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Influence of Surface Treatment after Applying Electrochemical Repair Method on Protection Effect against Steel Corrosion in Concrete

Kazuhide Nakayama¹, Takao Ueda²*, Masayuki Tsukagoshi³ and Akira Nanasawa⁴

Abstract

Realkalisation and desalination are electrochemical repair methods for reinforced concrete structures damaged by carbonation and chloride attack respectively. After completing realkalisation and desalination, surface protection method could be applied for sustaining the repair effect of electrochemical repair methods for a long time. However, past papers reported that the surface coating materials are sometimes deteriorated at an early stage due to the highly alkaline atmosphere of concrete after the application of the electrochemical repair method. In this research, the performance of surface treatment materials applied to the concrete after realkalisation or desalination was investigated. Furthermore, the protection effect of the surface treatment against steel corrosion after realkalisation and desalination under the condition of accelerated carbonation or chloride attack was estimated by measuring electrochemical steel corrosion indexes. As a result, the bond strength of polymer-cement mortar (PCM) or epoxy resin on concrete applied realkalisation maintained the sound level through the accelerated carbonation for 2 years. Moreover, the re-passivation of the steel in concrete after desalination occurred more quickly in the cases of silane-based impregnation than in the cases of PCM or epoxy resin.

1. Introduction

Realkalisation and desalination are effective repair methods for structures damaged by steel-corrosion due to carbonation and chloride attack of concrete respectively (Ueda et al. 1998; Othieno et al. 2016; Gonzalez et al. 2000; Gonzalez 2011), and the cases applying these repair techniques have been increased gradually (Luca 2008; Cromie 1999; Miyagawa 2000). However, the long term repair effect of these electrochemical treatments has not been clarified. Recent investigations reported that the repair effect of realkalisation and desalination had been maintained for approximately 20 years (Ashida 2004; Nomura 2012). After realkalisation or desalination, surface protection method is sometimes applied in order to prevent the ingress of the deterioration factors like chloride ions (Cl⁻) or carbon dioxide (CO₂) from the concrete surface for achieving longer protection effect against steel corrosion after the electrochemical repair methods. Whereas, alkalinity and moisture content in concrete after realkalisation or desalination are higher than the case of non-treated concrete due to an electric osmosis of the high alkaline electrolyte and generation of the hydroxyl ions by the cathodic reaction occurred around the rebar (Ribeiro 2013; Liu 2014). Therefore, it was pointed out that the surface coating materials after the removal of the anode system of realkalisation or desalination sometimes deteriorated at an early stage (Nomura 2004). Previous research (Nomura 2004) was conducted as an experimental investigation that using concrete specimens which applied various kinds of surface coating after immersing potassium carbonate solution (K₂CO₃). However, there are few researches investigating the effectiveness of surface coating after applying realkalisation or desalination.

From this background, this study conducted an experimental investigation to clarify the protective effect of surface treatment against steel corrosion after realkalisation or desalination under the condition of accelerated carbonation or chloride attack by employing electrochemical indexes. Furthermore, the influence of realkalisation or desalination on the bond strength and the water-permeability of surface treatment applied to the concrete after realkalisation or desalination was also investigated.

2. Experimental program

2.1 Materials and preparation of specimen

The specimens prepared for this study were RC prisms (100×100×250 mm), in which, a deformed steel bar D13 SD295A (JIS number) was embedded at the center of the square section (refer to Fig. 1). The mix proportion of the concrete used for the specimens is shown in Table 1. The water cement ratio (W/C) of concrete was 60 %. Ordinary portland cement (density: 3.16 g/cm³), fine aggregates (density: 2.56 g/cm³, F.M.: 2.63) and the coarse aggregate (Gmax: 15mm, density: 2.55 g/cm³) were used.
An amount of premixed $\text{Cl}^-$ was $2.0 \text{kg/m}^3$ in the specimens for realkalisation assuming the concrete using sea sand without the desalting process. This amount should be around the critical $\text{Cl}^-$ content for the initiation of steel corrosion. On the other hand, the specimens for desalination premixed $\text{Cl}^-$ of $8.0 \text{ kg/m}^3$, which is assumed to cause the severe chloride-induced corrosion of steel. The premixed NaCl was dissolved in the mixing water. All specimens were cured for 28 days in the moist condition at the temperature of 20°C. After curing, five faces of each specimen were insulated with epoxy resin coating, excepting one exposed surface (100×210 mm) as shown in Fig. 1.

