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The environmental load reduction effect by the desalination method of construction and the re-alkalization method of construction

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ABSTRACT

In this study, desalination method and re-alkalization method were examined as electrochemical repair methods for concrete, and the environmental load reduction effects of each method, as applied to actual RC concrete structures, were examined in comparison with the conventional pach repair method. Since the desalination method and the re-alkalization method rarely require chipping of degraded parts or use of pach repair mortar, environmental load can be significantly reduced by either method, even if power consumption for energization is taken into consideration. Comparing the environmental load reduction effects, it was found that carbon-dioxide emission could be reduced to approximately 7% with the re-alkalization method and to approximately 37% with the desalination method, compared to the pach repair method. Furthermore, in the case of the desalination method, even greater environmental load reduction effects were confirmed when the prediction of degradation after repair is taken into consideration.

Keywords. Desalination, Re-alkalization, The environmental load reduction effect, CO_2, Pach repair, Carbon-dioxide emission

1. Introduction

The construction industry, which aimed at developing social capital to keep pace with high economic growth in the past, is now changing course to maintaining social capital. From such a viewpoint, priority is shifting from construction of new structures to maintenance and management of existing structures, and development of efficient technology to enhance durability is required. Under these circumstances, electrochemical repair method for concrete structure is considered to be an effective repair method against degradation phenomena where reinforced concrete is corroded, such as neutralization and salt damage.

In the past, methods such as the surface treatment method and the pach repair method were employed to repair the degradation of concrete structures involving steel corrosion. These methods had both advantages and problems; in particular, the pach repair method is a method with high environmental load because it uses pach repair mortar such as mortar, which increase the amount of cement used for repair, after degraded concrete is chipped off[1)].

Thus, in the present study, we calculated the amount of carbon-dioxide emission when re-alkalization construction method and desalination construction method were applied to steel-reinforced concrete structures as electrochemical repair methods and compared the results to cases where the conventional pach repair method was used. In addition, environmental load was evaluated for desalination method taking into consideration the in-service period of the structure and prediction of re-degradation.

2. Outline of the experiment

2.1 Environmental load evaluation

To calculate the amount of carbon-dioxide emitted during construction for the re-alkalization method and the desalination method, construction steps of each method are described as follows: First, part of concrete is chipped off and lead wire is attached to reinforced concrete to form a cathode. Using titanium mesh and such as anode material, anode is temporarily constructed on the concrete surface and connected to DC power supply together with the lead line on the cathode side. After the electrodes are installed, alkaline solution has to be supplied. Methods to supply the electrolyte solution include the fiber method and the panel method, which are commercially used. DC current is applied on the concrete surface at current density of 1.0A/m^2 for two weeks in the case of re-alkalization method and eight weeks in the case of desalination method. During energization, electrolyte solution is replenished as needed by spraying. After energization is completed and re-alkalization effects and desalination effects are measured, temporary anode is removed.

The items and conditions that cause emission of carbon dioxide during construction using the re-alkalization method, desalination method and pach repair method were assumed as listed in **Table 1** and **Table 2**. In this calculation, the construction area was assumed to be 200 m^2 of concrete structure. For the pach repair method, the use of the spray method was assumed due to the large construction area. A water-cement ratio of 35% and a sand-cement ratio of 2 to 1 were assumed for the composition of mortar used for pach repair. 80 mm of the covering was assumed to be chipped off. Fiber method was assumed for the re-alkalization method and desalination method. In this method, cellulose fiber, which was recycled from old newspapers and magazines, is used as retention material for the electrolyte solution. Although cellulose fiber has the opposite effect of carbon dioxide emission, this effect was omitted in the present study. Also, since carbonate solution is often used as electrolyte solution in the re-alkalization method and it absorbs and produces carbon dioxide, this effect was taken into consideration. Carbon dioxide emission intensity[2)] used for the calculation is shown in **Table 3**.

