

APPLICATION OF CATHODIC PROTECTION ON REINFORCED CONCRETE DETERIORATED BY ALKALI-SILICA REACTION

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Abstract

A cathodic protection method was applied to specimens suffered from the combined deterioration of alkali-silica reaction (ASR) and chloride attack. The purpose of this study was to verify through experiment the effects of cathodic protection on expansion due to ASR.

Specimens were deteriorated by ASR or chloride attack and ASR, by exposing specimens in outdoors or immersing them in salt water for three years after fabrication. These specimens have been operated through 1.0 mA of current volume for approximately two years under the different curing condition. As a result, encouragement of expansion and changes in external appearance caused by the cathodic protection method was not observed. In addition, corrosion protection effects of cathodic protection were recognized.

KEYWORDS: cathodic protection, ASR, expansion, outdoor exposure test, alkali accumulation

1 INTRODUCTION

The cathodic protection has been widely used as a method for suppressing the corrosion of steel reinforcement in a concrete structure. The cathodic protection method is a method of applying the current to the reinforcing steel surface in the concrete from an anode installed on the surface of the structure. In addition, it is method that keeps passing the current to the structure. In general, the current density used by the cathodic protection is from 0.001 to 0.03A/m² and it is very minute. For the cause of the anti-corrosion current, it is reported[1] that the alkali ions may accumulate around the reinforcing steel and it depend on the size of the current density, as shown in Figure 1. For accelerated effect of ASR by cathodic protection method, Page reported that ASR is promoted in the vicinity of the cathode by using small specimens [2]. These results were, however, obtained on the condition of the larger current density than general. In addition, there have been few reports that experimentally examined the effects of cathodic protection method on specimens suffered from ASR or the combined deterioration of chloride attack and ASR.

Under such circumstance, specimens made of reinforced concrete were prepared using reactive aggregates. For three years after manufacture of specimens, the specimens were subject to

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deterioration of ASR or the combined deterioration of chloride attack and ASR, by exposing specimens to outdoors or immersing them in salt water. Later, these specimens were operated through current volume commonly used in cathodic protection method. The purpose of this experiment was to grasp anti-corrosion effects, the transfer of alkali ions due to operation, and the behavior of ASR expansion following operation.

2 OUTLINE OF EXPERIMENT

2.1 Mix proportions

Mix proportions of concrete are given in Table 1. Two types of cement were used: 1) ordinary Portland cement ($\text{Na}_2\text{O}_{\text{eq}}$: 0.556wt%, Na_2O : 0.26wt%, K_2O : 0.45wt%), and 2) blast furnace cement ($\text{Na}_2\text{O}_{\text{eq}}$: 0.407wt%, Na_2O : 0.19wt%, K_2O : 0.33wt%). The water / cement ratio of both mixtures was 0.65% by mass. As coarse aggregates, crushed stone (andesite, density: 2.61 g/cm³) was used, classified as “non-innocuous” according to the chemical method (JIS A 1145-2001 with $\text{Sc}=197$, $\text{Rc}=127$ mmol/l, and $\text{Sc/Rc}=1.6$). For fine aggregate, river sand (density: 2.62 g/cm³) was used, which classifies as “innocuous” ($\text{Sc}=33$, $\text{Rc}=61$ mmol/l, $\text{Sc/Rc}=0.54$). The $\text{Na}_2\text{O}_{\text{eq}}$ of the concrete was adjusted to 6.0 kg/m³ using 10 mol/l NaOH solution. A specimen was made to be a cubic form of 600×600×600 mm as shown in Figure. 2. Two types of variant reinforcing steel (D10 and D13) were distributed in cage shape, and reinforcing steel ratio at each side of A-D was set at 0.266%.

2.2 Exposure conditions

Exposure conditions are summarized in Table 2. A specimen was subject to formwork removal on the following day, and subject to 28 days of spray curing. Specimens 1N, 3B and 5N were exposed to outdoors. Specimens 2N, 4B and 6N were immersed in salt water (30 g NaCl/l) up to the height of 2/3 of a specimen in a laboratory without air-conditioning facilities. After 1,052 days of exposure test, a specimen was transferred to outdoors environment, and an operation test was applied to evaluate the applicability of cathodic protection method to ASR. In order to adjust exposure conditions in outdoors environment to the ebb and flow of oceanic environment, saltwater (30 g NaCl/l) spraying and natural drying were repeated every six hours.

The setting place of anodes and used anodes are shown in Figure. 3. An impressed current system was adopted as the cathodic protection method, and titanium ribbon mesh was used as an anode material. On the operation specimens, in order to examine the presence or absence of the effects of operation, anode material setting sides (C and D) and non-setting sides (A and B) were installed, and 12 anode materials, each 6 for C and D sides, were fixed. Then, various tests were applied to determine proper current volume, using these 12 anodes. Thereafter, with focus on current volume that affects ion movement quantity, current volume of 1.0 mA was uniformly applied to four anodes indicated in Figure. 3, since 1,053th day of the exposure test.

