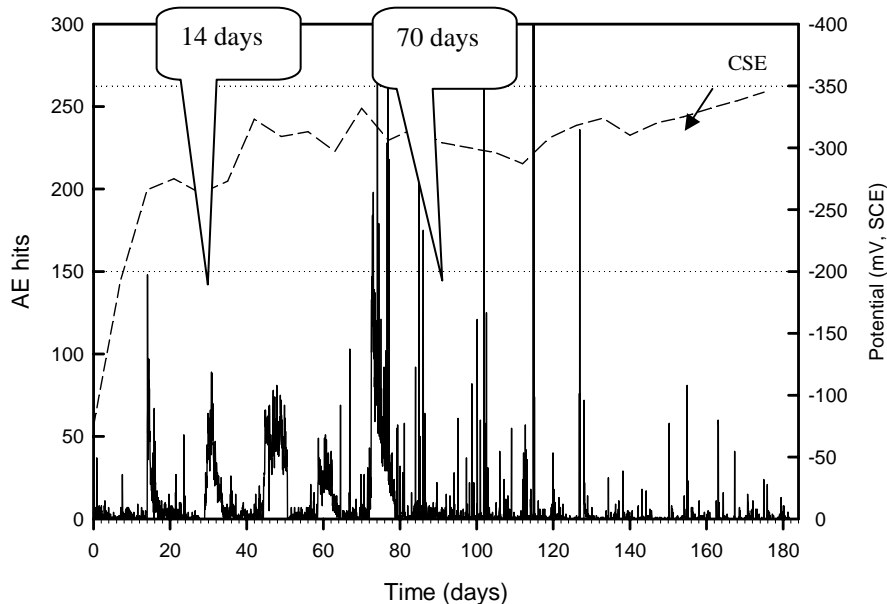

Fig 7. Results of AE Activity and Half-cell Potential.
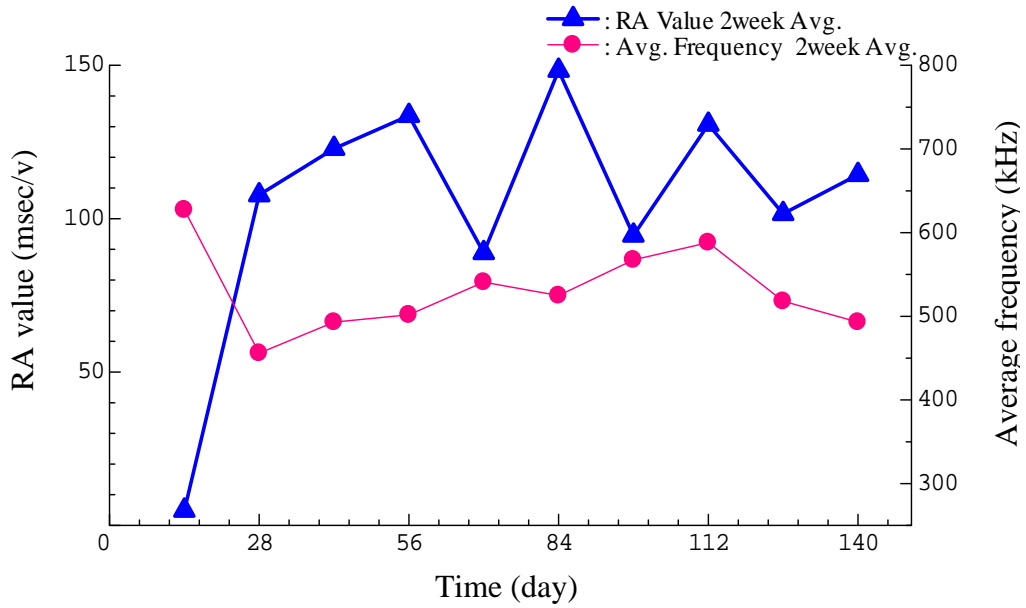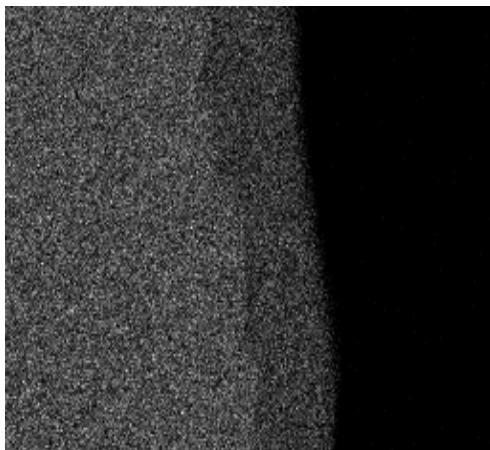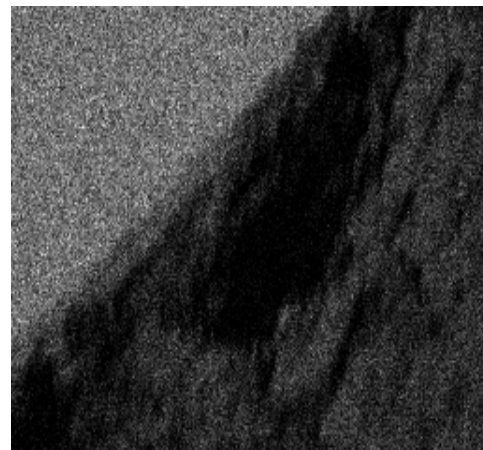
Fig 8. Variation of Average Frequencies and RA Values

(a) Distribution of ferrous ions before the test.   (b) Distribution of ferrous ions after the first stage.