2.2 Electrochemical treatment
After epoxy resin coating, the electrochemical treatment was applied to the RC specimens, the direct electric current was applied between the titanium meshes and the steel in concrete. The electric current density was constantly 1.0 A/m$^2$ to the concrete surface. The treated periods were 2 weeks for realkalisation and 8 weeks for desalination. As the electrolyte solution, 1.5 N K$_2$CO$_3$ solution for realkalisation and 0.1 N Li$_3$BO$_3$ solution for desalination were selected respectively. In addition, non-treated control specimens in each case were prepared, and placed in a moist and a constant temperature (20°C) condition during the period for electrochemical treatment.

2.3 Application of surface treatment
Surface water content of the specimens was controlled to around 8% in a room of 60% R.H. and 20°C before applying surface treatment to the exposed surface. Three kinds of surface treatment, epoxy resin coating, PCM coating and silane-based impregnation were selected. Details of surface treatment are shown in Table 2. All surface treatment were cured for 14 days in a room of

| Table 1 Mix proportion of concrete. |
|-----------------------------------|
| Type of the electrochemical treatment | W/C (%) | s/a (%) | Gmax (mm) | C | W | S | G | WRA | AEA | NaCl |
|-----------------------------------|---------|---------|-----------|-----|---|---|---|-----|-----|------|
| Realkalisation                    | 60      | 48      | 15        | 300 | 180| 826| 895| 0.9 | 0.019| 3.3  |
| Desalination                      |         |         |           |     |    |    |    |     |     | 13.2 |

60% R.H. and 20°C. The appearance of 3 kinds of surface treatment are shown in Fig. 2. Specimens without surface treatment were also prepared.

2.4 Various tests after electrochemical treatment followed by surface treatment
2.4.1 Chemical analysis of concrete
Distribution profiles of ion content ($\text{Cl}^-$, $\text{Na}^+$, $\text{K}^+$) and pH distribution in the concrete were measured immediately after the electrochemical treatment using powder samples grinded from concrete plates cut out from a specimen as shown in Fig. 3. The $\text{Na}^+$ and $\text{K}^+$ contents were
measured by means of atomic absorption spectrometry using a crushed fine powder sample dissolved by HNO₃ solution. Total Cl⁻ content and water soluble Cl⁻ content were measured according to JIS A 1154. For measuring pH values, sample solution was prepared by mixing 12.5 g of crushed fine powder and 25 ml of pure water, and a pH electrode was used for the measurement. The dilution ratio (sample powder/water) was determined from referring past papers (Behnood et al. 2016; Francisco 2007; Räsänen and Penttala 2004).

### 2.4.2 Measurement of electrochemical indexes of steel corrosion in specimens stored in steel corrosion environment

After applying surface treatment, the specimens for realkalisation were kept in accelerated carbonation environment (20°C, 60% R.H., 5% CO₂), and the specimens for desalination were kept in spraying salt water condition (cyclic spraying 5% NaCl solution for 21 hr and drying for 3 hr in 35°C). The list of specimens used in this research is shown in Table 3. The number of specimens for each experimental factor was two.

During the storage in the accelerated deterioration environment, electrochemical steel corrosion indexes (half-cell potential, polarization resistance and concrete resistivity) were measured at regular intervals for all specimens. As a reference electrode, saturated Ag/AgCl was used, and as a counter electrode, titanium mesh was used. Polarization resistance was measured by the rectangular wave electric current polarization method. The impedance values at 800 Hz and 0.1 Hz were used for

| Name | Current Density (A/m²) | Electrolyte solution | Surface coating | Accelerated condition after Surface treatment |
|------|-----------------------|----------------------|----------------|-----------------------------------------------|
| NR   | 1.0                   | 1.5N K₂CO₃           | Epoxy          | Spraying of salt water condition for 24 months |
| R-E  |                       |                      | PCM            |                                               |
| R-P  |                       |                      | Silane         |                                               |
| R-S  |                       |                      |                |                                               |
| ND   |                       |                      | Epoxy          |                                               |
| ND-P |                       |                      | PCM            |                                               |
| ND-S |                       |                      | Silane         |                                               |
| D    |                       |                      |                |                                               |
| D-E  |                       |                      | Epoxy          |                                               |
| D-P  |                       |                      | PCM            |                                               |
| D-S  |                       |                      | Silane         |                                               |

