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Crack closure of reinforced concrete by electrodeposition technique

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Abstract

The electrodeposition method for rehabilitation of cracked reinforced concrete, based on the electrochemical technique, is presented here. Investigations on reinforced concrete beams of size 15 × 15 × 125 cm were conducted in this study. Specimens cracked by chloride attack for 18 months were immersed in a $ZnSO_4$ solution, and were applied with a constant current for 8 weeks. The development of crack closure due to the precipitation of electrodeposits (ZnO) was evaluated. Water permeability, chloride ion concentration, polarization curve and half-cell potential were measured in order to assess the effectiveness of this method in the improvement of concrete properties. The results indicate that electrodeposits formed on the concrete surface were able to close the concrete cracks and to decrease the concrete permeability. In addition, the investigation shows that the application of electrodeposition have effects on the desalination of concrete and re-passivity of the reinforcing steel in concrete.

Keywords: Electrodeposition; Rehabilitation; Reinforced concrete; Permeability; Chloride

1. Introduction

The problem of cracking of concrete structures is inevitable, and its consideration is of utmost importance for infrastructure. Concrete crack is caused by various factors involving construction technique and environmental condition. Depending on the type of crack, there are many repair methods available such as epoxy injection, routing and sealing, and grouting.

One of the techniques in dealing with crack is by electrodeposition method. Electrodeposition refers to the precipitation of material on the surface of an electrode by electrolysis. Investigations carried out in Japan in the late 1980s proved that it is possible to close the crack in reinforced concrete by applying an electric current, especially under marine environment where other traditional repair systems are inefficient or very expensive [1,2]. The aim of electrodeposition method is to fill the crack in concrete and to coat the concrete surface by electrodeposits of chemical compounds such as $CaCO_3$ and $Mg(OH)_2$. The CO_3^{2-} ions present in the seawater form $CaCO_3$ but not $MgCO_3$ because $Mg(OH)_2$ is less soluble than $MgCO_3$. In the case of Ca^{2+} the contrary is the case and therefore $CaCO_3$ is formed. These layers of inorganic compounds are known to provide a physical barrier, and reduce the flux of gas or solution inside the concrete. This can be accomplished by feeding a weak direct current between the reinforced steel (the cathode) in concrete structure and an electrode (the anode) located under seawater (Fig. 1). As concrete itself is a conductor, a hard layer of electrodeposits is formed on the submerged surface of concrete.

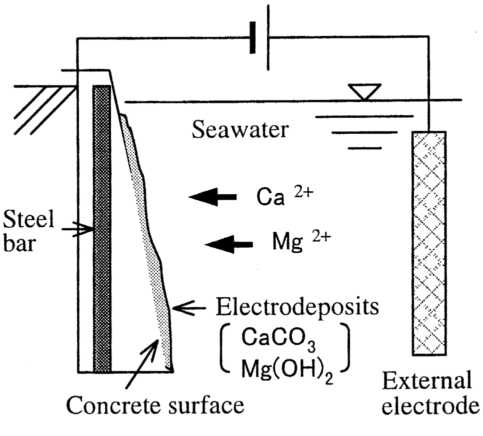

Fig. 1. Application of electrodeposition in marine structure.

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In this paper, experiments were performed to examine the possibility of the electrodeposition method as a crack closure of reinforced concrete members. In addition, the crack by chloride attack was chosen in order to examine and introduce electrodeposition technique as a rehabilitation method for concrete structures damaged due to corrosion of the reinforcements in this study.

2. Experimental methods

2.1. Preparation of specimens

2.1.1. Materials and mix proportions

Ordinary Portland cement (specific gravity: 3.17; Blaine fineness: 3270 cm^2/g; ignition loss: 0.6%) was used as binder in this investigation. Fine aggregate used was river sand (SSD specific gravity: 2.62; water absorption: 1.73%; fineness modulus: 2.8) while coarse aggregate was crushed sandstone with G_{max} of 20 mm (SSD specific gravity: 2.63; water absorption: 0.68%; fineness modulus: 6.68). Japan Industrial Standard deformed steel bars were used. The diameters of the steel bars were 13 and 6 mm for main steels and stirrups, respectively.

The mixture proportion of concrete is shown in Table 1. The slump of fresh concrete was 12 ± 1 cm and air content was $4 \pm 1\%$. Water–cement ratio was 0.7. In order to accelerate the corrosion process, 10 kg/m^3 of NaCl was added during mixing of concrete.

