IN SITU MONITORING AND DAIGNOSIS OF REINFORCED CONCRETE MEMBERS IN AN EXPOSURE TEST AGAINST SALT ATTACK

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ABSTRACT

To maintain concrete structures in good conditions and in safety, monitoring and diagnosis against deteriorations are key issues. To inspect environmental conditions and develop a monitoring procedure for the deterioration due to salt attack, an exposure test was conducted at a site constructing the viaduct of Shin-Kitakyushu Airport. Monitoring by acoustic emission (AE) and ultrasonic testing (UT) had been carried out routinely from 1993 to 1999. Results showed a great promise for an applicability of AE technique to monitor the corrosion in reinforced concrete (RC) members. In order to confirm these results and apply to practical monitoring, comparable tests are performed in a laboratory. Based on diffusion analysis of chloride ions, quantitative nondestructive evaluation for the corrosion of rebars by AE is performed, and a promising procedure for monitoring and diagnosis on the salt damage is proposed.

INTRODUCTION

It is seriously recognized in concrete engineering that concrete structures are no longer maintenance-free. Consequently, a variety of activities for maintenance and repair of the concrete structures are reported. According to the Standard Specification for Concrete Structures on Maintenance by the Japan Society for Civil Engineers (JSCE, 2001), six mechanisms to be identified for the maintenance are specified. These are deteriorations due to salt attack, neutralization, chemical attack, freezing and thawing, alkali-aggregate reaction, and fatigue. In reinforced concrete (RC) structures, alkali passive layers on rebars (reinforcing steel-bars) could be broken due to ingress of chloride ions, and activated ferrite ions lead to corrosion of rebars. Because almost of all concrete structures are reinforced by rebars, the corrosion due to salt attack has been referred to as the most critical deterioration of RC structures.

At a construction site of the viaduct to New Kitakyushu Airport, an exposure test of RC beams against salt attack was conducted from 1993 to 1999. Since in situ monitoring techniques by acoustic emission (AE) were going to be standardized to estimate the structural integrity of the existing concrete structures (Yuyama et al., 1998; NDIS-2421, 2000), monitoring the corrosion by AE was attempted. So far, AE techniques have been studied in reinforced concrete (Ohtsu et al., 2002) and were applied to estimation of corroded members (Yoon et al., 2000).

Following the exposure test, an applicability of AE technique to the corrosion diagnosis in RC structures is investigated and confirmed in an accelerated corrosion test, comparing with permeation of chloride ions.

EXPERIMENTS

All mixture proportions of concrete tested are given in Table 1. In the exposure test, sixty samples of four mixtures in total were made and tested for six years. AE monitoring was conducted at three samples of No. 33, No. 45, and No. 47. The water-to-cement ratio (W/C) of No. 33 sample was the lowest as 35%, while those of No. 45 and No. 47 were fairly high as 55%. To increase in the resistance to water penetration, silica fume (SF) was added to the concrete of No. 47 sample. In the accelerated corrosion test, two kinds of mixture were employed, as W/C ratios were 45 % (A45) and 55% (A55). In all mixes, the maximum gravel size was 20 mm. Air-entraining admixture was added to control slump values as 5 cm or 10 cm and air contents of concrete as 5%. In the accelerated corrosion test, compressive strengths were determined at 28 days after moisture-cured in the standard room (20^{o}C). Averaged strengths of three samples were 40.9 MPa for A45 and 34.6 MPa for A55.

In the exposure test, RC samples of dimensions 15 cm x 15 cm x 120 cm were made, in which two rebars of 13 mm diameter were embedded. A sketch of the sample is shown in Fig. 1. The samples were exposed at seashore as illustrated in Fig. 2.

Table 1 Mixture proportions of concrete.

