Journal of Asian Concrete Federation
Vol. 3, No. 1, pp. 20-26, June 2017
ISSN 2465-7964 / eISSN 2465-7972
http://dx.doi.org/10.18702/acf.2017.06.3.1.20

Technical Paper

Diffusion of moisture and chloride ions in repaired concrete subjected to complex deterioration factors

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(Received: January 04, 2017; Accepted: May 23, 2017; Published online: July 05, 2017)

Abstract: Repairing a reinforced concrete structure reduces various deterioration factors, such as chloride ions, and extends its service life. However, short-term redeterioration has frequently been reported in repaired concrete. Although many researchers have tried to find the cause of short-term redeterioration in repaired concrete, the mechanism remains unclear. In this study, experimental investigation was conducted into the causes of short-term redeterioration in repaired concretes subjected to chloride-induced damage and complex deterioration (chloride-induced damage and frost damage) environments. According to the results, the complex deterioration environment increases the ingress of chloride ions into concrete to a greater degree than the chloride-induced damage environment. A patch material with frost resistance and dense structure, such as polymer cement mortar, reduces the transfer of chloride ions and moisture. These characteristics protect repaired concrete from short-term redeterioration.

Keywords: chloride ion content, moisture content, complex deterioration, redeterioration, chloride-induced damage, frost damage.

1. Introduction

The durability of reinforced concrete is vital to the sustainability of infrastructure. The deterioration of concrete reduces the durability of reinforced concrete structures. Since the “Japanese economic miracle” beginning in the 1950s, when many reinforced concrete structures were constructed, a significant number have deteriorated: in 2016, 20% of the total number of bridges in Japan were superannuated [1]. In general, the durability of reinforced concrete is influenced by various deterioration factors. One way to enhance durability is to mend the deteriorated concrete using patch repair. However, this approach is not a long-term solution because the redeterioration of concrete treated using patch repair occurs shortly after treatment (1–2 years) [2, 3]. Many researchers have tried to find the cause of short-term redeterioration in repaired concrete [4-7].

In cold regions, the short-term redeterioration of concrete has been reported to occur through complex deterioration [2, 8]: i.e., the mutual interference of frost damage and chloride-induced damage aggravates the deterioration of concrete [9]. When concrete is subjected to freezing and thawing in presence of chloride ion penetration, chloride ion concentration [10] and osmotic pressure increase. Scaling may occur on the surface of the concrete due to frost damage, allowing chloride ions to easily reach the rebar through the cover concrete [11].

This study examined the performance of repair materials in the complex deterioration environment of frost damage and chloride-induced damage. The moisture and chloride ion penetration from the repair material was studied to obtain a fundamental understanding of the cause of short-term redeterioration. A sodium chloride solution absorption test from one side and a freeze-thaw test were conducted to verify the behavior of moisture and chloride ions in concrete repaired by two different patch materials.

2. Experimental program

2.1 Experimental plan

Table 1 shows the experimental plan. The moisture and chloride ion contents of the repaired concrete were measured in the chloride-induced damage and complex deterioration environments, respectively. Differences in chloride ion content

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according to the repair material were also investigated.

Repair materials with frost resistance and dense structure are able to reduce the diffusion rates of moisture and chloride ions. Based on previous studies [12], cement mortar was selected as a material with relatively low frost resistance and no ability to inhibit chloride ion ingress. Polymer cement mortar was selected as a material with high frost resistance and greater effectiveness for inhibiting the penetration of chloride ions.

2.2 Experimental method

Concrete cylindrical specimens were fabricated at a size of ⌀100 × 200 mm using the mix proportions shown in Table 2. The specimens were subjected to two weeks of curing in water and two weeks of curing in air. The specimens were cut into samples of ⌀100 × 100 mm. A total of 13 specimen configurations were designed according to the deterioration conditions and patch materials. 6 sets of specimens (1 set = 2 specimens) were used to measure the chloride ion content by specified time interval, respectively. The remaining specimen was used to measure the moisture content as shown in Table 1. The specimens were sealed with epoxy to restrain water absorption from sides other than the testing surface. The testing surface of each specimen was exposed to 3.5% sodium chloride solution for one week. After exposure to the sodium chloride solution, the specimens were covered by polyethylene bags to maintain the moisture content.

