

FUNDAMENTAL STUDY ON DESALINATION AND RE-ALKALIZATION OF REINFORCED CONCRETE

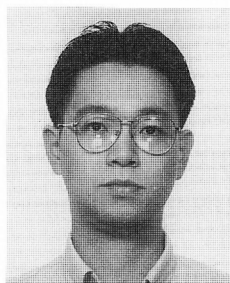
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For the purposes of desalination and re-alkalization, Electrically controlling of ion migration in concrete is considered. However, the mechanisms of ion migration and the effects of this method are still unclear. Therefore, in this paper, the effects and serviceability of electric control methods are experimentally investigated. Two controlling systems, an internal-electrode system (reinforcement was used as a cathode) and an external-electrode system (both electrodes were placed specimen surface), were prepared in this test. To evaluate these systems, contents of chloride ion and alkali ion were measured. Through these investigations, some useful information about the effects of these two systems were discussed.

Keywords: *Desalination, Re-passivation of Reinforcement, Chloride Ion, Internal-electrode system, External-electrode System, Electric Controlling Method, Migrations of Ions*

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1. INTRODUCTION

Deterioration of reinforced concrete structures due to steel corrosion induced by salt damage and carbonation has been drawing attention as a serious problem. It is vital to apply suitable maintenance and repair procedures to deteriorated concrete structures in order to restore their soundness.

Reinforcing steel has conventionally been considered to be protected from corrosion by the presence of a chemically stable film referred to as "passivation film" in the highly alkaline environment inside concrete. However, reinforcement corrosion can occur when this passivation film is destroyed, for example, by chloride ion penetration and diffusion into concrete in marine environments and the resulting lowered pH values due to carbonation. Various measures are taken to inhibit such reinforcement corrosion. Some of them have been applied to real structures, but there have been reported unfortunate examples in which such measures either did not take effect or even accelerated deterioration [1].

In recent years, electrochemical approaches have been attempted to inhibit corrosion of steel reinforcement. These include cathodic protection[2], whereby corrosion is inhibited by maintaining the potential of reinforcing steel sufficiently negative by directly applying minute electric currents, and electro-deposition[3], whereby the surfaces of concrete are coated with inorganic substances, e.g., sodium and calcium in water. As a remedial measure for existing concrete structures deteriorated by salt damage and carbonation, a method referred to as the "desalination/re-alkalization method"[4] is attracting attention. Large electric current, compared with cathodic protection and electro-deposition, are impressed for a short time to deteriorated concrete with the aim of removing chloride ions and re-alkalizing the concrete. This method intends to force chloride ions out of concrete and restore an alkaline atmosphere, thereby restoring the sound environment for reinforcing steel. This method is said to be qualitatively effective, but the migration mechanism of various ions in concrete, as well as analysis techniques, have not yet been sufficiently elucidated.

This study intends to clarify the fundamental points of the desalination/re-alkalization method against chloride-induced corrosion of reinforcing steel in concrete. Specifically, two systems of electric current impression conceivable for this desalination/re-alkalization were tested: an internal electrode system (cathode on reinforcing steel and anodes on the concrete surface) and an external electrode system (cathode and anode on the concrete surface). Their characteristics were compared and investigated to obtain fundamental information for the commercialization of this method.

2. OUTLINE OF DESALINATION / RE-ALKALIZATION METHOD

2.1 Principles

Two systems of electric current impression are conceivable for the desalination/re-alkalization method using an electrochemical technique as shown in Figs. 1 and 2. The reinforcing bars in both Fig. . ures represent bars vulnerable to corrosion, those with damaged passivation films. In the system shown in Fig. 1, the reinforcing bar does not serve as an electrode; the anode and cathode are placed on both sides of the concrete specimen to desalinate and re-alkalize it. This is referred to as the "external electrode system". In this system, chloride ions (negative) migrate towards the

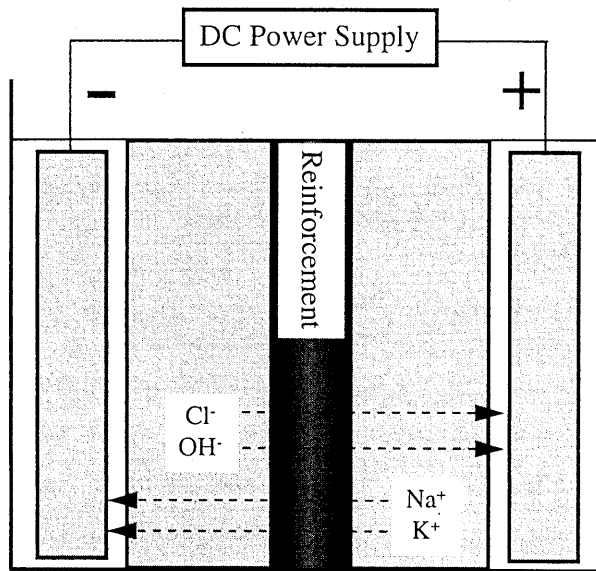


Fig. 1 Schematic Drawing of External Electrode System

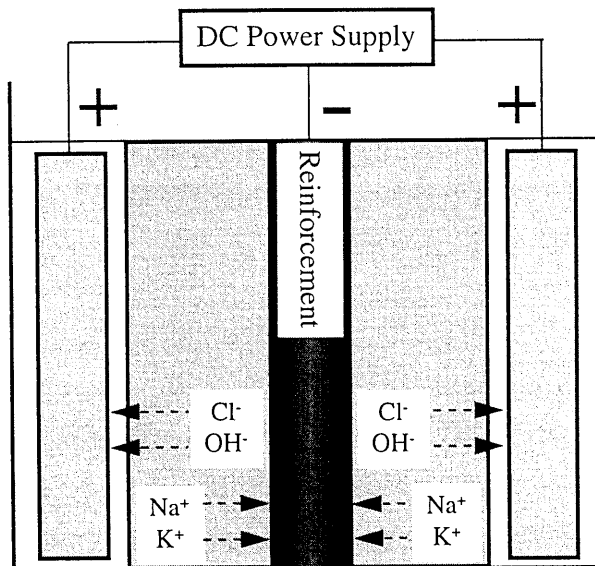


Fig. 2 Schematic Drawing of Internal Electrode System

anode side, and positive ions towards the cathode side. In addition, other suitable ions are supplied from outside to the pore structure. This is considered to accomplish re-alkalization of the concrete, thereby re-passivation of the reinforcing bar.