2.2 Assessment during exposure

The examination items and measurement positions in this study are shown in Table 3 and Figure 3. Before applying cathodic protection, the following tests were conducted: Measurement of strain on the surface and of the inside of concrete, observation of the surface appearance, measurement of the natural potential of reinforcing steel, measurement of chloride content (JCI-SC5), and measurement of water-soluble alkali content (atomic absorption analysis of the solution after warm-water extraction at 40°C). During applying the cathodic protection, the following tests were conducted: Test on depolarization shift, measurement of the surface strain of concrete, observation of the surface appearance, and measurement of concrete core expansion. In addition, through sampling concrete cores from the specimens after applying operation for approximately two years, the following tests were conducted: Measurement of water-soluble alkali content, test on compressive strength (JIS A1107 and JIS A1108), and test on elastic modulus (JIS A1149). In addition, by digging up reinforcing steel inside the concrete, the following tests were conducted: Measurement of rust development area (to sketch the rust development conditions of reinforcing steel and to measure rust development area), and measurement of the rust mass of reinforcing steel (after immersing reinforcing steel in diammonium hydrogen citrate solution at 35°C for 24 hours, the rust mass was calculated from the difference in the mass before and after immersion).

3 RESULTS

The measurement results of degradation of specimens before operation are shown in Figure 4, 5, 6 and Table 3. Figure 4, 5 and 6 shows the observation results of the surface appearance, change with time of concrete surface strain, and change with time of concrete internal strain. Table 3 shows

the corrosion conditions of reinforcing steel.

The measurement results of anti-corrosion effects are shown in Figure 7 and 8. Figure 7 shows the relationship between the mass decrease rate and rust development area rate of reinforcing steel. Figure 8 shows the average measurement values of depolarization shift at each measurement point during the operation (refer to Fig. 2).

Concrete cores were sampled from specimens 5N and 6N, which were not treated with cathodic protection method. Then, the concrete cores were immersed in saturated NaCl solution at 50°C, and residual expansion quantity was measured. The measurement results are shown in Table 5.

The effect of the cathodic protection on alkali silica expansion was investigated. The distribution of $\text{Na}_2\text{O}_{\text{eq}}$ accumulation and the change with time of $\text{Na}_2\text{O}_{\text{eq}}$ accumulation after operation are shown in Figures 10 and 11, respectively. And the observation results of the surface appearance change with time of surface stain, and measurement results of elastic modulus are shown in Figs. 12, 13 and 14, respectively.

4 DISCUSSION

4.1 Deterioration conditions before application of operation

The observation results of the surface appearance show that on the ordinary cement specimens, cracking of hexagonal patterns on specimen surface and cracking along reinforcing steel were generated. From the change with time of surface and internal strain, expansion behavior similar to that in the report of the previous study [3] was observed: Stepwise expansion behavior showing seasonal changes that was features to concrete structure by the ASR expansion, where expansion was encouraged during summer with higher temperatures and gradually suppressed in winter with lower temperatures.

On the other hand, on the blast furnace cement (3B and 4B), both the surface strain and internal strain of concrete before operation a little changed due to only temperature changes, and large strain due to ASR was not recognized.

The specimens of outdoors exposure (1N, 3B and 5N) had a little chloride quantity and their natural potential showed noble value of around -100 mV. According to the evaluation criteria of ASTM C876 [4], this steel was judged as “without corrosion with probability of 90% or above.”

On the specimens of saltwater immersion, the measurement results of the middle part of immersion and the outside part of immersion are respectively shown in Table 4. The specimens of saltwater immersion (2N and 6N) had approximately -550 mV of natural potential, which was judged to be “with corrosion with probability of 90% or above” according to the evaluation criteria of ASTM C876. In addition, chloride quantity at the position of reinforcing steel exceeded 1.2 kg/m^3 of the critical mass of reinforcement corrosion by large margin. These results suggested that reinforcement corrosion inside the specimens have progressed.

From the above results, regarding the deterioration conditions of ordinary cement specimens before application of cathodic protection process, the specimens of air exposure (1N and 5N) were considered to have sole deterioration due to ASR. The specimens of saltwater immersion (2N and 6N) were considered to have the combined deterioration of ASR and chloride attack.

The reinforcing steel outside salt water of the blast furnace specimens was judged to be “with corrosion with probability of 90% or above,” and that of inside salt water was judged to be “uncertain,” according to ASTM C876. The chloride quantity was smaller than 1.2 kg/m^3 as the critical mass of reinforcement corrosion. From these results, although the reinforcing steel corrosion of specimen 4B was progressing, the reinforcing steel corrosion of specimen 4B was trivial compared with that of ordinary cement specimens.

Regarding the deterioration conditions of the specimens made of blast furnace cement before applying cathodic protection method, specimen 4B was considered to have suffered deterioration due to chloride attack, while specimen 3B was considered to be sound state.

4.2 Anti-corrosion effects and effect radius due to operation

After applying the cathodic protection method, the reinforcing steels in the vertical direction at four corners shown in Figure.7 were dug out. Then, in order to confirm the anti-corrosion effects on reinforcing steel, measurement of the rust development area rate and mass decrease quantity of the dug-out reinforcing steels was conducted.

Although the corrosion of reinforcing steel in the specimens of outdoors exposure (1N, 3B and 5N) was only slightly recognized, the specimens were mostly sound independently of existence of operation. The depolarization shift of specimens 1N and 3B satisfied the anti-corrosion control standard of 100 mV shift at all measurement positions.

Under saltwater spraying environment, judging from Figure.8, operation specimen 2N looked not to have obtained sufficient anti-corrosion effects compared with non-operation specimen 6N. In conventional studies, Kawamata et al [5] report that under severe corrosive conditions, 200 mV or above of shift quantity was necessary. In Figures 8 and 9, anti-corrosion effects were recognized in rebar (1) just under operation with approximately 250 mV of depolarization shift of specimen 2N. From this result, it was suggested that for corrosion protection under saltwater spraying environment, 250 mV or above of shift was required.