### Table 3 List of concrete specimens.

![Fig. 3 Cutting of concrete specimen for chemical analysis](image)

![Fig. 4 Measuring situation of electrochemical indexes of steel corrosion](image)
calculating concrete resistivity. For the electrochemical measurement after applying surface treatment, a 20 mm square part of epoxy resin coating at the center of the opposite surface to that for surface treatment was opened (refer to Fig. 1, Fig. 4(a)). In addition, concrete resistivity of specimens without surface treatment and specimens applying silane-based impregnation were measured from the exposed surface as shown in Fig. 4(b). After measuring electrochemical steel corrosion indexes, the square measurement window was sealed by an aluminum tape to prevent the penetration of deterioration factors such as water and Cl\(^-\) during the accelerated deterioration. Moreover, the contact angle of a water drop on the concrete surface applied silane-based impregnation was measured for evaluating water-repellent effect of the surface. The contact angle was measured by using the close up photo of a water drop with 2mm in diameter, as shown in Fig. 5.

2.5 Various tests using specimens for realalkalisation after accelerated carbonation for 24 months

After the accelerated carbonation for 24-months, the distribution profiles of ion content (Cl\(^-\), Na\(^+\), K\(^+\)) and pH distribution in concrete of the specimens for realalkalisation were measured by the methods shown in 2.4.1 In addition, carbonation depth of concrete was measured according to JIS A 1152. Moreover, the bond strength of epoxy resin and PCM coating after accelerated carbonation for 24 month were measured according to JSCE-K-531-2013. The water permeability of the surface was measured using the all specimens after accelerated carbonation for 24 months according to JSCE-K-571-2005.

3. Results and discussions

3.1 Distribution of Cl\(^-\) and R\(_2\)O content in concrete just after electrochemical treatment

Distribution curves of Cl\(^-\) content in the concrete just after completing electrochemical treatment are shown in Fig. 6. The origin of horizontal axis in Fig. 6 corresponds to the exposed surface and the steel bar is located at the center (43.5 mm from the exposed surface) of each specimens. The Cl\(^-\) content around the steel bar and cover concrete area is decreased by the desalination from 8.0 kg/m\(^3\) of premixed Cl\(^-\). However, Cl\(^-\) extracting from the 2.0 kg/m\(^3\) premixed Cl\(^-\) was not remarkable after the realalkalisation. The reason for this would be that the treatment period of the realalkalisation was shorter than that of desalination. Moreover, most of the premixed Cl\(^-\) was fixed as the Friedel’s salt, because the premixed Cl\(^-\) in the specimens for realalkalisation was relatively low.

The distributions of Na\(^+\) and K\(^+\) content in the concrete just after the electrochemical treatment are shown in Fig. 7. The distribution of R\(_2\)O as total amount of alkali and pH in the concrete just after completing electrochemical treatment are shown in Fig. 8. The amount of R\(_2\)O is calculated by Equation. 1.
According to Fig. 8, the specimens subjected to desalination show generally high pH level distribution, and the pH level around the steel bar is the highest, because Na\(^+\) ions in the concrete accumulated by electrophoresis (refer to Fig. 7). While, in the specimens subjected to realkalisation, the pH level value around the concrete surface becomes highest, because of the K\(^+\) ions introduced from the electrolyte (K\(_2\)CO\(_3\) solution) by electro-osmosis with realkalisation (refer to Fig. 7). The high alkali condition at the concrete surface just after the realkalisation could cause the early deterioration of surface treatment materials applied after the electrochemical treatment.

### 3.2 The appearance of specimens applied surface coating after electrochemical treatment under accelerated deterioration environment

The appearance photos of specimens applied surface treatment after electrochemical treatment followed by the accelerated deterioration for 24 months are shown in Figs. 9 and 10. The names of the specimens are defined in Table 3.

![Fig. 8 Distributions of R\(_2\)O in concrete just after completing electrochemical treatment.](image)

![Fig. 9 Appearance of specimens applied surface treatment after realkalisation followed by the accelerated carbonation for 24 months.](image)

![Fig. 10 Appearance of specimens applied surface treatment after desalination followed by the spraying of salt water condition for 24 months.](image)
Significant change, bob float, blistering, of the appearance of the surface coating after the accelerated carbonation for 24 months or spraying of salt water for 24 months was not observed regardless of the kind of the electrochemical treatment or the kind of surface coating. However, the specimens for desalination coated by PCM turned a little white and the specimens coated by epoxy resin lost gloss compared with the condition before the salt water spraying. These changes in the appearance of the surface coating could be caused by the physical effect like erosion due to salt water spraying rather than the chemical effect of desalination.