In the system shown in Fig. 2, the reinforcing bar serves as the cathode, and the anodes are placed on the concrete surface to desalinate and re-alkalize it. This is referred to as the “internal electrode system”. Since chloride ions in the concrete are negative in this system, they migrate from the cathodic bar surface towards the anodes on the concrete surfaces. Conversely, positive ions migrate towards the bar. Hydroxide ions are also generated near the bar, due to the electrolysis of water. Accordingly, an alkaline atmosphere is restored around the bar, which is considered to repassivate the bar. Internal electrode systems have already been applied to real structures.[5]

2.2 Significance

Repair methods for salt-damaged concrete structures include the conventional (1) surface coating method and (2) patching method; recently developed electrochemical techniques, such as the (3) cathodic protection method, (4) electro-deposition method, and the above-mentioned (5) desalination/re-alkalization method.

As stated above, this study focuses on the (5) desalination/re-alkalization method. In this method, the internal electrode system has conventionally been studied and has experience in application to real structures. However, the ion migration, passivation film restoration, and other fundamental mechanisms are yet to be elucidated. In the internal electrode system, there have also been reported that problems such as alkali condensation near the reinforcement are reported as well[6]. The external electrode system is a system newly proposed by the authors with the aim of solving the alkali condensation problem of the internal electrode system, and therefore is only in the first stage. Accordingly, this study intends to elucidate the unknown functioning of the internal electrode system and grasp the basic characteristics of the external electrode system, thereby distinguishing the characteristics of both systems.

3. EXPERIMENTAL PROCEDURES

3.1 Outline

In this study, chloride-induced corrosion of reinforcing steel is classified into two categories, i.e., one induced by extraneous chloride ions and the other induced by intrinsic chloride ions, and each category is investigated using both the internal and external electrode systems. Accordingly, experiments are conducted on four groups of models in which steel reinforcement is embedded in mortar specimens. In these model experiments, the authors focus on the migration of chloride ions in mortar specimens, passivation of reinforcement surfaces, and migration of alkali ions (Na^+ , K^+), to distinguish the characteristics of both systems.

3.2 Materials and Specimens

Mortar specimens with embedded reinforcing bars were fabricated using ordinary portland cement for laboratories, fine aggregate from Japan (Obitsu, Chiba Pref.), and reinforcing bars (SR235-D10, JIS G 3112). Chemical and physical properties of the cement and bars are given in Tables 1 and 2. The bars, 1 cm in diameter and 10cm in length, were immersed in a 10% di-ammonium citrate solution for 24 hours and then were sufficiently cleared of rust and stains before placing. The mix

Table 1 Chemical and Physical Properties of Cement

Physical properties			Chemical properties		
Specific gravity		3.17	i. g. loss	%	0.6
Specific surface area by Blaine	cm ² /g	3270	Insol.	%	0.1
Percentage retained on 88µm sieve	%	0.7	SiO ₂	%	21.3
Setting: water content	%	27.0	Al ₂ O ₃	%	5.3
initial	h-m	2-05	Fe ₂ O ₃	%	2.6
final	h-m	2-55	CaO	%	64.4
Soundness (boil method)		good	MgO	%	2.2
Mortar flow	mm	248	SO ₃	%	1.9
Compressive strength 3 days	kgf/cm ²	157	Na ₂ O	%	0.28
7 days	kgf/cm ²	267	K ₂ O	%	0.60
28 days	kgf/cm ²	425	TiO ₂	%	0.37
Flexural strength 3 days	kgf/cm ²	36	P ₂ O ₅	%	0.20
7 days	kgf/cm ²	55	MnO	%	0.10
28 days	kgf/cm ²	74			

Table 2 Chemical Components of Reinforcement

C (%)	0.013
Si (%)	0.012
Mn (%)	0.049
P (%)	0.0026
S (%)	0.0021

proportions of mortar for intrinsic Cl⁻ were W/C = 0.5, S/C = 3.0 for the internal electrode system, while the external electrode system had two types of mixes, W/C = 0.5 and 1.0, S/C = 3.0. The mixing water for these mortars was added with commonly available salt at a proportion of 10 kg/m³. The mix proportions for extraneous chloride ions were W/C = 1.0 and S/C = 3.0 for both the internal and external electrode systems. The mixes with W/C = 1.0 were added with a methyl cellulose anti-washout underwater admixture at 1.2% by weight of water, to prevent segregation (with the flow spread of the mortars with a W/C of 0.5 and 1.0 being 170 mm and 230 mm, respectively). The materials were mixed in accordance with JIS A 5201 using tap water. After being placed in molds, the specimens were moist-air-cured for 24 hr in a room with a temperature of 20 degrees C. The demolded specimens, with all surfaces except the exposed surfaces sealed with epoxy resin, were then moist-air-cured for 28 days. The specimens for extraneous Cl⁻ were exposed to a 5% NaCl solution for 60 days after curing.

In the case of the external electrode system, both mortars for extraneous and intrinsic Cl⁻ were made into prismatic specimens 10 x 10 x 5 cm in size, with all surfaces except the exposed surfaces sealed with epoxy resin. After confirming the breakdown of passivation film by the polarization curves,

each specimen was glued to the walls of a vinyl chloride container with a sealing compound, leaving no space in between. Five hundred and fifty cubic centimeters of a saturated calcium hydroxide solution was filled and a titanium electrode was immersed in each side of the container, to impress electric currents. The current density was 1 A/m^2 of exposed surfaces. The geometry of the prismatic specimens and the current-impressing set-up are shown in Figs. 3 and 4, respectively.