The rebar of specimen 4B, which used blast furnace cement, showed a nearly sound condition, and its depolarization shift satisfied 250 mV or above.

Above data suggest that specimens 1N, 3B and 4B showed corrosion protection effects in all positions of specimens and specimen 2N showed corrosion protection effects just under operation.

4.3 Effects of operation on RC structure suffering from ASR

Measurement of residual expansion on concrete cores

One out of two cores sampled from specimen 5N showed 0.1% or above of expansion rate. This fact suggests that when alkali ions are supplied from outside, residual expansion property due to ASR probably exists. In addition, when alkali ions concentrate at near reinforcing steel by applying cathodic protection method, expansion property may appear.

Effect of cathodic protection on alkali ions

From Figure 10, it was judged that the $\text{Na}_2\text{O}_{\text{eq}}$ quantity of outdoors exposure specimens tended to be high at near reinforcing steel independently of existence or absence of operation. In addition, as for the $\text{Na}_2\text{O}_{\text{eq}}$ quantity before application of operation in Figure 11, it also showed high tendency at near reinforcing steel 4-6 cm from specimen surface. On the other hand, the $\text{Na}_2\text{O}_{\text{eq}}$ quantity of saltwater spraying specimens tended to be high at near the reinforcing steel of ordinary cement specimens 2N and 6N, and at near the reinforcing steel and surface part of blast furnace cement specimen 4B. These results were similar in the distribution of $\text{Na}_2\text{O}_{\text{eq}}$ accumulation before operation, which suggested that effects of operation were minor.

In Figure 11, alkali inside the concrete tended to decrease as time passed. The prominent accumulation of alkali ions at the position of reinforcing steel was not recognized. As the causes for $\text{Na}_2\text{O}_{\text{eq}}$ accumulation decrease, conventional papers [6,7] reported as follows: 1) elution of alkali in concrete due to intrusion of rainwater through the crack on concrete surface, 2) carbonation due to the inflow of carbon dioxide through the crack, 3) consumption of alkali ions due to ASR. This study also suggested that decrease in $\text{Na}_2\text{O}_{\text{eq}}$ quantity occurred due to these causes.

The above results showed that when operation was applied with minute current volume, accumulation of alkali ions at near reinforcing steel was not recognized, which suggested the effects were minor.

Effect of cathodic protection on ASR

The elastic modulus was measured on the concrete cores sampled from specimens after operation, together with compressive strength of the sampled concrete cores.

In specimens using ordinary cement, independently of existence of operation, change with time of surface strain showed stepwise expansion behavior showing seasonal changes, where expansion was encouraged in summer and gradually decreased in winter, in the same way as in the specimens before operation. Although strain showed a slightly large value at the operation position of specimen 2N, prominent encouragement of ASR expansion did not appear. The observation results of the surface appearance and the measurement of elastic modulus showed nearly the same tendency independently of existence of operation. On the other hand, specimens 3B and 4B, which used blast furnace cement, did not show expansion trend and decrease in elastic modulus specific to reinforced concrete deteriorated by ASR, which suggested the absence of effects of operation.

The above results showed that when minute current was passed on reinforced concrete deteriorated by ASR, prominent ASR expansion was not recognized.

5 CONCLUSIONS

- (1) Under the general current density, cathodic protection is applicable as a method to a concrete structure suffering from ASR.
- (2) In corrosion protection under conditions of repeated wetting and drying due to saltwater spraying, potential shift of 250 mV or above is required.
- (3) As a result of operation with 1.0 mA of current volume, accumulation of alkali ions at near

reinforcing steel working as a cathode is scarce, and its effects are minor. Encouragement of ASR expansion due to operation is not recognized.

6 REFERENCES

- [1] Kuroi, T (1989): A fundamental study on reinforced concrete subjected to electrolysis. Journal of Materials, Concrete Structures and Pavements (10): 3-42.
- [2] Page, CL, Sergi, G, and Thompson, DM (1992): Development of alkali-silica reaction in reinforced concrete subjected to cathodic protection. In: Poole, AB (editor): Proceedings of the 9th International Conference on Alkali-Aggregate Reaction in Concrete, London, United Kingdom: 774–781.
- [3] Takeuchi, K, Kawamura, M, Torii, K, and Tanikawa, S (1995): Concretes under the natural environment. Concrete Research and Technology (6): 38-46.
- [4] ASTM C 876-91 (1999): Standard test method for half-cell potentials for uncoated reinforcing steel in concrete. American Society for Testing and Materials, West Conshohocken, PA.
- [5] Kawamata, K, Takekawa, K, and Mariyasu, Y (1997): Study on potential shift criterion of cathodic protection for concrete structure. Proceedings of the Japan Concrete Institute (19).
- [6] Diamond, S (1996): Alkali reactions - some paradoxes. In: Shayan, A (editor): Proceedings of the 10th International Conference on Alkali-Aggregate Reaction in Concrete, Melbourne, Australia: 3-14.
- [7] Kagimoto, H, Sato, M, and Kawamura, M (2000): Evaluation of the degree of deterioration in ASR damaged concretes and analyses of their pore solutions. Journal of Materials, Concrete Structures and Pavements (46): 241-251.