The experimental conditions were set as follows: Case 1) chloride-induced damage condition (20℃ and 60% relative humidity) and Case 2) complex deterioration condition (freeze-thaw cycles from -20℃ to 20℃). These conditions simulated the moisture and chloride ion transfer through the patch material caused by the complex deterioration of repaired concrete.

The top 30 mm of each specimen, which had absorbed sodium chloride solution from one side for a week, was cut off. These portions were considered to have been deteriorated by chloride ions. Each specimen was then repaired using cement mortar with a water cement ratio (W/C) of 0.50 or polymer cement mortar, the mixture proportions of which are shown in Tables 3 and 4. The repaired specimens were exposed for four weeks to each deterioration environment (Case 1 and Case 2).

Figure 1 shows the experimental flow of moisture and chloride ion contents. Specimens were measured at the marked points (●). Measurements were conducted before deterioration (O), before repair (1stD), and after repair during redeterioration. After 1stD, moisture content and chloride ion measurements were performed for four successive weeks (1W, 2W, 3W, 4W), as shown in Fig. 1. To investigate the transfer of moisture and chloride ions from the testing surface through the repair material and the concrete, the specimens were divided into four sections: 0 mm (the testing surface)–15 mm (1F), 15–30 mm (2F), 30–45 mm (3F), and 45–60 mm (4F), as shown in Fig. 2. The interval was set at 15 mm to install moisture sensor electrodes in the specimen. The moisture sensor consisted of two parallel electrodes. The length configuration of the moisture sensor is shown in Fig. 3: a (radius of an electrode) < d (distance between two electrodes) < L (length of an electrode) [13]. To determine the moisture content, the temperature of the specimen and specific resistance (ρ) were first measured using thermocouple and electrode gauge specific resistance (ρ), respectively. Finally, moisture content was calculated through Eq. (1) using the measured values.

$$M = \frac{\frac{3892}{273+t} - \ln(\rho) + 1.576}{1.085} \tag{1}$$

where M: moisture content (%)
t: measured temperature (℃)
ρ: specific resistance (Ω·mm)

Each specimen was cut into four sections (1F–4F), and chloride ion content was then measured using the potentiometric titration method of JIS A 1154. Because of the differences in total chloride ion content between concrete, cement mortar, and polymer cement mortar, the initial chloride ion content of all specimens was set as 0%.

3. Results and discussion

3.1 Chloride ion content

The chloride ion content measurements were classified depending on the deterioration environment and patch material. Figure 4 shows the cumulative value of chloride ion contents at 1F–4F. Before the repair (1stD in Fig. 1), the cumulative chloride ion content (1F–4F) is 1.1 kg/m^3 in Case 1 and 6.5 kg/m^3 in Case 2. Three weeks (3W) after repair, the chloride ion content of the specimen repaired with cement mortar is 5.0 kg/m^3 in Case 1 and 30.0 kg/m^3 in Case 2; the content in Case 2 is thus six times as large as that in Case 1. This result shows that the chloride ion content increased because of the cracks and scaling due to frost damage. The concentration of chloride ions in concrete associated with growing ice crystals in the

Table 1 – Experimental plan

Environmental deterioration	Repair material	Measurement item (Specimen configuration)
- Case 1: Chloride-induced damage Absorption of sodium solution (NaCl 3.5%) Temperature 20℃, relative humidity 60% - Case 2: Complex deterioration (Chloride-induced damage and frost damage) Absorption of sodium solution (NaCl 3.5%) Freezing and thawing (-20℃ (2.5h)–20℃ (1.5h))	- Cement mortar (CM) - Polymer cement mortar (PCM)	- Chloride ion content* 1st set: before deterioration (O) 2nd set: before repair (1stD) 3rd set: at 1w 4th set: at 2w 5th set: at 3w 6th set: at 4w Total: 12 specimens (2 specimens × 6 set) - Moisture content** Total: 1 specimen (1 × six times measurement)