3.3 The performance of surface treatment applied after electrochemical treatment under accelerated deterioration environment

3.3.1 The performance of silane-based impregnation applied after the electrochemical treatment

The variation curves of the contact angle of a water drop on the concrete surface applying silane-based impregnation are shown in Fig. 11. According to Fig. 11, under accelerated carbonation environment, the water contact angles of the realkalisation specimens (R-S) maintains a water-repellent effect while a little lower than the case of the non realkalisation specimens (NR-S). The reason for this would be that the formation of hydrophobic group at the water repellent layer due to the silane-based impregnation was inhibited by the alkali ions accumulated at the concrete surface. In contrast, under spraying salt water, the contact angle of the specimens for desalination shows relatively early and rapid decreasing. As the reason for this, it is considered that the salt deposition on to the surface under spraying salt water condition reduced the water-repellent effect.

The variation curves of the concrete resistivity of the specimen applying silane-based impregnation are shown in Figs. 12 and 13. The cases of the non-surface-treatment specimens are also shown in these figures as the reference. Regardless of the electrochemical treatments, the concrete resistivity of the specimen applying silane-based impregnation is larger than the cases of non-surface-treatment one. So, it can be said that the differences of concrete resistivity between the cases of non-surface-treatment specimens and those applied silane-based impregnation show the protection effect of the silane-based impregnation. Therefore, according to Fig. 12, the protection effect is reduced by the application of the realkalisation. Such tendency is in accordance with the results of the contact angle shown in Fig. 11. According to Fig. 13, the protection effect of the specimens applied desalination (D-S) is larger than that of non-desalination case (ND-S). And the significant drop of the concrete resistivity due to spraying of salt water like the results shown in Fig. 13 is not observed. The water-repellent effect of the concrete surface evaluated by the contact angles would be lost relatively early by the physical action from the spraying of salt water, but the protection effect by the impregnation layer in the con-
crete are sustained regardless of the application of the desalination.

3.3.2 The Bond strength of PCM and epoxy resin applied after realkalisation followed by the accelerated carbonation for 24 months

The bond strength of PCM and epoxy resin applied after realkalisation followed by accelerated carbonation for 24 months are shown in Fig. 14. As shown in Fig. 14, the bond strength of R-P was smaller than that of NR-P. Fracture mode of R-P was interface fracture, however that of NR-P was base material fracture or fracture within the PCM layer. The reason for this would be that the high alkaline condition at the concrete surface after realkalisation (refer to Fig. 7) could cause the alkaline hydrolysis of PCM, and it decreases the bond strength between concrete and PCM. On the other hand, the bond strength of R-E was smaller than that of NR-E, although both of the fracture modes were base material fractures. All cases of bond strength exceeded 1.0 N/mm² which is generally required in Japan, and significant change of the appearance of surface coatings was not observed.

3.3.3 Water permeability of the specimen for realkalisation after accelerated carbonation for 24 months

The suppression ratio of water permeation of the realkalisation specimen after accelerated carbonation for 24 months are shown in Fig. 15. The suppression ratio of water permeation was calculated by Eq. (2).

\[
\text{Suppression ratio of water permeation (\%) = } \frac{100 \times \text{Water permeation of non-treated specimen (R)}}{\text{Measured water permeation (ml)}}
\]

As shown in Fig. 15, regardless of whether realkalisation is applied or not, the suppression ratio of water permeation of PCM or epoxy resin is approximately 98%. Therefore, it was thought that the influence of deterioration of the bond strength caused by realkalisation on the water permeability was small. However, the suppression ratio of R-S was lower than NR-S. The reason of this would be that the water-repellent effect of silane-based impregnation was decreased (refer to Figs. 11, 12), and the formation of hydrophobic group at the water repellent layer due to the silane-based impregnation was inhibited by the application of the realkalisation as it was previously mentioned (3.3.1).