Table 1. Calculation conditions for CO_2 emission for re-alkalization and desalination methods

Construction item	Calculation conditions
Electrolyte solution	Consumption during energization: 1,160kg (re-alkalization)※
	Consumption during energization: 1,660kg (desalination)
Spraying of electrolyte solution	Construction time: 8 h/day×2 days
	Pump power: 200V, 18A (1 unit)
Resupply of electrolyte solution	Construction time: 4 h/day×14 days (re-alkalization method)
	Construction time: 4 h/day×56 days (desalination method)
	Pump power: 200V, 10A (1 unit)
Energization	Construction time: 4 h/day×14 days (re-alkalization method)
	Construction time: 4 h/day×56 days (desalination method)
	DC power: 200V, 50A (1 unit)
Disposal of temporary anode materials	Titanium mesh, wood, etc.
Transportation	10-ton truck (one truck, 30km)

※Electrolyte solution used in re-alkalization method is calculated as CO_2 absorption.

Table 2. Calculation conditions for CO_2 emission for pach repair method

Construction item	Calculation conditions
Chipping of concrete	Equipment used: Air pick (2 units)
	Construction time: 8 h/day×10 days
	Power: Diesel oil 7.5L/h
Mixing of repair mortar	Equipment used: Mortar mixer (1 unit)
	Construction time: 8 h/day×10 days
	Power: 1kW
Spraying of repair mortar	Equipment used: Squeeze pump (1 unit)
	Construction time: 8 h/day×10 days
	Power: 3.7kW
	Equipment used: Compressor (1 unit)
	Construction time: 8 h/day×10 days
	Power: Diesel oil 7.5L/h
Repair mortar (W/C=35%, C/S=1/2)	Ordinaly Portland cement Crushed sand
Disposal of chipped concrete	Chipped concrete
Transportation	20-ton truck (2 trucks, 30km) 10-ton dump truck (4 trucks, 30km)

Table 3. CO_2 emission intensity[2)]

Classification	CO_2 emission intensity
Ordinary Portland cement	765.5 [kg-CO_2/t]
Crushed sand	3.4 [kg-CO_2/t]
Electric power	0.37 [kg-CO_2/kWh]
Diesel oil	2.64 [kg-CO_2/L]
Disposal (control type)	3.3 [kg-CO_2/t]
Disposal (stable type)	1.6 [kg-CO_2/t]

2.2 Desalination method[3)]

Desalination method was applied to a bridge support made of reinforced concrete on a national road facing the Sea of Japan. The bridge support, which is located about 50 meters inland from the rocky coastline, had been damaged by flying seawater. For desalination method, cellulose fiber was sprayed on concrete together with saturated calcium hydroxide solution and direct current of $1A/m^2$ (at voltage of 20-30V) was applied for eight weeks. After the energizing process, the anode electrode, cellulose fiber and rectangular lumber were removed, concrete surface was washed with high-pressure water and cleaned, and the desalination method was completed.

2.3 Measurement items

To verify the conditions before and after the desalination method and the durability after the treatment, the salt content and polarization resistance inside the concrete were measured. Follow-up survey after the treatment was conducted one, three and five years after the completion of desalination.

(1) Salt content

Core samples (φ10cm×20cm) were collected from each of the four sides (north, south, east and west) of the bridge support, which were cut into slices at a 2-cm interval from the surface. Then, after each slice was crushed to 0.15mm or less and dissolved in nitric acid solution to extract chlorine, total salt content was measured by the potentiometric titration method.

(2) Polarization resistance

Polarization resistance was measured by collecting core samples (φ10cm) with the reinforcing bar contained in the center and measuring the anode polarization curve with a fully-automatic polarization curve measurement device. Relation between the electric potential and current was measured by changing the electric potential from the natural potential to +1000 mV at a sweep rate of 1 mV/sec. Polarization resistance of the reinforced concrete was calculated from the inclination at the natural potential position in the measured curve[4)], after polarizing the sample from the natural potential to +50 mV to the anode side.

3. Experimental results and examination

3.1 Calculation results of carbon-dioxide emission

Calculation results of the amount of carbon-dioxide emission during construction by the re-alkalization, desalination and pach repair methods are shown in **Figure 1**. Also, breakdown of the carbon-dioxide emission for the re-alkalization and pach repair methods are shown in **Figure 2** and **Figure 3**. The results show that cement-based repair mortar, which have a high rate of carbon-dioxide emission, accounted for a large portion of the emission in the pach repair method, while emission from the electricity used in energization accounted for most of the emission in the re-alkalization and desalination methods. The amount of carbon-dioxide emission during construction by the re-alkalization method and the desalination method was approximately 7% and 37%, respectively, compared to the pach repair method, showing a significant effect in reducing the environmental load.

