



Crack Closure and Chloride Extraction of Concrete by Electrodeposition Method

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ABSTRACT

In this paper we present the electrodeposition method as a means of repair for deteriorated and cracked concrete structures and investigate the effects of this method on various concrete properties. We investigated the effects of electrodeposition on $\phi 10 \times 20$ cm concrete specimens with embedded reinforcing steel. After causing the specimens to crack under a specified load, we immersed them in a solution, and then imparted a constant current between the embedded steel in concrete and an electrode in the solution for 12 weeks. Afterwards, we examined and evaluated the weight change of the specimens, the degree of crack closure, the chloride concentration, and polarization curve. The results indicate that electrodeposits can close concrete crack. In addition, our investigation shows that electrodeposition method has effect of chloride extraction from concrete.

INTRODUCTION

The problem of cracking of concrete structures is inevitable and of the utmost importance for infrastructure. Concrete crack is caused by various factors involving construction technique and environmental condition. According to the type of crack, there are many repair methods available.

One of the techniques of dealing with crack is electrodeposition method. Investigations carried out in Japan in the late 1980s proved that it was possible to close the crack in reinforced concrete by applying an electric current, especially under marine environment (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 . 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 sea water (Fig. 1). As concrete itself is a conductor, a hard layer of electrodeposits is formed on the submerged surface of concrete. There are some studies on application to marine structures, however, trials on terrestrial structures of this relatively new method have not been carried out yet.

In this paper, experiments are performed to examine the possibility of electrodeposition method as a means of repair for cracked reinforced concrete structure, as well as to investigate the effects of this method on concrete properties.

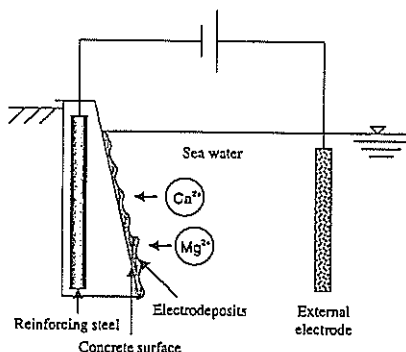


Fig. 1 - Schematic of electrodeposition method for marine structures

TEST PROGRAM

Materials

Cement : A normal portland cement (Specific gravity : 3.17, Blaine fineness : 3270 cm²/g, Ignition loss : 1.6%) was used. Its chemical composition is shown in Table 1.

Aggregates : Fine aggregate was river sand (SSD specific gravity : 2.59, Water absorption : 2.08%, Fineness modulus : 2.5) while coarse aggregate was crushed sandstone with G_{max} of 20 mm (SSD specific gravity : 2.61, Water absorption : 0.88%, Fineness modulus : 6.85).

Admixture : The chemical admixture used was a naphthalene-based AE and water reducing agent having a pH of 8~10 and specific gravity of 1.19~1.21.

Reinforcing bars : Plain steel bars (JIS SR235) were used. The chemical composition of the steel is shown in Table 2. The diameter of the steel bar was 16 mm.

Mixture Proportions

The mixture proportions of the materials are shown in Table 3. Six different types of concrete specimens were made. The slump was 10±2 cm and air content was 4±1%. Water-cement ratios of normal specimens were 0.4, 0.5 and 0.67. And chloride contents of chloride-containing specimens were 2, 5 and 10 kg/m³ (Cl by weight of concrete).

Table 1 - Chemical Composition of Cement

SiO ₂ %	Al ₂ O ₃ %	Fe ₂ O ₃ %	CaO %	MgO %	Others %	Σ %
20.1	5.0	3.0	61.6	1.1	9.2	100

Table 2 - Chemical Composition of Steel Bar

C %	Si %	Mn %	P %	S %	Fe %	Σ %
0.13	0.12	0.49	0.03	0.02	99.2	100

Table 3 - Mixture Proportions of Concrete

Specimen Type	W/C %	Water kg/m ³	Cement kg/m ³	Gravel kg/m ³	Sand kg/m ³	NaCl kg/m ³	Ad* ml/m ³	Ad** ml/m ³
Normal Specimen	40	158	395	1006	753	-	1.19	1.58
	50	170	340	979	795	-	1.02	1.36
	67	181	270	959	844	-	0.81	1.08
Chloride-Containing Specimen	50	170	340	979	795	3.3	1.02	1.36
	50	170	340	979	795	8.3	1.02	1.36
	50	170	340	979	795	16.6	1.02	1.36