3.4 Protection effect against steel corrosion after electrochemical treatment

3.4.1 Protection effect against steel corrosion just after completing electrochemical treatment

The measured values of the half-cell potential of concrete steel bar, polarization resistance and concrete resistivity before and after applying electrochemical treatment are shown in Table 4. Referring to the criteria of steel corrosion in concrete shown in ASTM C 876-91, the half-cell potential nobler than -0.09 V to saturated Ag/AgCl as the reference electrode indicates non-corrosion with a probability of 90% or more, the

| Kinds of electrochemical treatments | Half-cell potential (V vs Ag/AgCl) | Polarization resistance (kΩ) | Concrete resistivity (kΩ) |
|-----------------------------------|-----------------------------------|-----------------------------|-------------------------|
| Before                            |                                    |                             |                         |
| Realalkalisation                  | -0.071                            | 0.994                       | 0.252                   |
| Desalination                      | -0.260                            | 0.201                       | 0.399                   |
| After                             |                                    |                             |                         |
| Realalkalisation                  | -0.666                            | 0.003                       | 0.130                   |
| Desalination                      | -1.099                            | 0.030                       | 0.320                   |
potential lower than -0.24 V indicates corrosion with a probability of 90% or more, and the potential between them means uncertain about the corrosion state.

Table 4 shows that the value of half-cell potential measured before applying realkalkisation indicates non-corrosion state, whereas that measured before applying desalination indicates corrosion state due to the premixed Cl\textsuperscript- of 8.0 kg/m\textsuperscript{3}. However, after applying electrochemical treatment, the potential maintains around -0.7 V to -1.0 V which is considered the cathodic protection range of the potential, caused by the cathodic polarization with the electrochemical treatment. Furthermore, the specimens after applying desalination show a strong influence of the cathodic polarization compared with after applying realkalkisation, because the desalination period is longer than that of realkalkisation.

According to Table 4, the polarization resistance value after electrochemical treatment becomes smaller than that of before applying electrochemical treatment. Generally speaking, a polarization resistance value is inversely proportional to the steel corrosion rate. However, according to the past study (Fajardo 2006), the polarization resistance value becomes extremely small due to cathodic polarization with electrochemical treatment. And, it was also reported that the value will gradually increase with the reproduction of the passivation film of steel bar due to the supply of oxygen after electrochemical treatment (Ueda et al. 1999). The values of concrete resistivity decrease by applying the electrochemical treatment, and the reduction of the concrete resistivity due to realkalkisation is larger than the case of desalination, which would be caused by the electro-osmosis of the electrolyte with the application of realkalkisation.

### 3.4.2 Protection effect against steel corrosion of specimens subjected to the accelerated carbonation for 24 month after realkalkisation

(A) The carbonation depth and distribution of ions in specimens subjected to the accelerated carbonation for 24 month after realkalkisation

Figure 16 shows distribution of R\textsubscript{2}O content in specimens subjected to the accelerated carbonation for 24 month after realkalkisation. From Fig. 16, the re-distribution of R\textsubscript{2}O after the realkalkisation seems to be promoted in the specimen applied epoxy resin (R-E) compared with the other cases (R, R-S, and R-P), because the epoxy resin coating prevented the drying of concrete than the other cases under accelerated carbonation, which could accelerate the migration of ions in R-E.

Figure 17 shows the carbonation depth of specimens subjected to the accelerated carbonation for 24 month.
after realkalisation. From Fig. 17, the carbonation depth of R-P was higher than that of non-realkalisation specimen (N-P). As the reason for this, it is considered that the PCM was deteriorated by the high alkaline condition at the concrete surface after realkalisation (refer to Fig. 7), which is confirmed by the results of bond strength. On the other hand, the carbonation depth of specimens applied epoxy resin (N-E, R-E) shows 0.0 mm, which suggests that epoxy resin prevented carbonation of concrete regardless of whether realkalisation is applied or not. However, the carbonation depth of R and R-S were similar to that of NR-S. The reason for this would be that the realkalisation was not effective for preventing the progress of carbonation because the condition of accelerated carbonation environment (5% CO$_2$) is much severer than the actual environment.