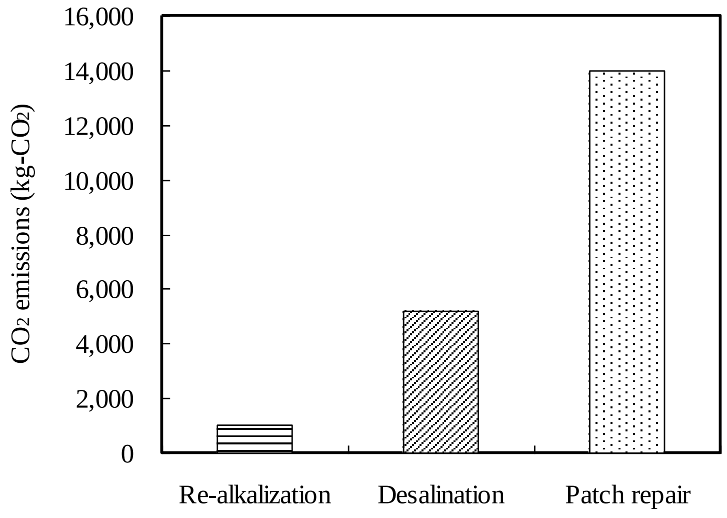
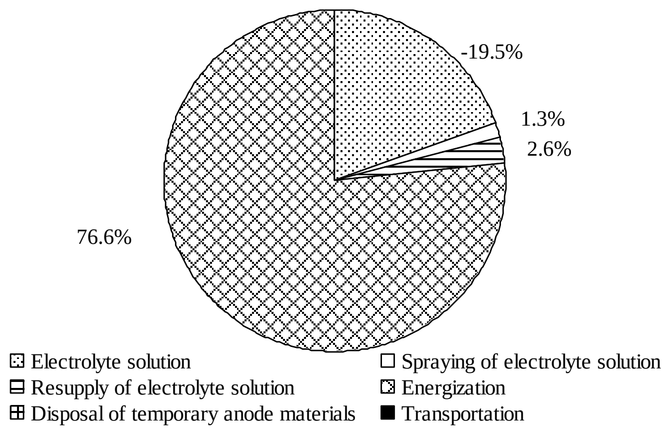


Figure 1. Total carbon-dioxide emission for each construction method



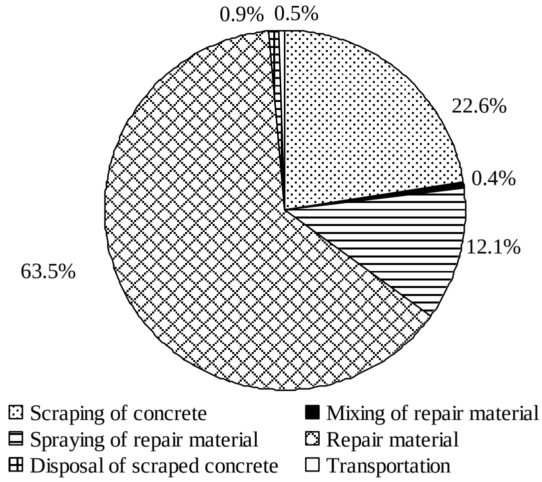


Figure 2. Breakdown of CO_2 emission for re-alkalization method

Figure 3. Breakdown of CO_2 emission for pach repair method

3.2 Change in salt content in the desalination method

Total salt content in the depth direction of concrete before and after desalination method is shown in **Figure 4**. Only the results for the east side of the bridge support is shown, where the salt content was highest before desalination method. The results show that salt content near the reinforcing bar can be significantly reduced by desalination method, causing salt to migrate from the inside of concrete to the surface by electrophoresis. In five years after the desalination method, salt content has gradually increased over time at the concrete surface. It is conceivable that salt has newly penetrated into the concrete because concrete is not treated with surface covering. On the other hand, there was almost no variation in salt content at the reinforcing bar, compared to right after the desalination method. Concrete on the west, south and north sides of the bridge support also showed similar tendencies.