Sample	W/(C +SF) (%)	Air contents (%)	Slump values (cm)	Unit weight per volume (kg/m^3)			
				Water	Cement + (SF)	Sand	Gravel
33(ch.1 & 2)	35	3.0	10.0	158	451	697	1050
45(ch. 3 & 4)	55	4.0	8.6	176	320	756	1050
47(ch. 5 & 6)	55	3.8	4.8	176	288 (32)	774	1032
A45	45	5.2	3.5	175	389	686	1138
A55	55	6.8	7.7	176	321	741	1179

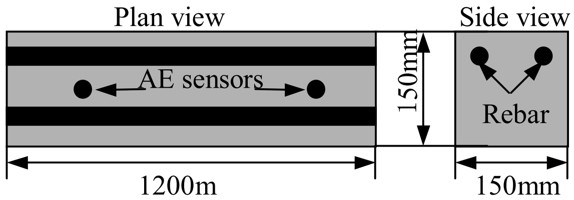

Fig. 1 Sample in the exposure test.

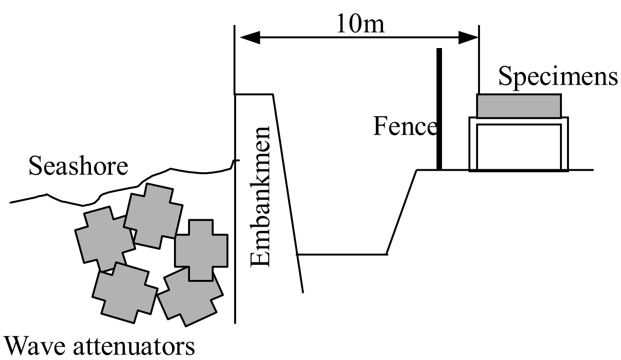

Fig. 2 Site for the exposure test.

Because the site was 10 m apart from the embankment, salt attack was not severe but mild. Consequently, a surface crack of around 0.2 mm width was introduced at the bottom of each sample, by a bending test prior to exposure. At 360 days elapsed, 1045 days elapsed and 2156 days elapsed, core samples were taken from samples of the same mixture and then chloride contents were measured by the potentiometric titration

In the accelerated corrosion test, an RC slab of dimensions 10 cm x 25 cm x 40 cm was cast. A sketch of the slab is shown in Fig. 3, which was placed in a tank as shown in Fig. 4. A copper plate was placed at the bottom, and then 100 mA electric current was charged between rebars and the copper plate. To keep electrical conductivity good, the tank was filled with 3% NaCl solution. After the tests, core samples denoted by dotted cylinders in Fig. 3 were taken, sliced and crashed. Then, chloride contents in depth were measured by the potentiometric titration

AE sensors of 50 kHz resonance (RA5; Physical Acoustics Corp.) were placed on the top surface in the samples. In the exposure test, two sensors were attached to each sample. Thus, ch. 1 and ch. 2 for No. 33 sample, ch.3 and ch. 4 for No. 45 sample, and ch. 5 and ch. 6 for No. 47 sample were set up as indicated in Table 1. The velocity of ultrasonic wave was also measured during the exposure. In the accelerated corrosion test, five sensors were placed as shown in Fig. 3. In both the exposure test and the accelerated corrosion test, amplification was 40 dB gain in total and the frequency range was set from10 kHz to 200 kHz. AE hits generated during the test were detected continuously.

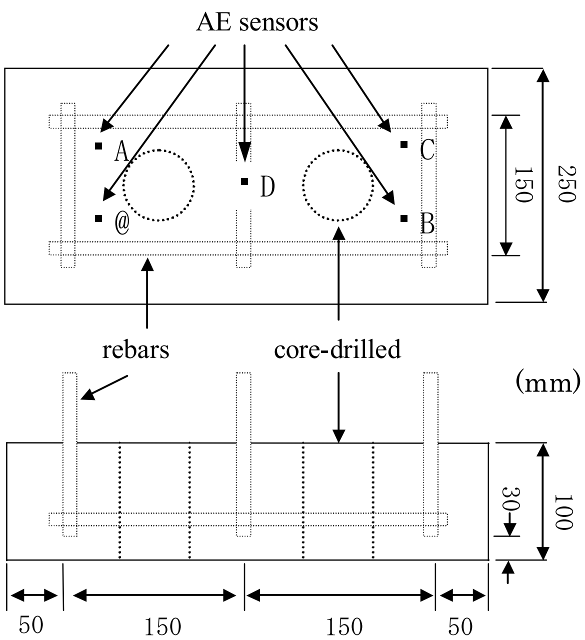

Fig. 3 Sample in the accelerated corrosion test.