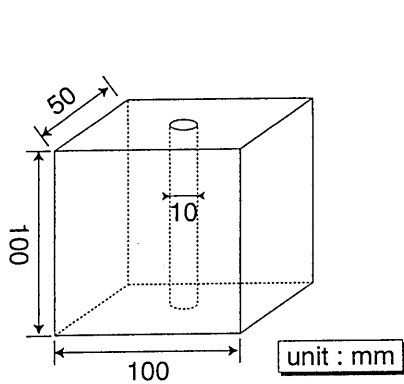


Fig. 3 Geometry of A Prismatic Specimen

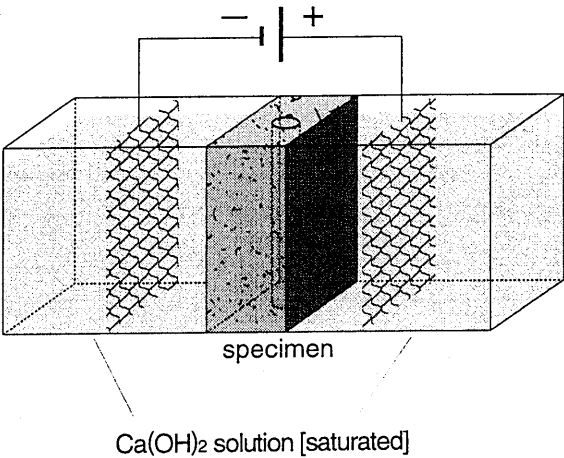


Fig. 4 External Electrode System Setup

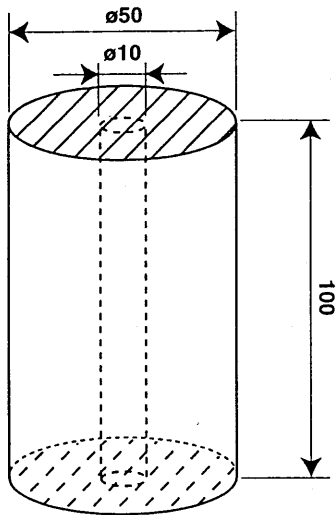


Fig. 5 Geometry of a Cylindrical Specimen

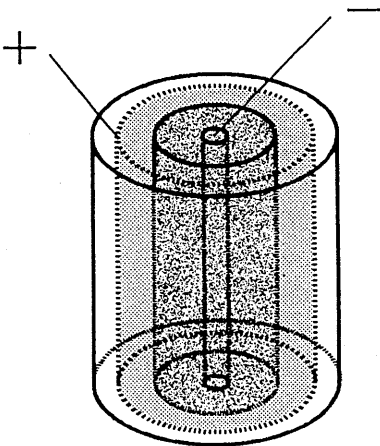


Fig. 6 Setup for a Cylindrical Specimen
(Internal Electrode System)

In the case of the internal electrode system, the specimens for intrinsic Cl^- were cylinders 5 cm in diameter and 10 cm in length with lead-out wire connected to each bar after the mortar was placed in the mold. The mortar specimens for extraneous Cl^- were prisms $10 \times 10 \times 5$ cm in size, with the bar placed in the center. After confirming the breakdown of passivation film, the container in which a specimen and titanium electrodes were placed was filled with 700 to 1000 cm^3 of a saturated calcium hydroxide solution, to impress electric currents. The current density was 5 A/m^2 of the reinforcement surface area. The cylindrical and prismatic specimens used for this experiment are shown in Figs. 5 and 3, respectively, and their current-impressing set-ups are shown in Figs. 6 and 7, respectively.

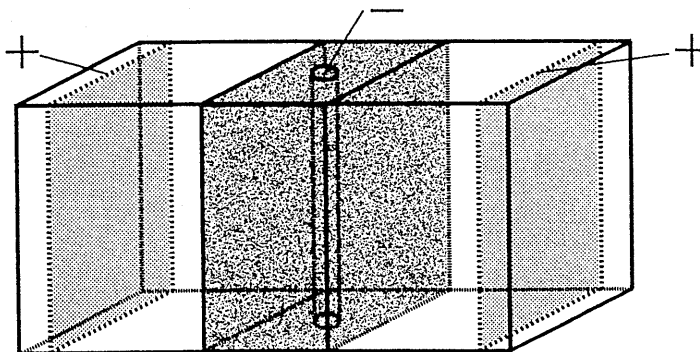


Fig. 7 Setup for A Prismatic Specimen
(External Electrode System)

3.3 Measurement Items

a) Potential Difference

The potential differences between cathodes and anodes were measured using a tester.

b) Content of Chloride Ions Expelled from The Specimens

1 cc of the external solution was taken, and the changes in chloride concentration over time were measured without refilling the sampled amount.

c) Soluble Chloride Ion Content

The portions to be measured were cut from each specimen with a dry diamond cutter, and then after 1 week, 1 month, and 2 months of current impression. The samples were dried for 24 hours at 105 degrees C in a drying oven, and the water absorption of each portion was calculated from the difference in weights before and after the drying. Ten grams of each sample sieved with a $105 \mu\text{m}$ standard sieve was then taken and immersed in 100 g of distilled water for 24 hours. The chloride ion concentration of these sample solutions was measured.

d) Polarization Curves

A full-automatic polarizer which combines a potentiostat (output voltage: max. $\pm 50\text{V}$, output

current: max. +/- 1A) and a function generator (potential range: -9999 mV to +9999 mV, minimum setting: 1 mV) was used. A saturated silver chloride electrode was used as the reference electrode.

e) Alkali Ion Content

The portions to be measured were cut out from each specimen with a dry diamond cutter before, and after 1 week, 1 month, and 2 months of current impression. The samples were dried for 24 hours at 105 degrees C in a drying oven. 10 g of each sample sieved with a 105 μm standard sieve was then taken and dissolved in 100 g of distilled water, and boiled for 10 min. After being left to cool down, the solution was filtered, and the filtrate was analyzed by means of ion-exchange chromatography.

4. RESULTS AND DISCUSSIONS

4.1 External Electrode System

a) Desalination Effects

The measurements of potential differences are plotted in Fig. 8. These potential differences contain the solution resistance between the electrodes, potential differences across the specimen, and potential losses at the electrodes due to the electrode reaction. The potential loss by the electrode reaction measured at the laboratory was approximately 2V[7]. This suggests that actual potential differences across the specimen may not be very large as compared with the solution resistance and potential losses by the electrode reaction. These results reveal that a lower W/C requires a higher potential difference. This Fig. 8 shows little difference between the potential differences of the specimens with a W/C of 1.0 for intrinsic and extraneous Cl^- . The measurements of the amounts of chloride ions expelled from the specimens are shown in Fig. 9. In the case of the external electrode system, the amounts of both intrinsic and extraneous chloride ions leaving the specimens increase almost linearly over the current impression time. Table 3 compares intrinsic and extraneous chloride ions of specimens with $\text{W/C} = 1.0$ under impressed currents, in terms of the total desalination due to the combined effects of current impression and diffusion, as well as the chloride removal rates indicating only the effects of the impressed currents.