3.3 Polarization resistance

Polarization resistance values are shown in **Table 4**. Polarization resistance, which was 8.6-19.4 kΩ・cm^2 before desalination, increased to 33.7-56.9 kΩ・cm^2 at one year after method and to 75.8-156.3 kΩ・cm^2 at five years after treatment, showing that concrete was shifting to a healthy condition that prevents corrosion of reinforcing bar.

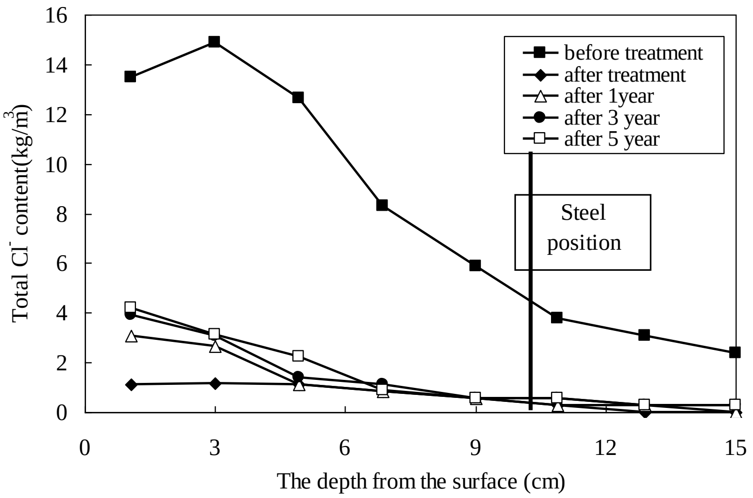


Figure 4. Total salt content before and after desalination method

Table 4. Polarization resistance values(kΩ cm^2)

	before treatment	after 1 year	after 3 year	after 5 year
east sides	8.6	56.7	—	76.9
west sides	18.5	56.9	—	75.8
south sides	13.4	33.3	—	156.3
north sides	19.4	47.1	52.6	100.0

Table 5. The average corrosion depth per year PDY(×10^{-3}mm/year)

	before treatment	after 1 year	after 3 year	after 5 year
east sides	34.8	5.3	—	3.9
west sides	16.2	5.5	—	3.9
south sides	22.0	9.0	—	2.0
north sides	15.1	6.4	5.7	3.0
Average	22.0	6.6	5.7	3.2

3.4 Prediction of re-degradation

In CEB-FIP[5)], criterion for the corrosion rate of reinforcing bar is determined by using the corrosion current density. Also, yearly average corrosion depth PDY (mm/year) can be derived from the corrosion current density, based on Faraday's Second Law. PDY can be calculated from expression (1), using polarization resistance Rct in **Table 4** and assuming a proportionality constant of K=0.026 (V)[6)].

$$PDY=K\times(1/R_{ct})\times11.6 \qquad (1)$$

PDY values, before and after desalination method, are shown in **Table 5**. PDY, which was 0.0151-0.0348 mm before desalination, decreased to roughly one-third at one year after treatment and to roughly one-seventh at five years after treatment.

Corrosion limit for reinforcing bar with uneven surface corrosions such as pitting corrosion is known to be 80-100 mg/cm^2, based on outdoor exposure tests and investigation results of actual structures. This value is converted to corrosion depth of 0.10-0.13 mm (0.12 mm on average) by dividing it with iron density (7.8g/cm^3). Therefore, it is predicted that crack will occur in concrete when corrosion on the surface of reinforcing bar reaches the depth of roughly 0.12 mm.

Because PDY before desalination method is 0.0220mm (average value) from **Table 5**, the time period for corrosion depth to reach 0.12 mm is roughly five years. Since PDY at five years after treatment is 0.0032 mm (average value), the time period for corrosion depth to reach 0.12 mm is roughly 38 years. In other words, whereas untreated concrete will start to develop cracks roughly five years after reinforcing bar starts corroding, it will take roughly 38 years for treated concrete to develop new cracks.