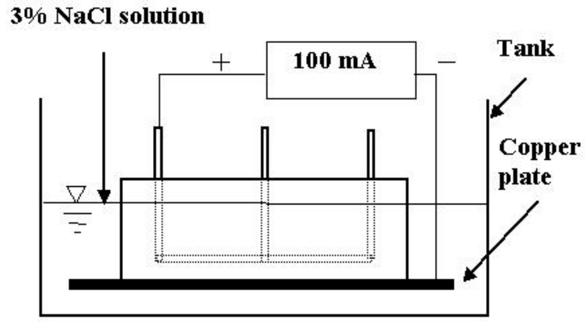

Fig. 4 Set-up for accelerated corrosion test.

RESULTS AND DISCUSSION

(1) Exposure Test

Results of chloride concentration in the exposure test are given in Fig. 5. Here, No. 57 sample is of the same mixture as No. 33 and No. 58 is the same as No. 45. In the case that W/C ratio is as low as 35 %, chloride has penetrated up to around 50 mm after 6 years, while the chloride concentration was little after 1 year. At 1 year later, the penetration of chloride in the concrete of 55% W/C is similar to that of 35% W/C. After 6 years, in contrast, chloride concentration more than 5 kg/m^3 is observed in Fig. 5 (b) even at 5 cm depth. Because the cover thickness was 20 mm and the trigger level of chloride concentration for rebar corrosion is known to be 1.2 kg/m^3, these results suggest that rebars in all the samples could corrode after 6 years or might initiate the corrosion sometime between 1 year and 6 years.

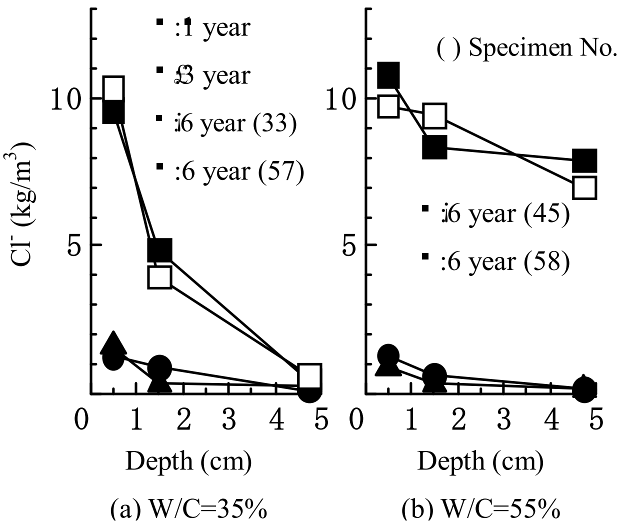

Fig. 5 Chloride concentration in samples of No. 33 and No. 45.

During the test, velocities of ultrasonic waves were measured at the site. Measured points in the sample are illustrated in Fig. 6. Time of flight between neighboring two points was measured, and then the velocity of P wave was calculated. Until 4 years elapsed, no particular variation of velocity distribution was found in the all samples. As seen in Fig. 7 of No. 47 sample, the low velocity is only observed at the pre-crack location. Then, after 4 years, the variations were observed in some samples. In 1998 (after 5 years), the velocities started to decrease entirely in No. 47 sample. This may implies that the corrosion might occur inside concrete. In order to accelerate the corrosion in all the remaining samples, 3% NaCl solution was supplied to the samples right before the test was completed. Thus, the increase in the velocity was observed in 1999.