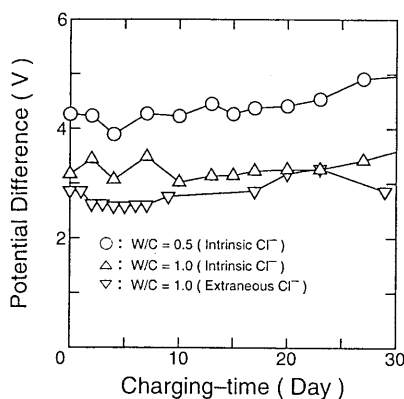


Fig. 8 Changes in Potential Difference Over Time (External Electrode System)

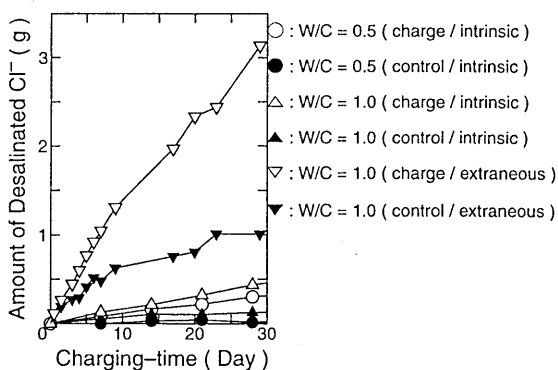


Fig. 9 Chloride Ions Migrating Out of The Specimen (External Electrode System)

Table 3 Total Amount Desalinated and Percentage Removed by Impressed Currents

	Total amount desalinated		Percentage of Cl^- removal by current impression	
	Intrinsic	Extraneous	Intrinsic	Extraneous
Before charging	3 g	11 g	—	—
After 1 w.	0.13 g (4.3%)	1.05 g (9.6%)	2.0 %	5.5 %
After 1 mo.	0.48 g (15.8%)	3.13 g (28.5%)	9.6 %	19.5 %

The values in parentheses indicate the rate of desalination = $\frac{(\text{total amount desalinated})}{(\text{total amount of } \text{Cl}^- \text{ present before current impression})}$

Total amount desalinated = (amount desalinated only by current impression) + (amount desalinated only by natural diffusion)

Percentage of Cl^- removal by current impression = $\frac{(\text{total amount desalinated}) - (\text{amount desalinated by natural diffusion})}{(\text{total amount of } \text{Cl}^- \text{ present before current impression})}$

The chloride removal rate in this table, which is an index for the ease of desalination by impressed currents, is obtained by subtracting the amount of expelled ions due to natural diffusion from the total amount of expelled ions in the external solution at each age, and by dividing this by the total chloride ion amount contained in the specimen before the diffusion/current impression. In other words, ions indicating a higher value can be desalinated more easily. This table indicates that, in the case of a specimen for intrinsic Cl^- , approximately 3 g of chloride ions were contained before current impression and only 15% was removed after a current impression for one month, while in the case of an extraneous Cl^- specimen, one month of current impression led to removal of 30% of the 11g of chloride ions that had penetrated before the diffusion/current impression. At each age, extraneous chloride ions are found to be slightly more easily expelled than intrinsic chloride ions by impressed currents.

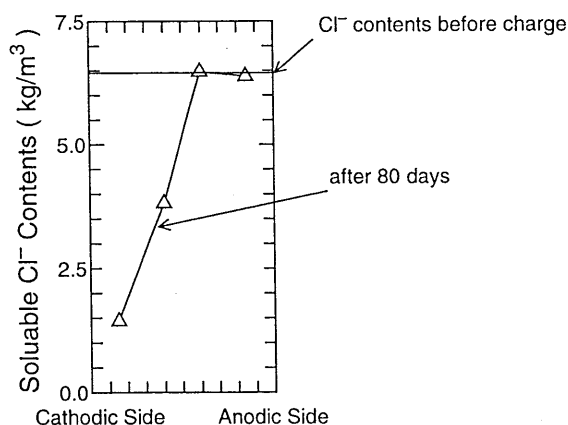


Fig. 10 Soluble Chloride Ion Content Distribution (W/C = 1.0, Intrinsic)

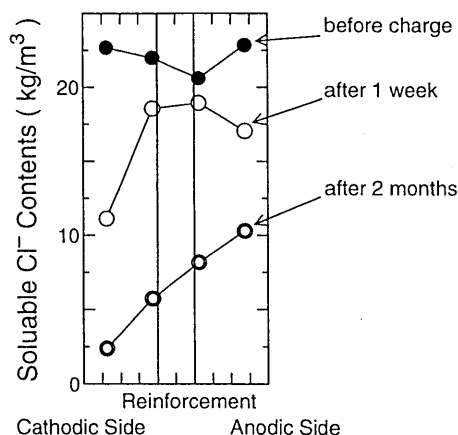


Fig. 11 Soluble Chloride Ion Content Distribution (W/C = 1.0, Extraneous)

The changes in soluble chloride ion content distribution in the specimens are shown in Figs. 10 and 11. Fig. 10 shows the measured soluble chloride ion content after 80 days of current impression in the specimens for intrinsic Cl^- ($W/C = 1.0$). Fig. 11 shows the soluble chloride ion content distributions in the specimens extraneous Cl^- ($W/C = 1.0$). Though the specimens are generally desalinated, with chloride ions migrating from the cathodic side to the anodic side, little change is observed in the chloride ion content near the bar in the specimens for intrinsic Cl^- . On the other hand, the specimens for extraneous Cl^- are desalinated, with 60 to 70% of the soluble chloride ions initially present removed, even from around the bar after, 2 months of current impression, though chloride ions with a significantly high concentration of 7.5 kg/m^3 are still present around the bar. Further current impression may therefore be necessary to remove chloride ions from around the bar.