Permeation of chloride ion into concrete can be generally expressed by the Fick's Second Law, because it is considered that chloride ion permeates into the inside of structures through pore solution in the concrete hardening body by concentration diffusion. Assuming an initial condition of $C(x,0)=0$ and boundary condition of $C(0,t)=C_0$ (constant), permeation of chloride ion can be expressed as in expression (2) below.

$$C(x,t)=C_0(1-\mathrm{erf}(x/(2(D\cdot t)^{1/2})) \qquad (2)$$

C_0: amount of surface salt content, erf: error function

Assuming an in-service period of five years, the surface salt content C_0 on the east side of the bridge support under test is calculated to be 5.28 kg/m^3 at five years after desalination method from expression (2) and the diffusion coefficient D of chloride ion will be 8.68×10^{-8} cm^2/s. Also, since the surface salt content C_0 in actual structures tends to increase with time and can be deemed to be proportional to square root of time[7], as in expression (3).

$$C_0=S\times t^{1/2} \qquad (3)$$

Based on the surface salt content C_0 at five years after desalination method and the diffusion coefficient D of chloride ion, $S=4.2\times10^{-4}$(kg/m^3・s$^{1/2}$) is derived from expression (3). Using this expression, salt content at 5-20 years after desalination method was predicted from expression (2). The results are shown in **Figure 5**. In the figure, the rough standard for the allowable salt content at the reinforcing bar position,1.2 kg/m^3, as provided in the draft standard of the Japan Society of Civil Engineers[8], is shown with a dotted line.

Assuming the allowable salt content at the reinforcing bar position to be 1.2 kg/m^3 on the east side of the bridge support under test, the time period for sufficient amount of chloride ion to permeate to cause the reinforcing bar to start corroding is predicted to be roughly 10 years after desalination method. Therefore, under a condition where flying salt content is continuously supplied, in order to ensure at least 10 years of in-service period, it is preferable to provide surface coating treatment such as paint after desalination treatment. In such cases, the time period for treated concrete to develop cracks due to re-degradation is estimated to be roughly 38 years as previously mentioned, since there is no need to consider re-permeation of salt.

3.5 Environmental load evaluation

Environmental load was evaluated based on the in-service period of the structure and prediction of re-degradation. **Figure 6** shows a schematic diagram of degradation prediction where pach repair, desalination method and surface coating treatment after desalination are applied. It is assumed that the structure will be restored at the point in time when its performance has degraded to the minimum required level, and the structure will continue to be used thereafter. In the case of pach repair, it is known that re-degradation will occur in a

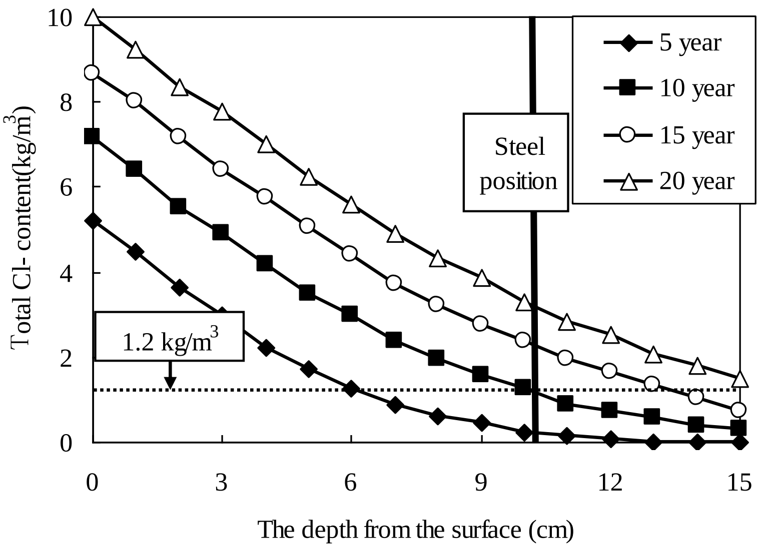


Figure 5. **Prediction salt content at 5-20 years after desalination method**

short period of time due to macro cell corrosion. It was therefore assumed that re-degradation will occur after roughly 10 years, as with the cases where desalination method is applied. On the other hand, the frequency of restoration can be reduced because it will take roughly 38 years before re-degradation will occur when surface coating treatment is applied after desalination, as previously mentioned.

Figure 7 shows the environmental load for the duration of the in-service period of 50 years after restoring the structure once. It is assumed that the effectiveness of the second or subsequent restoration will be the same as the first restoration. Desalination method will reduce the environmental load by roughly 30% compared to the pach repair method. Also, when surface coating treatment is applied after desalination treatment, there is no need to restore the structure again for roughly 38 years. Comparing at 50 years of in-service period, the environmental load will be reduced by roughly 85% compared to the pach repair method.