2.1.2. Specimens and exposure condition

Reinforced concrete prism specimens, having a cover depth of 2 cm, with the dimensions of 15 × 15 × 125 cm were made for investigation. The specimens were cured for 28 days [temperature: 20 ± 2 °C, and relative humidity (RH) $80 \pm 5\%$]. After curing, the specimens were demolded and transferred to the exposure site. During the exposure, salt-water solutions (3.5% by weight) were sprayed twice a week over the specimens in order to accelerate the corrosion process. The details of beams and crack maps of beams exposed for 18 months are shown in Fig. 2. Maximum recorded crack width of beams is 0.6 mm. After exposure, the specimens were sealed with epoxy except for the cracked side. They were then placed in plastic containers containing $ZnSO_4$ solution. The environmental conditions were kept constant throughout the period of investigation. A total of 12 beam specimens were made for the investigation.

Table 1
Mixture proportion of concrete

Water kg/m^3	Cement kg/m^3	Gravel kg/m^3	Sand kg/m^3	NaCl kg/m^3	Ad[a] ml/m^3	Ad[b] ml/m^3
165	236	1032	837	10	637	9.4

[a] Water-reducing agent.
[b] Air-entraining agent.

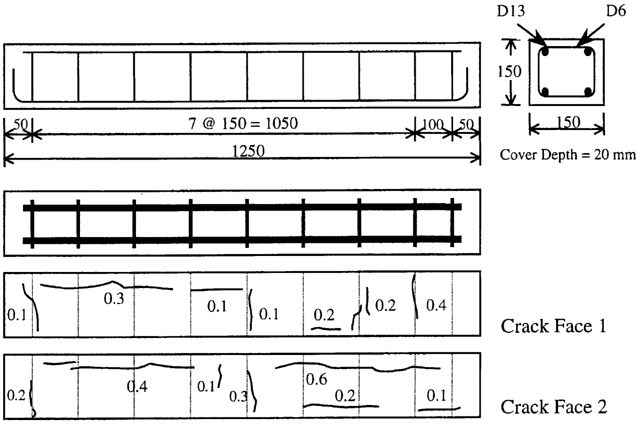

Fig. 2. Details and the crack maps of beam specimen.

2.2. Application of electric current

Direct current was fed by a power supply between the embedded reinforcing steel and a titanium mesh anode immersed in the solution and located at the bottom of the container (Fig. 3). The embedded steel was connected to the negative terminal of the potentiostat and the external anode was connected to the positive terminal. The potentiostat used as power supply was adjusted to deliver a current density (0.5 A/m^2) to the concrete surface for 8 weeks. This current density is relatively low, so the generation of OH^- and the potential for alkali–aggregate reaction are not expected [3]. If the current density is low, the treatment is longer.

2.3. Immersion solution

Based from previous investigation conducted by the authors in the selection of the immersion solutions [4,5], an electrolyte zinc sulfate solution ($ZnSO_4$) was selected in this study. In order to select appropriate external solution, eight types of electrolyte solutions [$MgCl_2$, $ZnSO_4$, $AgNO_3$, $CuCl_2$, $Mg(NO_3)_2$, $CuSO_4$, $Ca(OH)_2$, $NaHCO_3$] were

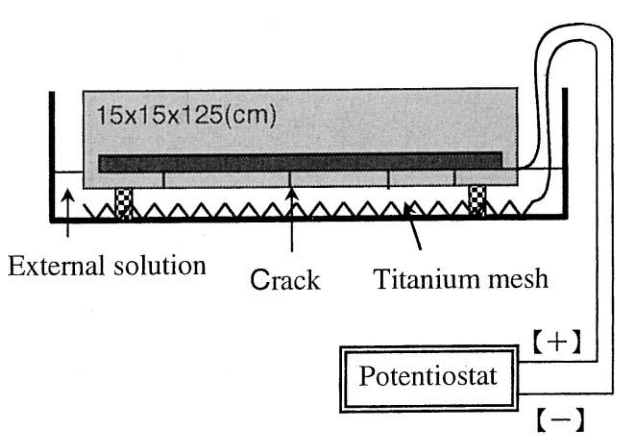

Fig. 3. Specimen orientation and current application.

selected in previous study. From the results of the previous study, it can be concluded that the $ZnSO_4$ solution is most effective for the purpose of precipitating the deposition product inside and outside the crack in concrete. The concentration of the solution was 0.1 mol/l. In order to maintain a constant concentration, the solution was replaced every 5 days.