TABLE 1: Proportions of the concrete mixes used

| Type of cement | W/C (%) | s/a (%) | Slump (mm) | Air (vol%) | content (kg/m ³) | | | | mix quantity(ml/m ³) | | Total alkali(kg/m ³) |
|----------------|---------|---------|------------|------------|------------------------------|-----|-----|-----|----------------------------------|--------------------|----------------------------------|
| | | | | | W | C | S | G | AE water reducing agent | AE auxiliary agent | |
| OPC | 65 | 47 | 80±20 | 4.5± | 175 | 269 | 858 | 968 | 2700 | 1614 | 6.0 |
| BFC | | | | 1.5 | | | 853 | 963 | | | |

OPC: ordinary Portland cement, BFC: blast furnace slag cement
 AE water reducing agent uses 25% solution, AE auxiliary agent uses 25% solution

TABLE 2: Experimental exposure conditions

| Specimen No. | Type of cement | Condition | | Cathodic Protection |
|--------------|----------------|----------------------------|----------------------|--------------------------|
| | | Before operation | During the operation | |
| 1N | OPC | Outdoor | | ~1.0mA of current volume |
| 2N | | Immersed in the salt water | Salt spray | |
| 3B | BFC | Outdoor | | |
| 4B | | Immersed in the salt water | Salt Spray | |
| 5N | OPC | Outdoor | | none |
| 6N | | Immersed in the salt water | Salt spray | |

TABLE 3: Assessment methods during/after exposure to cathodic protection

| Time interval | assessment methods |
|--------------------|--|
| Before current | Strain of the concrete on its surface and of the inside of the concrete, Development of cracking of concrete, Natural potential of steel, Chloride quantity(JCI-SC5), Alkali content (the solution extracted in 40 warm water was carried out by the atomic absorption spectrometry) |
| During the current | Depolarization shift, Strain of the concrete on its surface and of the inside of the concrete, Development of cracking of concrete, Core expansion |
| After current | Alkali content assay(EPMA, Alkali content), Elastic modulus(JIS A 1107, JIS A 1108, JIS A 1149), Rust development area, Weight of rust |

TABLE 5: Residual expansion

| Specimen | Residual expansion (in % ℓ/ℓ) | |
|----------|--|------|
| 5N | No.1 | 0.11 |
| | No.2 | 0.06 |
| 6N | No.1 | 0.05 |
| | No.2 | 0.06 |

| TABLE 4: Corrosion condition of reinforcement steel bars. According to ASTM C876 | | | | |
|--|-----------------------|--------------------------|--|---------------------------|
| Specimen | potential (mV vs CSE) | probability of corrosion | chloride content at steel surface (kg/m ³) | note |
| 1N | -83 | Less than 10% | - | |
| 2N | -556 | Greater than 90% | 3.68 | Outside part of immersion |
| | -533 | | 1.54 | Middle part of immersion |
| 3B | -60 | Less than 10% | 0.12 | |
| 4B | -375 | Greater than 90% | 0.55 | Outside part of immersion |
| | -315 | 50% | 0.14 | Middle part of immersion |
| 5N | -58 | Less than 10% | 0.14 | |
| 6N | -577 | Greater than 90% | - | Outside part of immersion |
| | -536 | | - | Middle part of immersion |