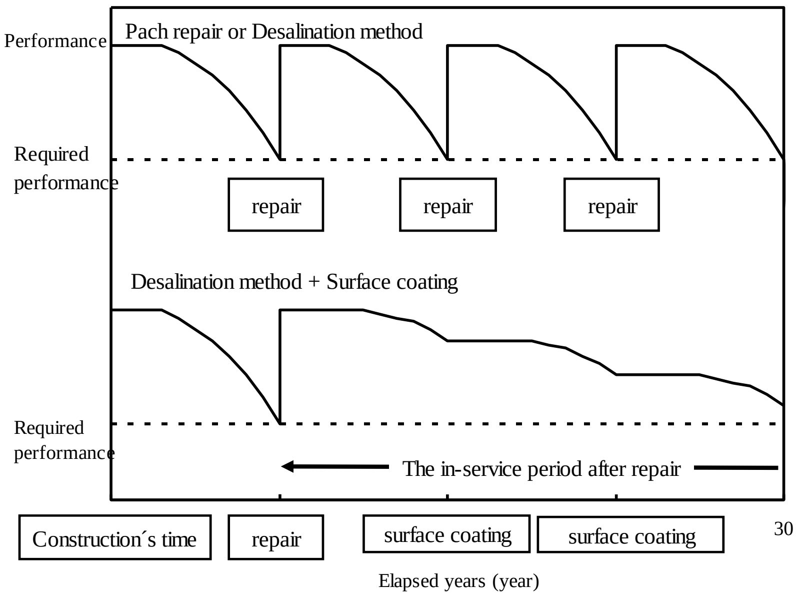


Figure 6 Prediction of re-degradation.

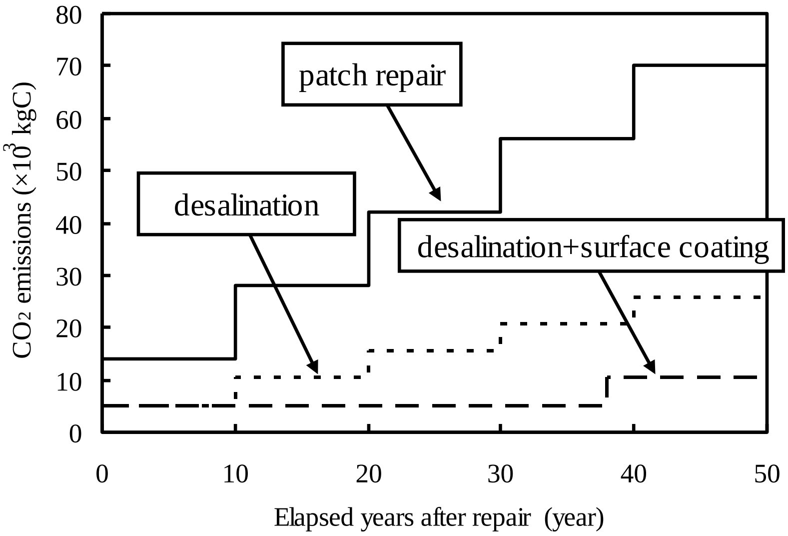


Figure 7 Elapsed years after repair and CO_2 emissions

4. Conclusions

1) The amount of carbon-dioxide emission during construction by the re-alkalization method and the desalination method was approximately 7% and 37%, respectively, compared to the pach repair method, showing a significant effect in reducing the environmental load.

2) For the structures examined in the present study, the anti-corrosion performance of the reinforcing bar that was restored by desalination method is estimated to be roughly 10 years when flying salt content is continuously supplied, and roughly 38 years flying salt content is not supplied.

3) Desalination method was found to be effective in reducing the environmental load compared to the conventional pach repair method, as environmental load was evaluated based on the in-service period of the structure and prediction of re-degradation. Environmental load reduction effect of the re-alkalization method is expected to be even higher when considering the prediction of re-degradation, because carbon-dioxide emission during construction is lower and resistance to re-neutralization is provided by the buffer action. Details on this subject will be issues for the future.

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