Consequently, it was found that the external electrode system is considered to be capable of removing chloride ions from all portions of mortar, but that it takes a significantly long time to desalinate the specimens with such minute currents, particularly from around the reinforcement. This low efficiency of desalination may be attributed to the saturated calcium hydroxide solution used as the external solution, in which the abundant hydroxide ions may participate in most of the ion migration, hampering the migration of chloride ions[7]. This poses a number of subjects to be investigated, such as the (1) extension of current impression time and (2) selection of a suitable external solution in order to increase chloride ion transference.

b) Passivation of Reinforcing Steel

The changes in polarization curves are shown in Figs. 12 through 14. Fig. 12 shows those of specimens for intrinsic Cl^- with a W/C of 0.5; Fig. 13, intrinsic Cl^- , $W/C = 1.0$, and Fig. 14, extraneous Cl^- , $W/C = 1.0$; The curves represent the results before, immediately after, and 1 week after a current impression of 2 months. The curves of the specimens for intrinsic Cl^- shown in Figs. 12 and 13 indicate little change in the surface conditions of the bars, showing little sign of improvement. This may be because the chloride ion content near the bar remained high, causing little improvement in the environment of the bar, as indicated in Fig. 10.

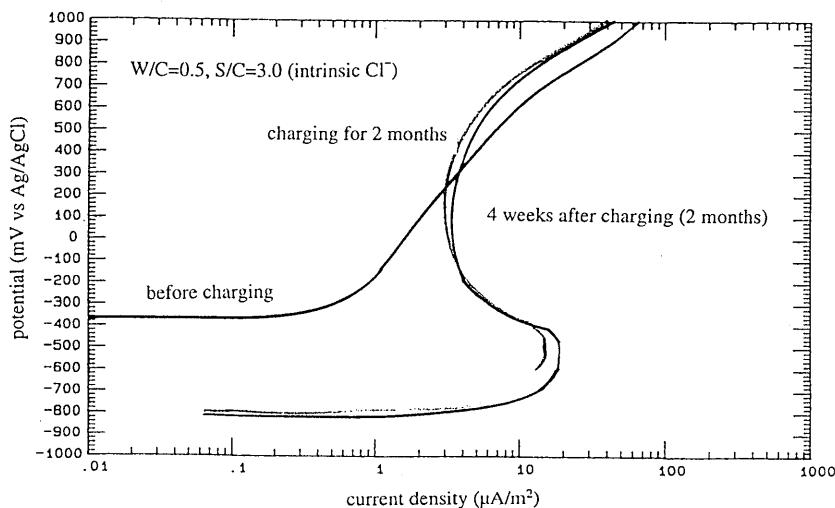


Fig. 12 Polarization Curves of Reinforcement

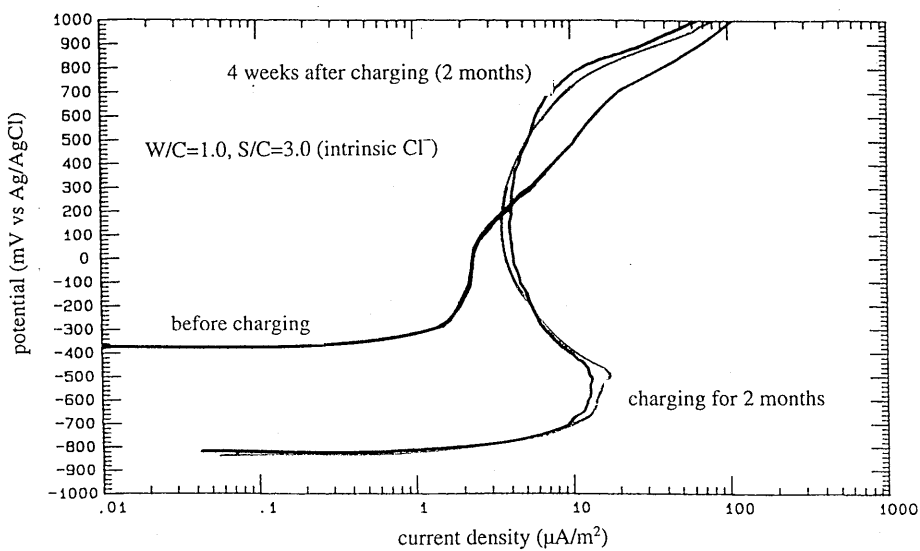


Fig. 13 Polarization Curves of Reinforcement

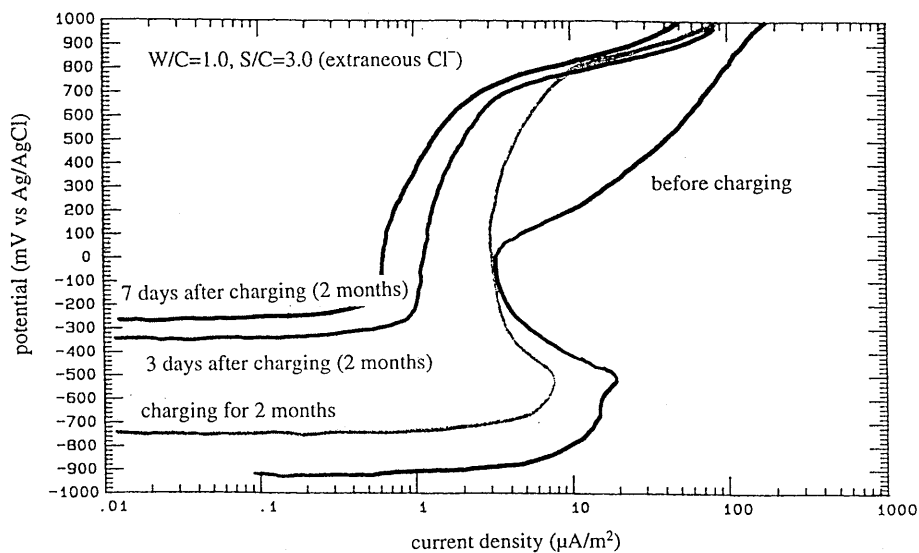


Fig. 14 Polarization Curves of Reinforcement

In Fig. 14, which refers to extraneous Cl⁻, the condition of the bar surface is significantly improved, due to the substantial reduction of chloride ions from around the bar, as stated in the previous section “Desalination Effects”. However, a large number of chloride ions still remain present near the bar after 2 months of current impression, as shown in Fig. 11. Further current impression for thorough removal of the chloride ions is important, in order to improve the condition of reinforcement.