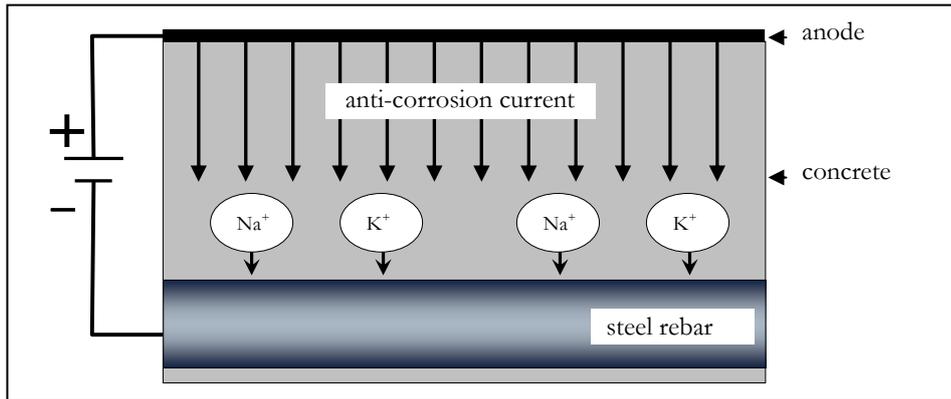


Figure 1: Movement of alkali ions induced by anti-corrosion current

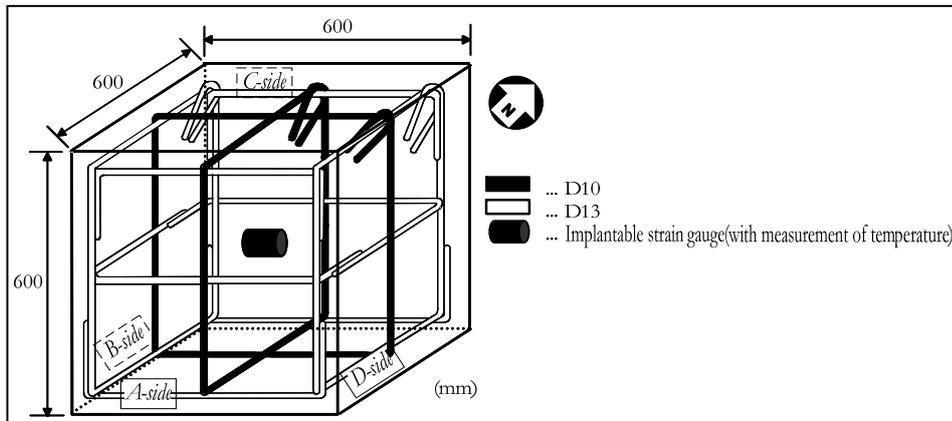


Figure 2: Specimen dimensions and geometry

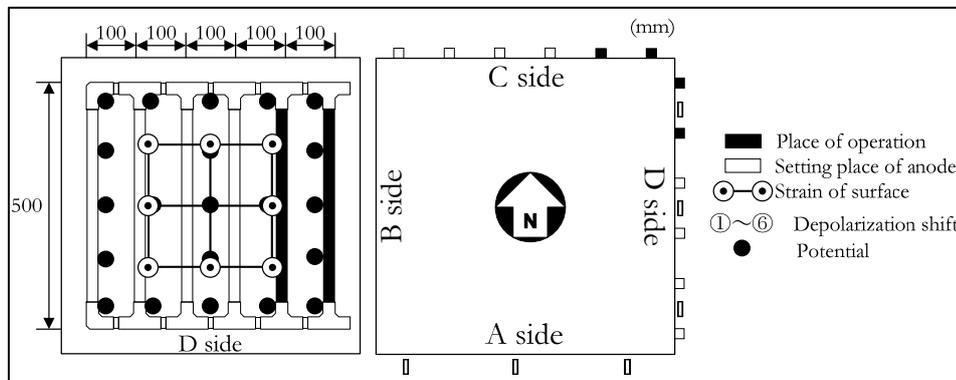


Figure 3: Positioning of anodes and location of measurement

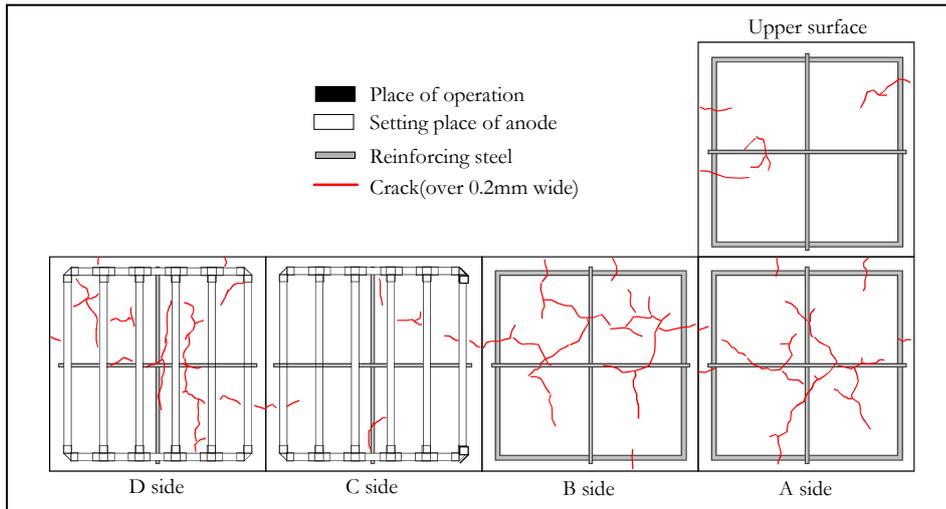


Figure 4: Development of concrete cracking of specimen 1N

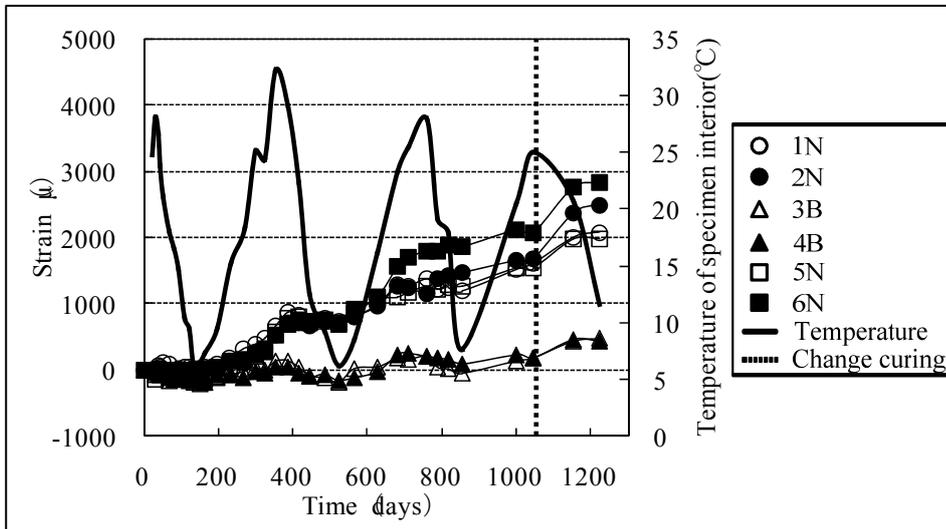


Figure 5: Development of surface strain over time (in days)