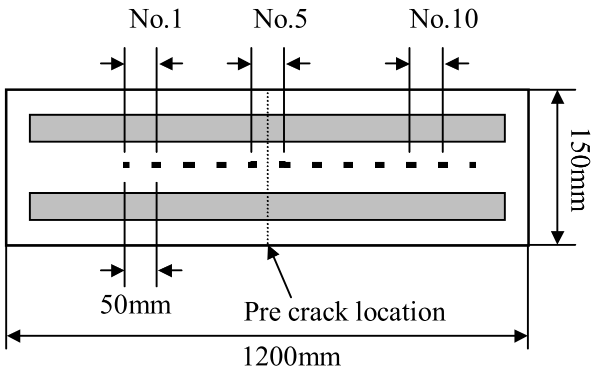

Fig. 6 Measured points in the ultrasonic test

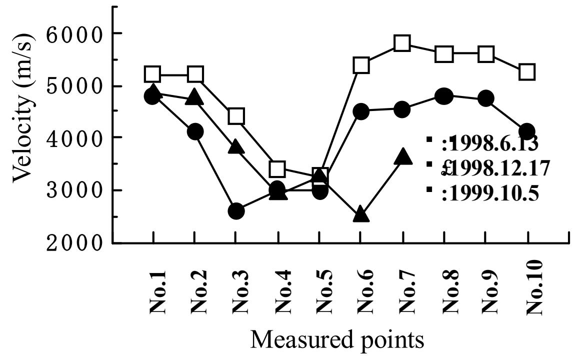

Fig. 7 Velocity distribution in No. 47 sample.

AE measurement was conducted such four times as, at the onset of the measurement, one year elapsed, three year elapsed and just before finish. In each case, AE activity was continuously measured for three months. In the beginning, AE activity was only observed due to rainfalls and no particular events were detected. In the final stage, high AE activity was observed in all the samples following rainfalls. In 1997 (at 4 year elapsed), from September 24 through December 5, remarkable precursor of corrosion was found during AE measurement. These are illustrated in Fig. 8, which shows AE events observed for 72 days. At channels 1 through 5, AE activities due to rainfalls are only observed because all activities are seen on identical days. At channel 6, in contrast, AE events are observed actively, following rainfalls at around 49 days and 60 days elapsed. This suggests that corrosion could be initiated following penetration of water due to rainfalls in No. 47 sample. According to the ultrasonic measurement, the decrease in the velocity was observed after 5 years. From the chloride penetration, it was considered that corrosion might be initiated after 1 year (1994) and before 6 years (1999). AE activity in 1997 suggests the onset of corrosion in No. 47 sample at 4 years elapsed. This result is in reasonable agreement with the results of the ultrasonic test in Fig. 7 and of the chloride concentration in Fig. 5.

(2) <u>Accelerated Corrosion Test</u>

In order to investigate results of the exposure test and confirm an applicability of AE measurement to corrosion monitoring, the accelerated corrosion test was carried out in a laboratory. Three specimens were prepared for each W/C ratio, and the potentiometric titration tests were conducted after the tests. For A45 specimens, core samples were taken after 4 days, 10 days, and 12 days elapsed, while those of 4 days, 8 days, and 10 days were prepared for A55. Then, distributions of chloride concentration in depth were determined. Results are given in Fig. 9. At the location of concrete cover-thickness, chloride ions per m^3 becomes higher than 1.2 kg after 12 days in the case of A45 sample (W/C = 45%). In contrast, it reaches over 1.2 kg after only 8 days for A55 sample (W/C = 55%). This is because the permeability becomes high with the increase in W/C ratio. According to the Standard Specification (JSCE 2001), lower and upper bounds for the corrosion are prescribed as 0. 3 kg/m^3 and 1.2 kg/m^3, respectively.