2.4. Method of testing

2.4.1. Measurement of crack closure

The rate of crack closure was qualitatively measured every week from beginning of the test. The rate of crack closure was defined as the percentage of the length of closed crack with respect to the total length of crack [6,7]. Series of photographs of cracked specimens were used to scale and evaluate the rate of closure of crack.

2.4.2. Permeability measurements

A modified method of Japan Industrial Standard permeability test B (JIS A 6909) was used to evaluate the coefficient of permeability [8]. It was obtained by measuring the level of water in the pipette while the water percolated in the specimen (Fig. 4). In order to avoid the error due to evaporation of water, liquid paraffin was placed on the water surface in the pipette. The following equation was used to compute the coefficient of permeability.

$$k = \frac{aL}{A(t_1 - t_0)} \ln \frac{h_0}{h_1}$$

where k = coefficient of permeability, cm/s; a = sectional area of standing pipe, cm^2; L = length of standing pipe, cm; A = surface area of specimen, cm^2; h_0 = water level at t_0, cm; h_1 = water level at t_1, cm.

2.4.3. Measurements of chloride ion concentration

After electrodeposition treatment, drilled concrete samples were taken from the crack locations at depths from 1.5 to 2.5 cm. The samples are represented the chloride concentrations on the surface of the steel. Chloride content was measured according to the Japan Concrete Institute's method.

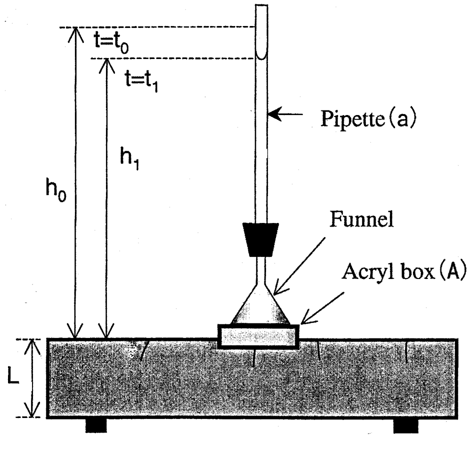

Fig. 4. The modified permeability test.

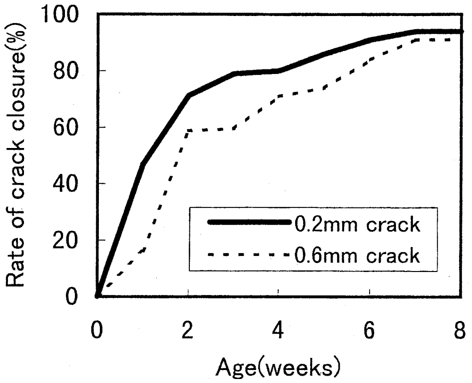

Fig. 5. Rate of crack closure versus age.

2.4.4. Electrochemical measurements

The electrochemical measurements as a half-cell potential and as a polarization curve were measured by using a portable corrosion monitor. The beams were covered with wet jute bags before electrochemical measurements in order to get stable electrochemical data. The passivity grades were evaluated by using the anodic polarization curves of the steel. The passivity grades are defined as follows.

1. Grade 0 indicates no passivity between +0.2 and +0.6 V; anodic current density is over 100 $\mu A/cm^2$ at least at one point.
2. Grade 1 indicates a certain degree of passivity, between +0.2 and +0.6 V; anodic current density is between 10 and 100 $\mu A/cm^2$.
3. Grade 2 indicates a certain degree of passivity that is better than Grade 1, between +0.2 and +0.6 V; anodic current density is over 10 $\mu A/cm^2$ at least at one point.
4. Grade 3 indicates a certain degree of passivity that is better than Grade 2, between +0.2 and +0.6 V; anodic current density is between 1 and 10 $\mu A/cm^2$.

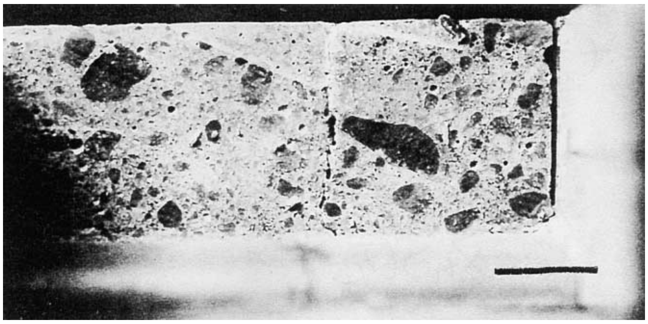

Fig. 6. Cross-section of electrodeposited specimen. Bar: 1 cm.