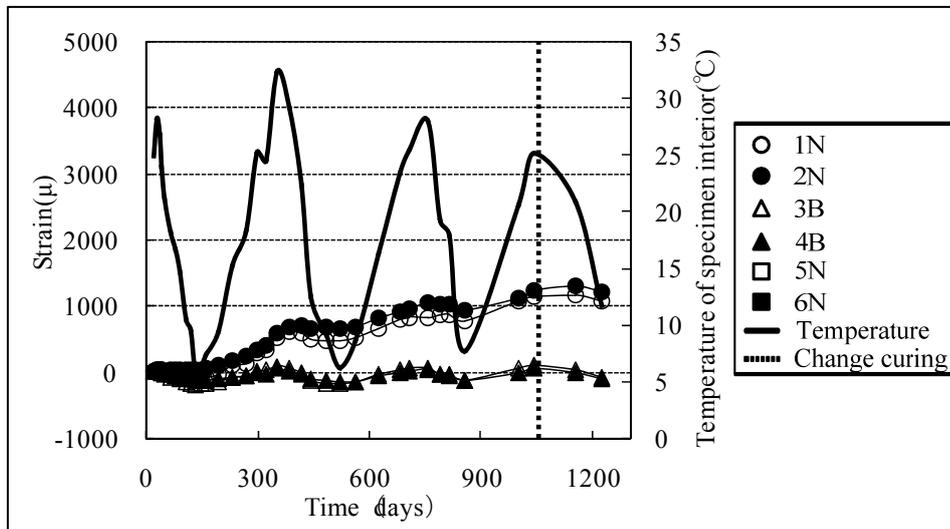


Figure 6: Development of interior strain over time (in days)