The distribution curves of total Cl$^-$ content in specimens subjected to the accelerated carbonation for 24 month after realkalisation are shown in Fig. 18. From Fig. 18, the distribution of total Cl$^-$ content of the specimen applied PCM or epoxy resin coating was not substantially changed although the carbonation was accelerated for 24 months after realkalisation. As for the carbonated specimens which were carbonated as shown in Fig. 17 (R, R-S and N-S), the total Cl$^-$ content in the carbonation part (approximately 0–35mm) decreased and the Cl$^-$ content in the non-carbonated part (approximately 40–55mm) increased compared with the case of just after applying realkalisation shown in Fig. 6. In the carbonation part, the Cl$^-$ ions fixed as the Friedel’s salt would be released as free Cl$^-$ ions, which would diffused to inside and the condensed Cl$^-$ layer could be formed at the carbonation front part (approximately 40–55mm). Especially, the total Cl$^-$ contents around steel in R, R-S and NR-S reach around 4.0 kg/m$^3$, which could initiate the steel corrosion.

(B) Electrochemical indexes

The variation curves of the electrochemical indexes of the specimens during the accelerated carbonation for 24 months after realkalisation are shown in Fig. 19.

(1) Half-cell potential

From Fig. 19a, after accelerated carbonation for about 700 days, the values of half-cell potential of realkalisation specimen (R) indicates the initiation of steel corrosion, due to the carbonation of concrete and concentration of Cl$^-$ due to carbonation (Figs. 17 and 18). On the other hand, the half-cell potential value of specimen applied silane-based impregnation regardless of whether realkalisation is applied or not (NR-S, R-S) starts to drop earlier than the case of R and later than the case of NR. Also, the values of NR, NR-S and R-S indicates the initiation of steel corrosion after accelerated carbonation for about 600 days. This means that the application of the silane-based impregnation is not effective for the preventing the carbonation of concrete. Regardless of applying realkalisation, the values of the specimens coated by epoxy resin or PCM (NR-E, R-E, NR-P and R-P) maintain the noble potential, which means low possibility of the steel corrosion.

(2) Polarization resistance

Figure 19b shows that the values of polarization resis-
tance of NR and NR-S increase during accelerated carbonation until around 420 days, because the inside of NR and NR-S were dried under the accelerated carbonation environment, compared with the case of NR-E and NR-P. However, the polarization resistance values of NR and NR-S start to drop after around 420 days due to the carbonation. On the other hand, the values of polarization resistance of realkalisation specimens maintain the value of just after applying realkalisation for 720 days, nevertheless half-cell potential once recovered from the negative value measured just after finishing realkalisation. It is considered that since the specimens for applying realkalisation was not carbonated before the electrochemical treatment, the steel in concrete after the realkalisation was in the over-protected state which means the electrochemical condition strongly affected by the cathodic polarization.

(3) Concrete resistivity

From Fig. 19c, the values of concrete resistivity of all specimen are increasing with time. Especially, non-treated specimen (NR, R) and specimen applied silane-based impregnation (NR-S, R-S) shows gradually higher resistivity than the specimen applied epoxy resin coating or PCM (NR-E, R-E, NR-P and R-P) during accelerated carbonation. The reason for this would be that the moisture content of R, NR, R-S and NR-S decreased rather than the other case under accelerated carbonation environment.

3.4.3 Protection effect against steel corrosion of specimens subjected to the spraying of salt water condition for 24 months after desalination

Figure 20 and Fig. 21 shows variation curves of the electrochemical indexes of the specimens during spraying of salt water for 24 months after desalination.

(1) Non-desalination specimen

Figure 20a shows the values of half-cell potential of non-desalination specimens suggest the initiation of corrosion regardless of kinds of surface treatment during spraying of salt water for 720 days. From Fig. 20b, the polarization resistance values of specimens applied silane-based impregnation and epoxy resin coating (ND-S, ND-E) are higher than those of specimens applied PCM (ND-P) and non-surface-treated specimen (ND). In general, it could not be expected that applying surface treatment prevents the steel corrosion in concrete containing much amount of Cl\textsuperscript{−}. However, in this experiment, the values of polarization resistance of ND-S and ND-E are increasing, because concrete resistivity increase than ND (Fig. 20c). The reasons for the change in concrete resistivity would be that the drying of concrete promoted by the silane-based impregnation, and the prevention of salt water penetration by the epoxy resin. On the other hand, the value of polarization resistance and concrete resistivity of ND-P was similar to ND (Figs. 20b, 20c), because PCM does not have the drying effect of concrete such as silane-based impregnation and not impervious like epoxy resin.