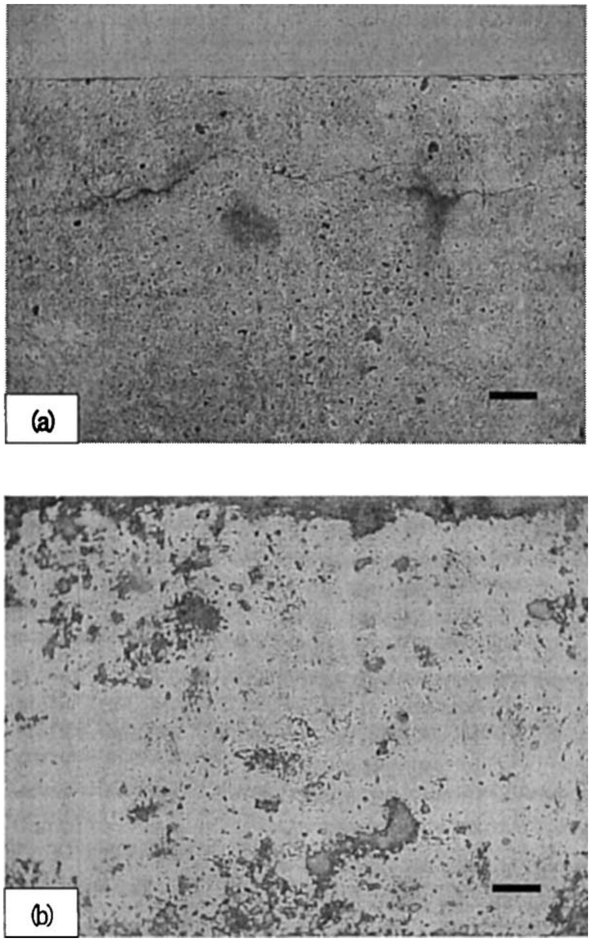

Fig. 7. Appearance of electrodeposits on the surface: (a) before charging and (b) 8 weeks after charging. Bar : 1 cm.

5. Grade 4 indicates a certain degree of passivity that is better than Grade 3, between +0.2 and +0.6 V; anodic current density is over 1 μA/cm^2 at least at one point.
6. Grade 5 indicates excellent passivity, between +0.2 and +0.6 V; anodic current density is always less than 1 μA/cm^2.

3. Results and discussion

3.1. Crack closing

The development of crack closure is shown in Fig. 5. It is observed that the rate of crack closure increases with the testing period and the closing speed of 0.2 mm crack is slightly faster than that of 0.6 mm crack. It is also observed from Fig. 5 that the rate of crack closure increases rapidly by the first 2 weeks and the rate of closure reaches close to 90% at the end of the testing period of 8 weeks. In addition, Fig. 6 shows cross-section, illustrating the depth of electrodeposition as they filled a crack. From the observation on cross-section, it can be seen that the electrodeposits penetrate deep into the crack and the depth of penetration is about 2 mm (0.2 mm crack) to 8 mm (0.6 mm crack). Therefore, it is understood that electrodeposition starts at the electrode (rebar) level and gradually fills the depth and closes the crack of concrete.

Table 2
Chemical reactions in the electrode and solution

Electrode reaction	(anode) $2H_2O \rightarrow O_2\uparrow + 4H^+ + 4e^-$
	(cathode) $2H_2O + 2e^- \rightarrow H_2\uparrow + 2OH^-$
Aqueous reaction	$ZnSO_4 \rightarrow Zn^{2+} + SO_4^{2-}$
	$H_2O \rightarrow OH^- + H^+$
	$Zn^{2+} + 2OH^- \rightarrow ZnO\downarrow + H_2O$

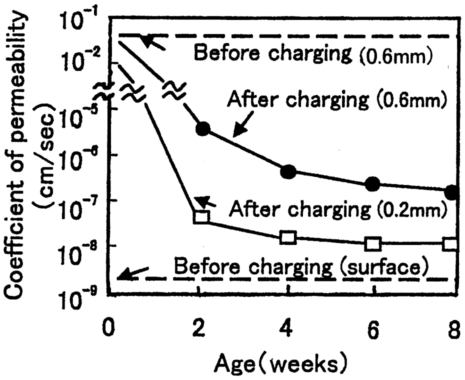

Fig. 8. Coefficient of permeability versus age.