In order to determine the chloride concentration at rebars, first the coefficients of diffusion, D, were determined from the results in Fig. 9. Then amount of chloride contents, C(t), at the cover-thickness was computed by Fick's law (JSCE, 2001),

$$C(t) = Co(1 - erf(x/2[Dt]^{1/2})). \qquad (1)$$

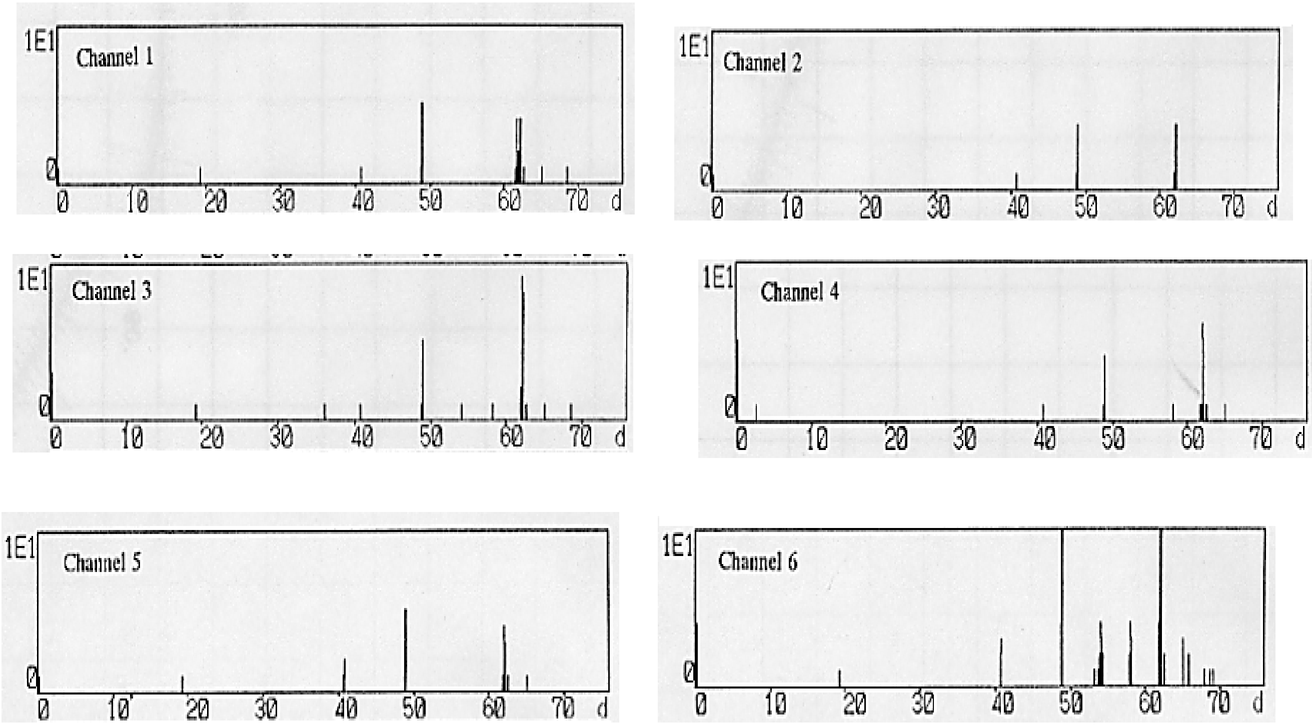

Fig. 8 AE events observed during the exposure test in 1997.