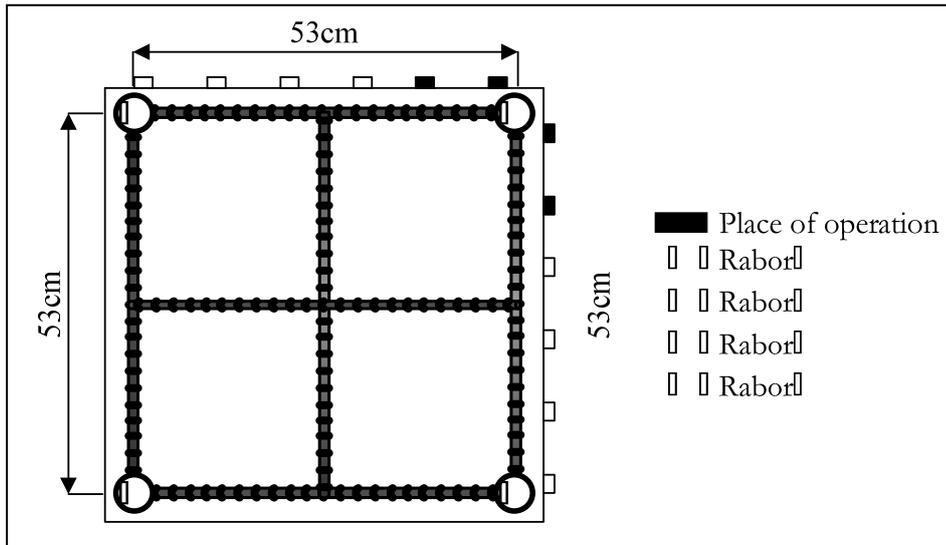


Figure 7: Positioning of the steel corrosion assessment

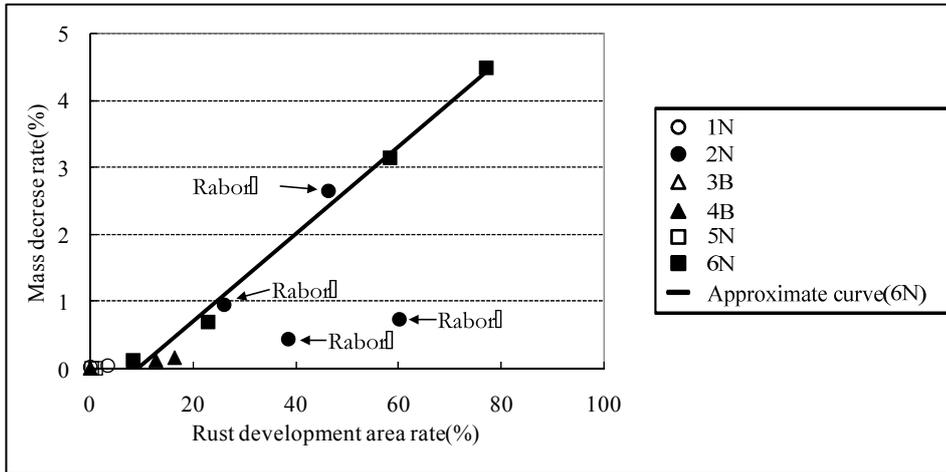


Figure 8: Relationship between rust development area rate and mass decrease rate

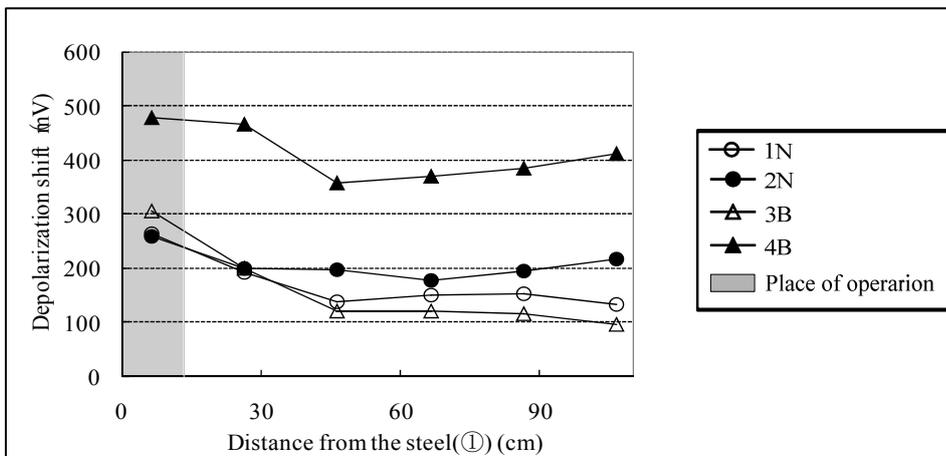


Figure 9: Depolarization shift with distance from steel surface

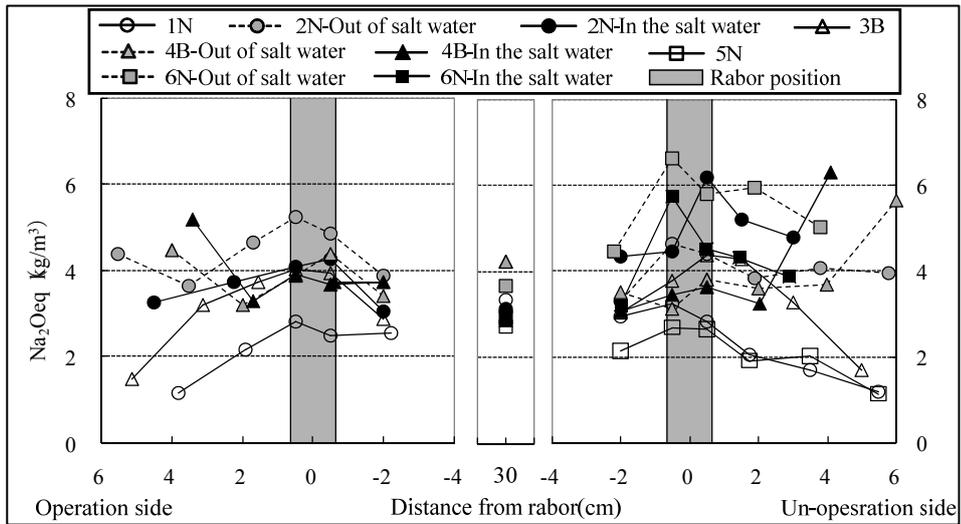


Figure 10: $\text{Na}_2\text{O}_{\text{eq}}$ distribution (after applied CP current)

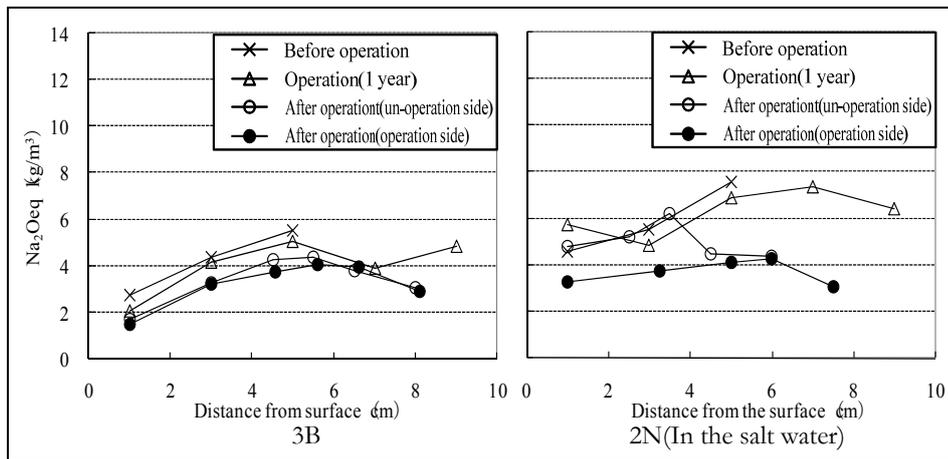


Figure 11: development of $\text{Na}_2\text{O}_{\text{eq}}$ distribution with time