Fig. 7 shows the growth appearance of electrodeposits on the concrete surface. It is observed that electrodeposition developed uniformly on the concrete surface and along the crack. From the result of a cross-sectional investigation of the specimens, it became clear that almost all concrete surfaces had been coated with a layer of electrodeposits, and the thickness of the electrodeposit layer on the concrete surface was about 0.5–2 mm. In the cracked-part of specimen, the deposits grew around the crack, and had even penetrated deep into the crack. From the observations, it can be confirmed that precipitation starts at the crack shortly after application of the charge. The reason for the early precipitation of electrodeposits in the crack is that a higher current density exists near the crack caused by a

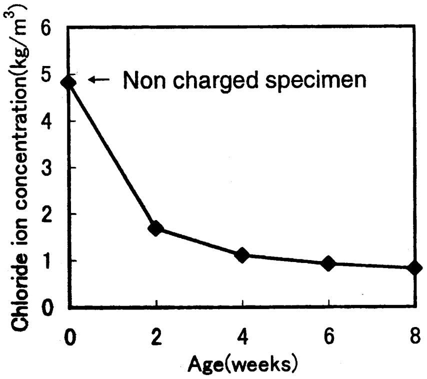

Fig. 9. Chloride concentration over the steel surface.

lower degree of electrical resistance. It is also observed from the result of X-ray powder diffraction analysis that this electrodeposit is ZnO having density of 6.16 g/cm^3. The chemical reactions in the electrode and solution are shown in Table 2.

The results in these figures therefore show clearly that electrodeposits can be precipitated on the concrete surface by applying an electrical charge.

3.2. Improvement of permeability resistance

A modified permeability test was conducted to examine the watertightness of the electrodeposited concrete. Fig. 8 shows the relationship between the test period and coefficient of permeability at the crack of 0.2 and 0.6 mm in width. It is observed that the permeability coefficients of electrodeposited specimens are much lower than that of noncharged specimens, and stand at about 3.2×10^{-8} cm/s (the crack of 0.2 mm in width after 8 weeks of charging). Such a low permeability is close to that of noncracked specimens. This decrease of permeability is attributed to the closure of concrete crack and the refinement of concrete surface due to the precipitation of electrodeposits. From the results of the permeability test, it is understood that the electrodeposits on the concrete surface help to improve the concrete quality and reduce the coefficient of water permeability.

3.3. Chloride removal

As a result of the applied potential difference, negatively charged ions (chloride, hydroxide) will move towards the anode and positive ions (sodium, potassium) will move to the cathode. This process is called migration. It is a very important process with regard to chloride removal because it transports chloride ions away from the reinforcement towards the anode and into the external electrolyte.

The measurements of chloride ion concentrations in the concrete were carried out to examine the effectiveness of electrodeposition technique as a means of removing chloride ions from chloride-containing concrete specimens.

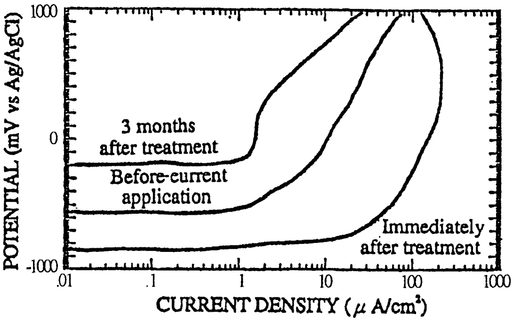

Fig. 10. Polarization curve of steel bar.

Table 3
Passivity grades of reinforcing steel

	Case 1	Case 2	Case 3	Case 4
Noncharged	1	0	1	1
Charged	4	3	2	3

Fig. 9 indicates the distribution of chloride ion concentrations over the steel surface. Samples taken from noncharged specimens showed high levels of chloride ion concentration. Nevertheless, it was confirmed that the chloride ions could be removed from the specimens by applying a negative charge to the reinforcing steel. After 4 weeks of continuous charging, about 70% decrease in the chloride ion concentration was observed around the reinforcing steels. This phenomenon seems to show that negatively charged chloride ions were removed toward the anode in the external solution.