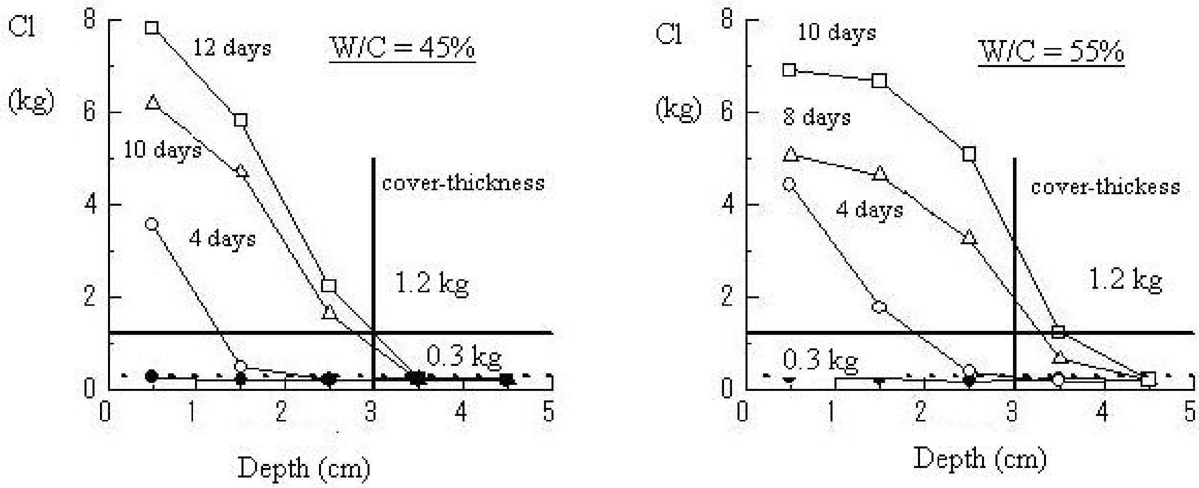

Fig. 9 Distribution of chloride contents in depth.

Where Co is the chloride concentration at the surface, which was estimated by the least-square-approximation, and *erf* means Gauss's error function. Results are compared with AE activities in Fig. 10. Right after the chloride concentration at the cover-thickness becomes higher than the lower bound (0.3 kg), high AE activity is observed in the both samples of A45 and A55. Then, when the chloride contents surpass the upper bound (1.2 kg), another AE activity is observed. At the stage, in addition, the half-cell potential measurement was conducted. It was confirmed that the potentials became lower than –350 mV (C.S. E). These results clarify the presence of two stages on high AE activities, which are observed in the accelerated corrosion test. One is the first stage where the chloride content becomes over 0.3 kg/m^3, and the other is the second stage where the chloride level surpasses 1.2 kg/m^3 in concrete, and the half-cell potentials shift toward lower than –350 mV.

The presence of these two stages are in remarkable agreement with the deterioration process due to salt attack, which is prescribed in the Standard Specification and given as shown in Fig. 11. Two transition stages are prescribed. The first stage corresponding to onset of corrosion, where the transition from the incubation period to the development occurs. At the second stage, nucleation of cracking occurs and the transition from the development period to the accelerated is observed.

According to results in Fig. 10, there clearly exist the two stages of high AE activity. Since the first activity is observed over 0.3 kg/m^3 chloride concentration, it is reasonably considered that onset of corrosion occurs at the stage. The second activity is found after the chloride concentration becomes over 1.2 kg/m^3. Thus, the stage could suggest nucleation of cracking followed by the onset of corrosion. It is obvious that the two stages are readily identified by AE monitoring.