* Water-reducing agent

** Air-entraining agent

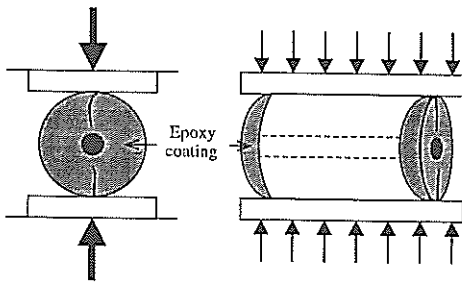


Fig. 2 - Crack-inducing method

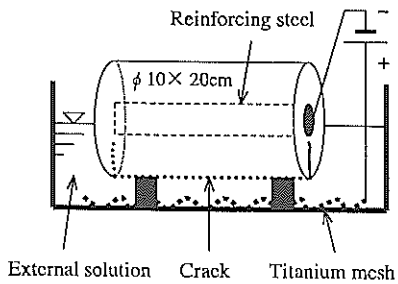


Fig. 3 - Specimen shape and current application

The Specimens

Reinforced concrete cylinder specimens with the dimensions of $\phi 100 \times 200$ mm were made for the investigation. After curing normal specimens in air at a temperature of 20C for 28 days and chloride-containing specimens in air at a temperature of 20C for 90 days, we created in all specimens a load-induced split crack 0.5 ± 0.1 mm wide from the concrete surface to the reinforcing steel, which simulated concrete deterioration in the actual environment. The crack-inducing method of specimens is shown in Fig. 2. Except for the immersed side, the other side of each of these specimens was sealed with epoxy. Then, we placed them in plastic containers containing solution. The environmental conditions were kept constant throughout the period of investigation. In total, 12 specimens were made for each type of specimen.

Application of Electric Current

Direct current was fed by a potentiostat as a power supply between the embedded reinforcing steel and a titanium-mesh anode immersed in the solution and positioned 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 was adjusted to deliver a current density of 0.5 A/m^2 to the concrete surface for 12 weeks.

Immersion Solution

Based on a previous investigation for selecting the immersion solution (3-4), we selected an electrolyte solution ($ZnSO_4$) for this study. The concentration of the solution was 0.1 mol/l . To maintain this concentration, we replaced the solution every five days.

TEST RESULTS AND DISCUSSION

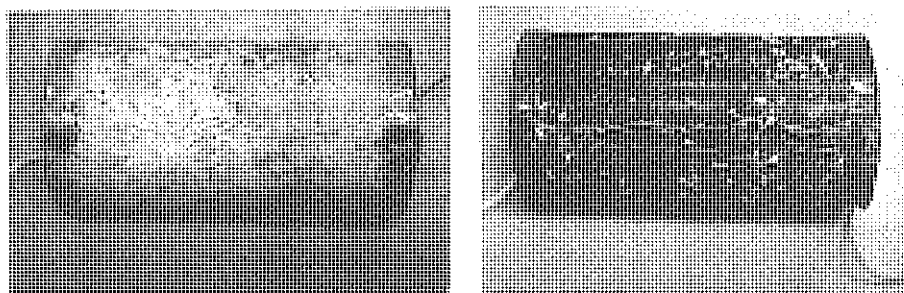
Precipitation of Electrodeposits

Electromigration can occur in concrete because concrete is a porous material having an electrolyte in the form of a pore solution. The electrodeposition process has been shown to rehabilitate marine concrete structures by using seawater as the electrolyte. In this investigation of the precipitation of the electrodeposits on the surface of cracked reinforced concrete, we selected an external solution and studied its characteristic.

Fig. 4 shows the appearance of electrodeposits on the concrete surface. The electrodeposits appear on the concrete surface and along the crack. Precipitation started at the crack soon after application of the charge. This immediate precipitation in the crack occurred because a higher current density exists near the crack, caused by a lower degree of electrical resistance. Electrodeposition formed on the concrete surface and almost perfectly closed the crack at the age of 3 weeks. X-ray powder diffraction analysis revealed that the electrodeposit is ZnO having density of 5.67 g/cm^3 .

The weight gains of the specimens are plotted against the duration of testing in Fig. 5. From Fig. 5, it can be seen that the weights of specimens of 67% water-cement ratio increase proportionally with the period of testing and the slope of the curve was flatter than that of 40% water-cement ratio. In addition, it can be seen that the concentration of electrodeposits was about 0.1 to 0.12 g/cm^2 at the age of 90 days.

These figures show clearly that electrodeposits can be precipitated on the concrete surface by applying an electrical charge. The concentration of electrodeposits varies according to the water-cement ratio.



(a) before the current application

(b) 3 weeks after electrodeposition

Fig. 4 - Appearance of electrodeposits on the concrete surface

Crack Closure

The development of crack closure is shown in Fig. 6. It is observed that the rates of crack closure increase with the testing period and the closure speed of 67% water-cement ratio is

faster than that of 40% water-cement ratio. It is also observed from Fig. 6 that the rates of crack closure increase rapidly by 10 days and the rates reach close to 100% at the testing period of 30 days.