c) Alkali Ion Content

The distributions of alkali ions, i.e., Na⁺ and K⁺, are shown in Figs. 15 and 16. Fig. 15 shows the measurements in the specimens for intrinsic Cl⁻ with a W/C of 1.0 after 80 days of current impression. Fig. 16 shows the changes over time in the specimens for extraneous Cl⁻ with a W/C of 1.0. These results suggest that alkali ions migrate, opposit to chloride ions, from the anodic side to the cathodic side. A comparison between Fig. 15 and Fig. 16 also reveals that Na⁺ ions penetrating from outside are more readily migratable. Accordingly, this system reduced excessive alkali ions in all areas of specimens, suggesting the possibility of solving problems due to alkali condensation, such as alkali-aggregate reaction. The external electrode system is considered to be effective not only as a desalinating process, but also for structures with a risk of alkali-aggregate reaction.

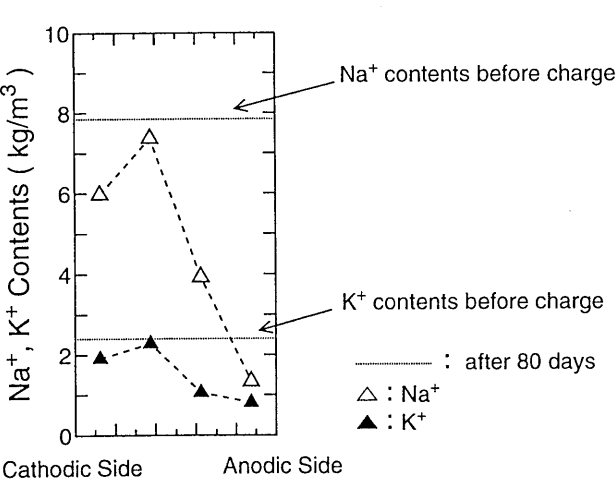


Fig. 15 Na⁺ and K⁺ Content Distributions
(W/C = 1.0, Intrinsic)

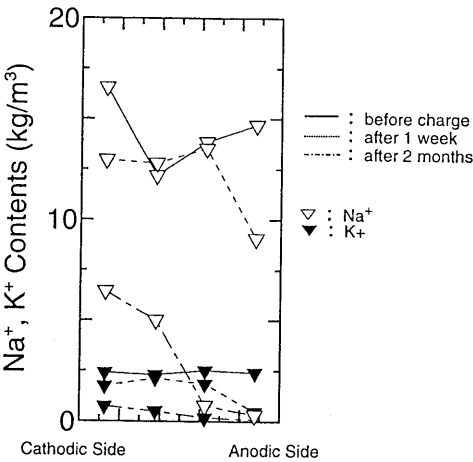


Fig. 16 Na⁺ and K⁺ Content Distributions
(W/C = 1.0, Extraneous)

Consequently, the external electrode system was found to be capable of desalinating all parts of concrete, causing no problems of alkali condensation, though the time required to improve the environment of reinforcement is long. It can also be said that extraneous chloride ions are more easily expelled than intrinsic chloride ions from specimens with the same mix proportions.

4.2 Internal Electrode System

a) Desalination Effects

The measurements of the potential differences are shown in Fig. 17. The potential differences are constant, independent of the period of current impression. The measurements of the amount of chloride ions expelled from the specimens are then shown in Fig. 18. This Figure suggests a tendency for the amount of chloride ions expelled from the specimens to increase linearly over the current impression time, though the slope gradually becomes less steep, and few chloride ions are expelled after a certain period of current impression. This may be because free chloride ions were expelled relatively easily at the beginning of the current impression, but such chloride ions decreased with time, and those absorbed by aggregate and cement were then forced to begin to migrate. Seen from another aspect, the increase in hydroxide ions near the bar may have hampered the migration of chloride ions.

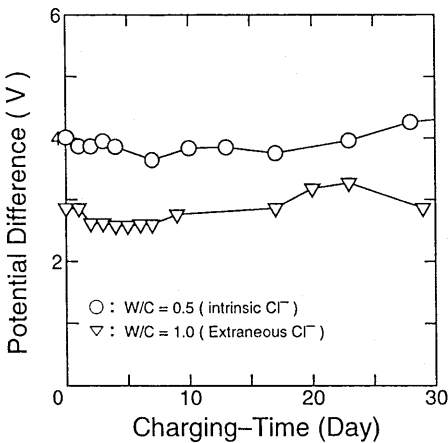


Fig. 17 Changes in Potential Difference Over Time (Internal Electrode System)

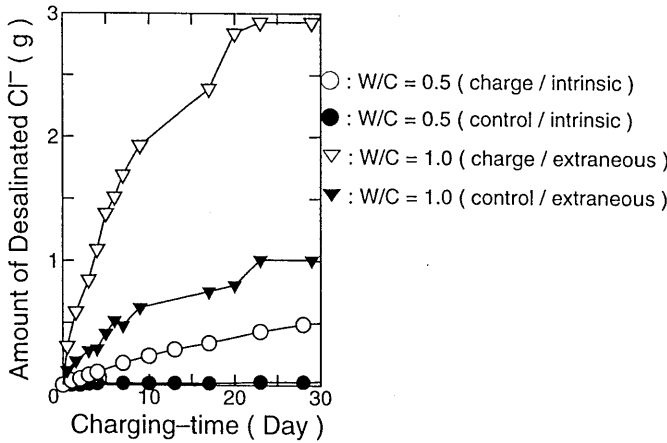


Fig. 18 Chloride Ions Migrating Out of The Specimen (Internal Electrode System)

The differences in the chloride ion distribution over time under impressed currents are then shown in Figs. 19 and 20. Fig. 19 shows the results of the specimens for intrinsic Cl⁻ with a W/C of 0.5, and Fig. 20 those of specimens for extraneous Cl⁻, W/C = 1.0. Both Figures indicate that chloride ions were removed from around the bar and gradually reduced. Nearly 90% of soluble chloride ions in the specimens for intrinsic Cl⁻ were removed from around the bar after a current impression of 2 months. In spite of this quick reduction from around the bar, a high content of soluble chloride ions is, however, still present near mortar surfaces. This suggests that the chloride ions unremoved and remaining near the mortar surfaces could naturally diffuse back in the mortar and accumulate around reinforcement after the current impression is discontinued. This concern should also be investigated.