(2) Desalination specimen

The specimens applied desalination strongly affected by the cathodic polarization, because the desalination period
is longer than that of realalkalisation. Therefore, at the initial time of a salt water spraying, the potential maintains around -1.0 V regardless of kinds of surface treatment (Fig. 21a). However, the half-cell potentials of the non-surface-treated specimens (D) and the specimen applied silane-based impregnation (D-S) rapidly grow to nobler potential until 50 days because the higher oxygen supply from the exposed surface after the desalination for these two kinds of specimens could re-form the steel passivity film in a short period. On the other hand, values of the specimens coated by PCM (D-P) grow to nobler potential slower than the case of D in 270 days. Furthermore, potential values of the specimens coated by epoxy resin coating (D-E) shifted nobler potential most slowly. So, it is considered that the re-formation rate of the steel passivity film would be affected by the oxygen transmission performance of the surface treatment. It means that the surface treatment using lower oxygen permeability materials like epoxy resin will cause the slower re-formation of the steel passivity film after the electrochemical treatment. However, regardless of kinds of surface treatment, the protection effect against steel corrosion for desalination maintains for 720 days. Figure 21b shows the values of polarization resistance grow to higher resistance gradually. Especially, values of D-S are larger than another kinds of specimens because of the rapid re-passivation rate and the low penetration of salt water. Regarding the concrete resistivity, the values of D and D-E are smaller than those of D-S and D-P (Fig. 21c). The reasons for this would be that the moisture content of D was high due to penetration of salt water, and D-E maintained the high moisture content caused by applying desalination because of its lower air-permeability than another kinds of surface treatment.

4. Proposal of effective kinds of surface treatment after electrochemical treatment

In this study, the durability of surface treatment after applying electrochemical treatment is influenced by the high alkali condition supplied by electrochemical treatment at the concrete surface. Furthermore, the high alkali condition differs by the kind of the electrochemical treatment because the electrolyte is different between that for desalination and that for realalkalisation. Hence, it is not that the suitable surface treatment applied after desalination can be applied to after realalkalisation. In view of the protection effect against steel corrosion, as for after realalkalisation, it is thought that the surface coating materials having good bond strength and low air-permeability under presence of a mass of K⁺ would be selected better than silane-based impregnation. Regarding after desalination, the surface treatment having high good air-permeability and impervious like silane-based impregnation would be effective.

Consequently, if surface treatment is applied properly, surface treatment would prevent the invasion of the deterioration factors after the electrochemical treatment. In addition, it is thought that the protection effect against steel corrosion for electrochemical treatment can be sustained over a long period, if the surface treatment is repainted in an interval of around ten years considering the service life of the surface treatment materials.

Fig. 21 Variation curves of the electrochemical indexes during salt water spraying for 24 months after desalination. (Desalination specimen’s data)
5. Conclusions

1) The appearance of the surface treatment materials applied after the electrochemical treatment did not change so much due to the accelerated deterioration environment for 24 months regardless of the kind of the electrochemical treatment and the kind of surface treatment.

2) After accelerated carbonation for 24 months, the suppression ratio of surface water permeation of concrete applied silane-based impregnation after realkalisation became approximately 52%, however in the cases of PCM and epoxy resin coating after realkalisation, the ratios were approximately 98%.

3) R2O content and pH values around the concrete surface increased with the application of realkalisation, because of the supply of K+ ions from the electrolyte (K2CO3 solution) with realkalisation. On the other hand, the application of desalination resulted in the accumulation of R2O around the steel bar due to the electrochemical migration of Na+ ions in the concrete.

4) In the case of applying the epoxy resin coating after realkalisation, the re-distribution of R2O content during the accelerated carbonation for 24 months was observed.

5) The bond strength of epoxy resin or PCM coating applied after realkalisation followed by the accelerated carbonation for 24-month was smaller than the non-realkalisation case, although exceeded 1.0 N/mm2 which is generally required in Japan.

6) The carbonation depth and electrochemical indexes of specimens applied realkalisation followed by the accelerated carbonation for 24 months indicated that the application of PCM or epoxy resin coating after realkalisation prevented the progress of the carbonation of concrete. However, the application of silane-based impregnation was not effective for preventing the carbonation of concrete regardless of whether realkalisation was applied or not.

7) In the cases of surface coating using silane-based impregnation after desalination, the re-passivation of the steel in concrete after desalination started earlier and the polarization resistance became larger than the cases applying PCM or epoxy resin coating during the spraying of salt water for 24 months.

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