Coating of Concrete Surface

Fig. 7 shows the relationship between the rate of surface coating and the period of testing. It is observed that the coating rates of 67% water-cement ratio increase rapidly within 4 weeks and then the rates reach up to over 60%. However, in the case of 40% water-cement ratio, the rates are around 50% at the end of the testing period.

In addition, it is observed from Fig. 7 that the coating rates of 40% water-cement ratio decrease at the period of 8 weeks. This may be caused by elution of electrodeposits on the concrete surface. However, after that time the rate of surface coating is recovered due to re-electrodeposition.

From the result of observation on cross-section, it can also be seen that the thickness of the electrodeposit layer on the concrete surface is about 1.0-1.5 mm. With regard to the problem of stability of the electrodeposits, tests are on going and based from preliminary tests on adhesion, the adhesive strength between the electrodeposit and the concrete surface is almost the same value as the tensile strength of concrete.

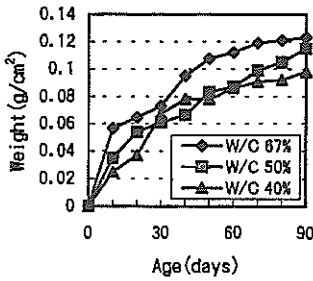


Fig.5 - Weight gain versus age

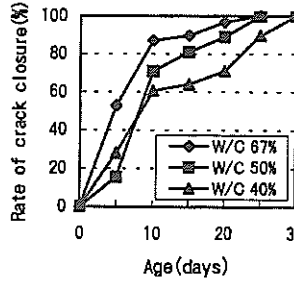


Fig.6 - Rate of crack closure

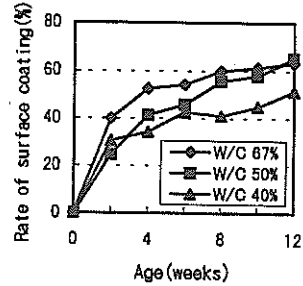


Fig.7 - Rate of surface coating

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 electromigration or electrophoresis. Electromigration is 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.

Test were carried out to examine the effectiveness of electrodeposition method as a means of removing chloride ions from chloride-containing concrete specimens. Chloride content was measured according to the Japan Concrete Institute's method.

Fig. 8 indicates the of chloride removal efficiency near the steel bar in the specimen. It can be seen that efficiency of chloride removal increases with the period of testing and initial chloride content. This is probably due to the fact that the percentage of free chloride increases with increasing total chloride content and the resistance decreases with increasing chloride content. After twelve weeks continuous charging, about 80% decrease in the chloride content was observed around the reinforcing steel. This phenomena seems that negatively charged chloride ions were removed toward the anode in the external solution.

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 are oxidised to oxygen and hydrogen ions. These reactions are referred to as electrolysis, which results in a pH increase around the reinforcement.

Fig. 9 indicates the polarization curve of reinforcing steel as was measured before current application, immediately after treatment, 3 months after treatment. It can be seen that electrodeposition helps to passivate the reinforcing steel after application of the charge. This is probably due to the fact that the pH increases at the reinforcing steel by electrolysis.

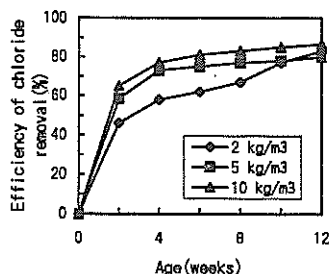


Fig. 8 - Chloride removal efficiency around rebar

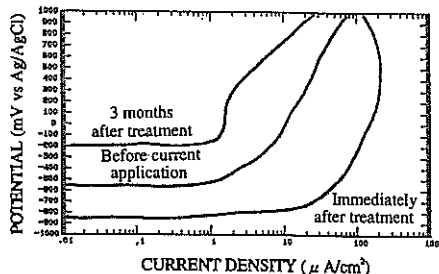


Fig. 9 - Polarization curve of steel rebar

CONCLUSIONS

By applying an electrical charge of 0.5 A/m² between the reinforcing steel in the concrete and an electrode in the external solution, the electrodeposits were precipitated on the concrete surface and in the crack. Owing to the formation of electrodeposits, weight increase of concrete specimen was observed.

The rates of crack closure and surface coating with the test period showed the development of electrodeposition. The cracks were closed almost perfectly at the end of the test period. However, the rates of surface coating varied between 40% and 50%, and these values varied according to the water-cement ratio.

Electrodeposition treatment effectively reduces the chloride content of the concrete and re-passivates the reinforcing steel.

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