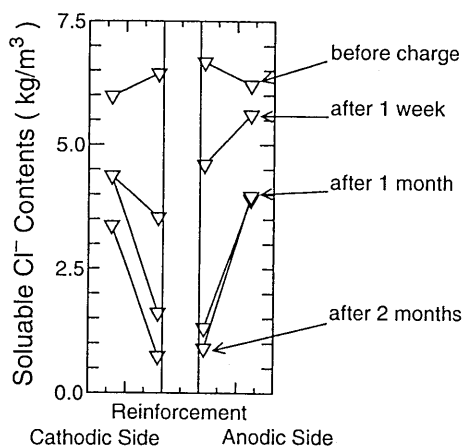


Fig. 19 Soluble Chloride Ion Content Distribution
(W/C=1.0, Intrinsic)

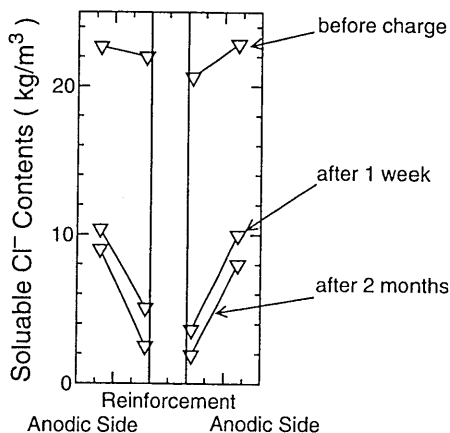


Fig. 20 Soluble Chloride Ion Content Distribution
(W/C = 1.0, Extraneous)

b) Passivation of Reinforcing Steel

The changes in polarization curves over time of the specimens for intrinsic Cl^- (W/C = 0.5) and extraneous Cl^- (W/C = 1.0) are shown in Figs. 21 and 22, respectively.

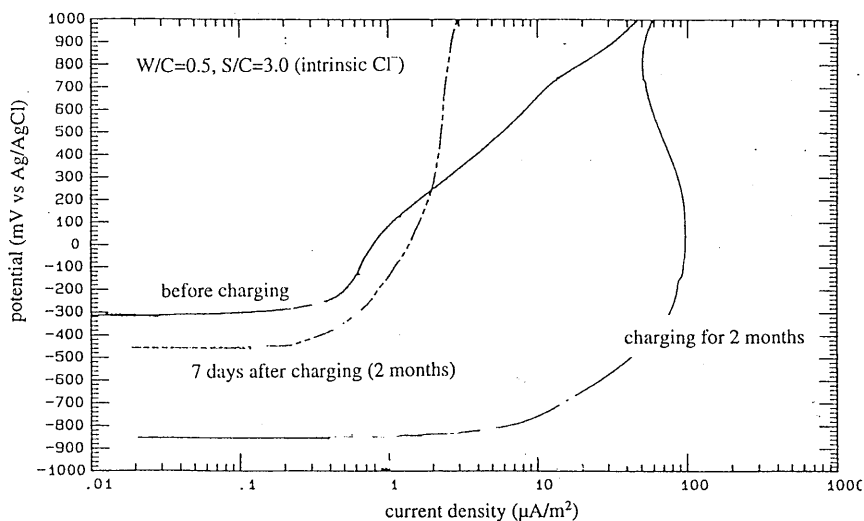


Fig. 21 Polarization Curves of Internal Reinforcement
(W/C = 0.5, Intrinsic)

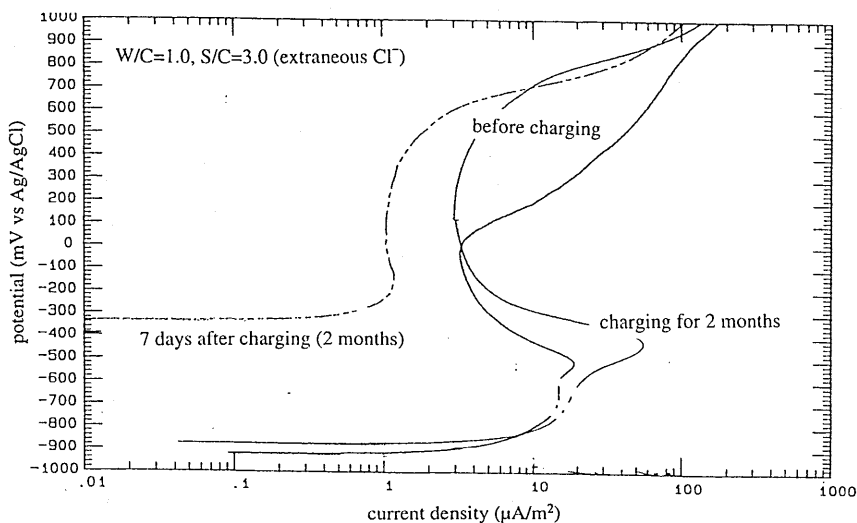


Fig. 21 Polarization Curves of Internal Reinforcement
(W/C = 1.0, Extraneous)

The measurements were made prior to, immediately after, 1 week after a 2-month current impression. These results evidently show the effects of impressed currents. A passivation film re-formed on the bar surface is found to be more stable than by the external electrode system. This may be mostly due to the removal of chloride ions from around the bar and due to re-alkalization in the mortar.

c) Alkali ion content

The measured distributions of alkali ion contents are shown in Figs. 23 and 24. Figs. 23 and 24 show the changes in Na^+ and K^+ ion distributions over time in the specimens for intrinsic Cl^- (W/C = 0.5) and extraneous Cl^- (W/C = 1.0), respectively.