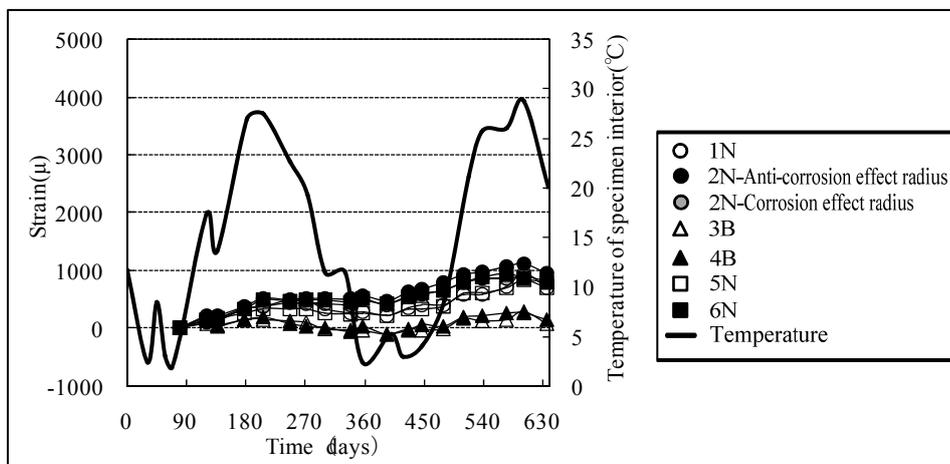


Figure 12: Development of surface strain of the concrete time

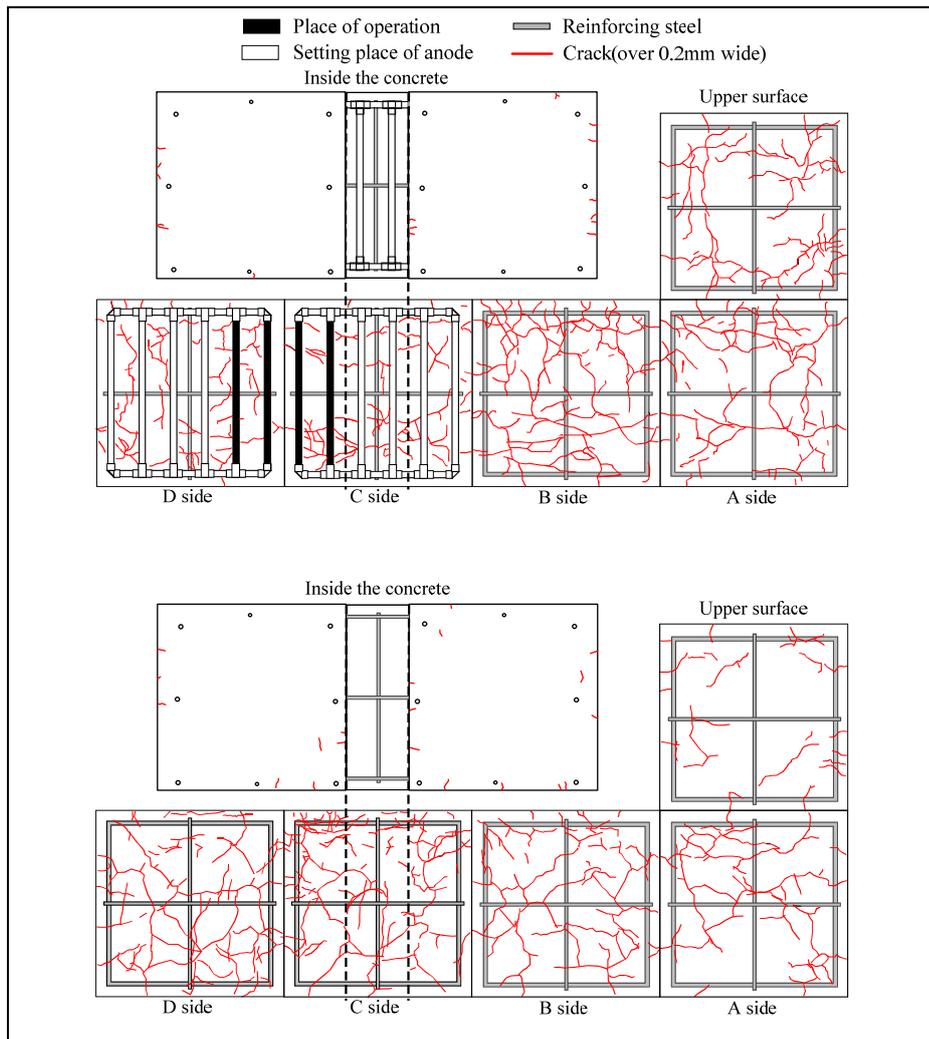


Figure 13: Development of surface cracking of specimen 2N and 6N

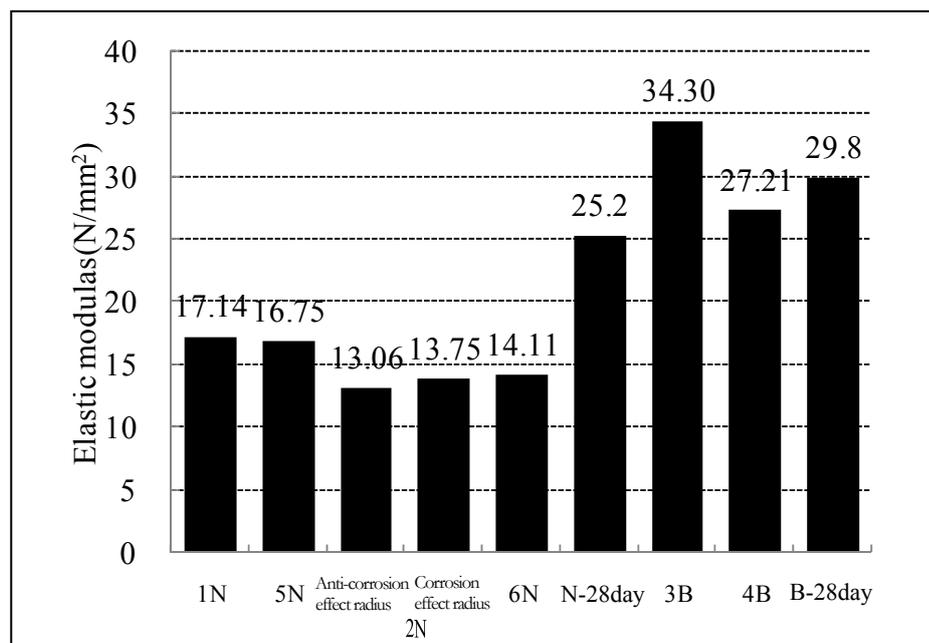


Figure 14: Elastic module