Fig 9. Microscopic Inspections of Rebars.

6.3 Chloride Concentration Profile

Chloride concentrations were estimated by Equation (4) at the initial stage (after curing), 28 days (4 weeks), 98 days (14 weeks) and at the end of the cyclic tests at 20 mm depth. From the water-cement-ratio, diffusion coefficient D was estimated as 6.05×10^{-8} cm^2/s based on Equation 5.
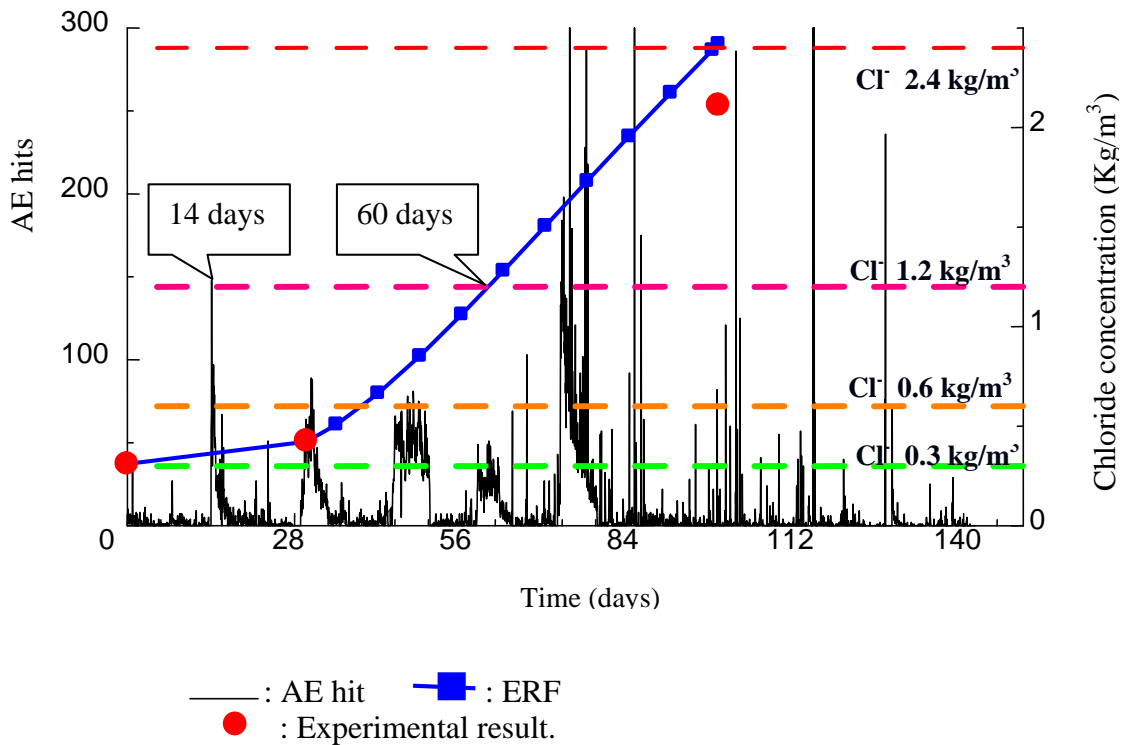
Fig 10. Chloride Concentration Profile and Corrosion Stages.

Chloride concentrations at the rebar level were calculated and compared with experimental results in Fig 10. It is observed that estimated chloride concentrations from Equations 4 and 5 are in a good agreement with experimental results. In this Figure, threshold level of 0.3 kg/m^3, 0.6 kg/m^3, 1.2 kg/m^3 and 2.4 kg/m^3 are indicated. Chloride concentrations at rebar level reached 0.3 kg/m^3 and 1.2 kg/m^3 levels after approximately 14 days and 60 days elapsed. After the chloride concentration surpasses these levels, high AE activities were observed.

7. CONCLUSIONS

It is found that the onset of corrosion starts, when the chloride concentration exceeds the critical level of 0.3 kg/m^3 ~ 0.6 kg/m^3. Nucleation of corrosion cracking is observed when the chloride concentration becomes over 1.2 kg/m^3. These transition periods were identified by the AE method. The experiment indicated that AE monitoring could detect the initiation of rebar corrosion through the first AE activity after 14 days. Initiation and propagation of corrosion were not identified by half-cell potentials measurements. Results show that the measured potentials values are below -350 mV and this indicate a case of uncertainty towards corrosion activity.

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