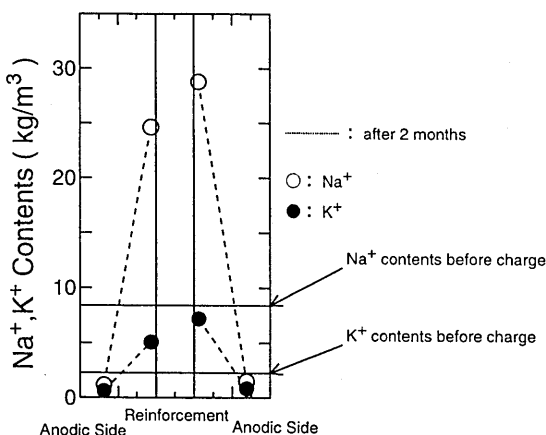


Fig. 23 Na^+ and K^+ content distributions
(W/C = 0.5, Intrinsic)

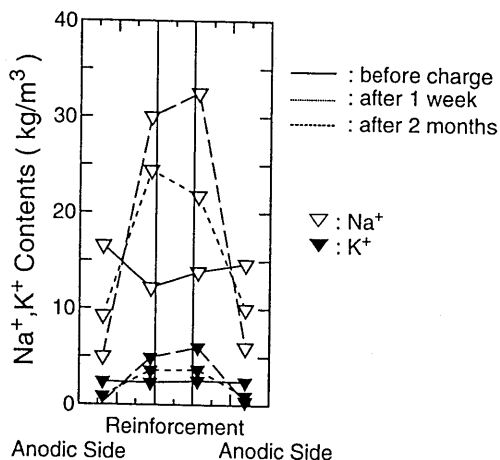


Fig. 24 Na^+ and K^+ content distributions
(W/C = 1.0, Extraneous)

These Figures suggest that impressed currents caused the Na^+ and K^+ ions to quickly concentrate around the bar. In Fig. 23, the amounts of alkali ions near the bar after a 2-month current impression increased to approximately three times the amount before current impression, while the amount of alkali ions near the mortar surfaces decreased to nearly one fifth. The maximum alkali ion content normally required for protective measures against alkali-aggregate reaction is 3.2 kg/m^3 [8]. Seen in this light, the internal electrode system is found to leave a significantly high risk of alkali-aggregate reaction near reinforcement, though it is capable of reducing such risks near mortar surfaces.

Consequently, it was found that the internal electrode system quickly effects temporary desalination and re-alkalization around reinforcement, but also causes problems due to alkali concentration near reinforcement.

5. COMPARISON BETWEEN THE INTERNAL AND EXTERNAL ELECTRODE SYSTEMS

The characteristics of the internal and external electrode systems are summarized from the experimental results as given in Table 4. This table shows that both systems have relative strengths and weaknesses. Both systems naturally lead to different migration behaviors. The ion migration (ion exchange) by the internal electrode system proceeds quickly near the bar, due to the steeper potential gradient nearer to the bar. On the other hand, the ion migration (ion exchange) by the external electrode system is carried out at a constant rate, as the potential gradient is constant everywhere.

Table 4 Comparison Between Characteristics of Electric Current Impressing Methods

	Intrinsic Cl^-		Extraneous Cl^-	
	External electrode system	Internal electrode system	External electrode system	Internal electrode system
Desalination	- Cl^- ions migrate from the cathodic side to the anodic side at a constant rate. - Desalination from all over the concrete is possible, but a long duration of minute current impression is necessary.	- Cl^- ions migrate quickly around rebars and slowly near concrete surfaces.	- Cl^- ions migrate from the cathodic side to the anodic side. Desalination from all over the concrete is possible, but a long duration of minute current impression is necessary.	- Cl^- ions are removed from around rebars. Desalination efficiency diminishes with the duration of current impression.
Passivation of rebars	- A long duration of minute current impression is necessary for repassivation of rebars. - Current density is restricted by rebar corrosion due to stray currents.	- Repassivation is completed by a short current impression.	- Passivating films are re-formed earlier than the case of intrinsic Cl^-. - Current density is restricted by rebar corrosion due to stray currents.	- Repassivation is completed by a short current impression.
Alkali concentration	- No alkali concentration of Na^+ and K^+. - Risk of AAR in concrete is reduced.	- Na^+ and K^+ ions concentrate around rebars. - Risk of AAR is high around rebars.	- No alkali concentration of Na^+ and K^+. - Na^+ ions penetrating from outside (extraneous Na^+) migrate more readily than intrinsic Na^+.	- Na^+ and K^+ ions concentrate around rebars. - Risk of AAR is high around rebars.

In other words, whereas the conventional internal electrode system is capable of desalinating and re-alkalizing mortar near reinforcing steel by temporarily impressed currents, it was found to cause quick alkali concentration as a reverse phenomenon. The external electrode system was found to be capable of desalinating and re-alkalizing mortar by long-range impression of weak electric currents without causing alkali concentration. It was also confirmed that desalination is more effective when the chloride ions involved in corrosion are extraneous instead of intrinsic. It is known that when a piece of metal is placed in an electrolytic aqueous solution with a potential gradient, electric currents generally flow into the metal at the high potential end and out from the low potential end, causing corrosion of the metal[9].

In the present experiments, in which a current density of 1 A/m^2 of exposed surfaces of the mortar specimens was adopted, no corrosion was observed to be induced by such stray currents. In fact, experimental results obtained in our laboratory included those in which a current density of 1 A/m^2 caused no such corrosion, while a current of 10 A/m^2 caused electrolytic corrosion. Stray currents associated with the application of the external electrode system should be examined in detail, as to the optimum current density, potential difference across the specimen, selection of the external solution, etc.

This study clarified the strengths and weaknesses of both systems. Further investigation was found to be necessary to commercialize these systems.

6. CONCLUSIONS

These experiments led to the following conclusions:

(1) About External Electrode System;

- a) This system is capable of removing chloride ions from all over the specimen by impressing electric currents. Extended impression of minute currents may re-form passivation films.
- b) Impressed currents reduce alkali ions, eliminating the problems caused by alkali concentration.

(2) About Internal Electrode System;

- a) This system is capable of removing chloride ions from around reinforcement by impressed currents and re-form sound passivation films.
- b) Impressed currents cause alkali ions to accumulate around the bar, suggesting a risk of problems due to alkali concentration.

(3) When comparing electric migration of intrinsic and extraneous chloride ions, extraneous chloride ions tend to migrate more readily.

It is important to the strengths of both internal and external electrode systems in order to commercialize this method. For structures where alkali concentration is of primary concern, an external electrode system with extended current impression time should be adopted the internal electrode system. Further investigation is required so that both systems are used individually or in combination to adapt to the situation of actual structures in a rational manner.

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