3.4. Re-passivity of reinforcing steel

Due to the electrical potential difference between the anode and the cathode, water is reduced to hydroxide ions at the reinforcement. At the external conductor, water or hydroxide is oxidized to oxygen and hydrogen ions. These reactions are referred to as electrolysis, which results in a pH increase around the reinforcement.

Fig. 10 indicates one of the anodic polarization curves of reinforcing steel as was measured before current application, immediately after treatment, and 3 months after treatment. It can be seen that electrodeposition helps to passivate the reinforcing steel after current application. This is probably due to the fact that Cl^- has been removed and that the pH increases at the reinforcing steel by electrolysis.

The passivity grades of the reinforcing steel were evaluated from the anodic polarization curve. The results are shown in Table 3. The reinforcing steels in the noncharged specimens show 0–1 passivity grades, indicating almost complete loss of passivity. However, the reinforcing steels in the charged specimens have two to four degrees of passivity. Comparing the passivity grades of the noncharged and the charged specimens, it is observed that the passivity grades of the charged specimen are comparatively better than of the noncharged specimen, indicating less corrosion activity of the charged specimen.

Table 4
Results of half-cell potential tests (unit: mV)

	Case 1	Case 2	Case 3	Case 4
Noncharged	− 420	− 522	− 360	− 404
Charged	− 169	− 96	− 214	− 102

The results of half-cell potential of reinforcing steel as was measured before charging and 3 months after charging are shown in Table 4. This shows dramatic reductions in potential indicating that the steel reinforcement passivated in most case. In this respect, the production of large amounts of hydroxyl ions around the steel reinforcement is likely to be as important as chloride removal.

4. Conclusions

The paper showed the potential of the electrodeposition technique in the rehabilitation of deteriorated reinforced concrete. This lays the groundwork for research on the practical application of this method on real structures. The following conclusions were obtained from the present study.

1. Electrodeposits were precipitated on the concrete surface and in the cracks by applying electrodeposition technique. The rate of crack closure increased rapidly by the first 2 weeks and the thickness of the electrodeposit layer on the concrete surface was about 0.5–2 mm.
2. The cracks in all the beam specimens were closed almost perfectly at the end of the test period. The crack closing helps to decrease the concrete permeability at the cracks. The filling depth of crack varied according to the crack width.
3. Electrodeposition treatment effectively reduced the chloride ions in the concrete. After 4 weeks' continuous charging, about 70% decrease in the chloride ion concentration was observed around the reinforcing steels.
4. Polarization curve test and half-cell potential test showed that the reinforcing steel in the concrete was re-passivated in most cases by applying electrodeposition treatment.

Acknowledgments

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References

[1] M. Yokoda, T. Fukute, Rehabilitation and protection of marine concrete structure using electrodeposition method, Proceedings of the International RILEM/CSIRO/ACRA Conference on Rehabilitation of Concrete Structures, RILEM, Melbourne, 1992, pp. 213–222.

[2] H. Sasaki, M. Yokoda, Repair method of marine reinforced concrete by electrodeposition technique, Proceedings of the Annual Conference of Japanese Concrete Institute, 1992, pp. 849–854.

[3] A.J. Hondel, R.B. Polder, Electrochemical re alkalisation and chloride removal of concrete, Concr. Repair (1992) 19–24 (Sep/Oct).

[4] J.S. Ryu, N. Otsuki, Crack block and surface improvement of electrodeposition, Proceedings of the Annual Conference of Japanese Society of Civil Engineers, 1998, pp. 270–271.

[5] N. Otsuki, J.S. Ryu, Use of electrodeposition for the repair of concrete with shrinkage cracks, J. Mater. Civ. Eng. (ASCE) (2001) 136–142 (Mar/Apr).

[6] J.S. Ryu, N. Otsuki, Application of electrodeposition technique for concrete rehabilitation, 5th International Conference CANMET/ACI, Barcelona, Spain, SP-192-56, 2000, pp. 917–930.

[7] J.S. Ryu, N. Otsuki, Crack closure and chloride extraction of concrete by electrodeposition method, 15th International Conference SMiRT, Seoul, Korea, Volume VI, 1999, pp. 65–70.

[8] JIS Handbook 24-1, Architecture/Material Part, 1995, pp. 764–765.