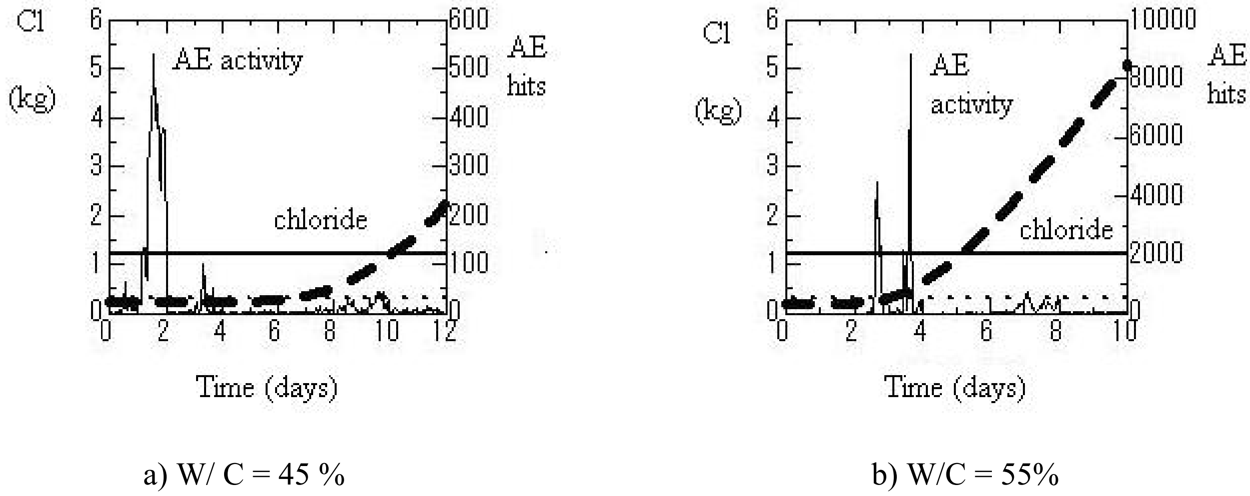

Fig. 10 Comparison between AE activities and chloride contents.

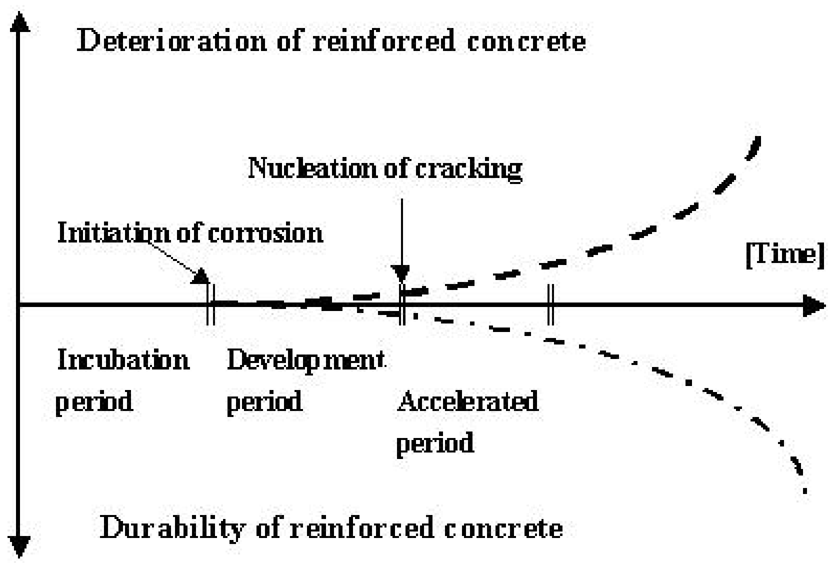

Fig. 11 Deterioration process due to salt attack.

CONCLUSION

Cracking of concrete due to corrosion of rebars in reinforced concrete is one of critical problems in the concrete structures. To develop a monitoring procedure for corrosion, the exposure test against salt attack was conducted at a site constructing the viaduct of Shin-Kitakyushu Airport. In order to confirm these results, comparable tests are performed in a laboratory. Thus, an applicability of AE to monitoring of corrosion in RC structures is confirmed. Results obtained are summarized, as follows:

1. In situ monitoring by AE and ultrasonics had been carried out at the construction site near seashore. According to the results of chloride concentration measured, it was considered that corrosion might be initiated after 1 year and before 6 years.
2. Until 3 years, mostly AE activities due to rainfalls had been only observed. At one sample, AE activities following rainfalls around 49 days and 60 days were observed at 4 years later. This suggests that the corrosion could be initiated following penetration of water due to rainfalls.
3. In order to investigate and confirm the results of the exposure test, the accelerated corrosion tests are conducted. AE occurrence was monitored continuously under electrolytic reaction. Comparing with the permeation of chloride ions, a relationship between chloride concentration and AE activity is clarified. Right after the chloride contents become higher than 0.3 kg, high AE activity is observed. Then, around the stage where the chloride contents surpass 1.2 kg, another AE activity is observed.
4. These two stages of high AE activities correspond remarkably to the deterioration process due to salt attack, where two stages for onset of corrosion from the incubation period to the development, and nucleation of cracking from the development period to the accelerated are prescribed. This suggests that these two stages can be identified by AE monitoring. Thus, an application of in situ AE monitoring to the salt damage in reinforced concrete (RC) members can be proposed as a practical means.

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