NOTE: *JIS A 1154 (Potentiometric titration method); **Specific resistance measurement for electrode method [13]

Table 2 – Mixture proportions of concrete

W/C (%)	s/a (%)	Unit amount (kg/m^3)				Air content (%)	Compressive strength (N/mm^2)	Total chloride ion content (kg/m^3)
		Water	Cement	Fine aggregate	Coarse aggregate			
50	44.4	185	370	816	1,025	0.9	39.6	0.15

Table 3 – Mixture proportions of cement mortar

W/C (%)	c/s (%)	Unit amount (kg/m^3)			Compressive strength (N/mm^2)	Bulk density (kg/m^3)	Total chloride ion content (kg/m^3)
		Water	Cement	Fine aggregate			
50	45	305	610	1,345	18.98	2,147	0.3

Table 4 – Mixture proportions of polymer cement mortar

Division	Main component	Mixing ratio (mass ratio)	Bulk density (kg/m^3)	Total chloride ion content (kg/m^3)
Main materials	Vinyl fibers, lightweight aggregate, ready-mixed mortar	20	1,315	3
Hardener	Cationic-SBR resin	5		

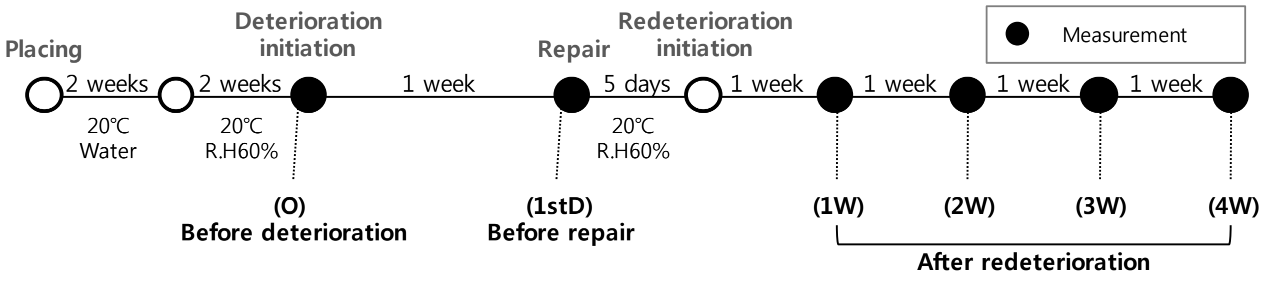


Fig. 1 – Experimental flow

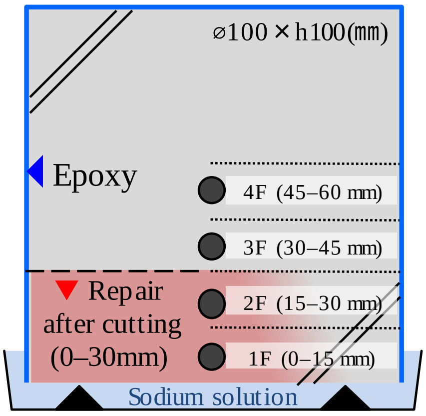


Fig. 2 – Specimen treatment

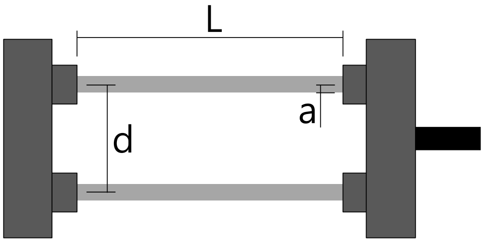


Fig. 3 – Moisture sensor

pores should be also considered [14]. Figure 5 shows an example of scaling in the specimen. The specimen was repaired using polymer cement mortar and exposed to complex deterioration (Case 2).

To evaluate the effectiveness of the patch materials against complex deterioration, the chloride ion contents of the patch materials (cement mortar and polymer cement mortar) were compared. At 3W in Case 1 (see Fig. 4), the chloride ion content (1F + 2F) in the cement mortar (5.0 kg/m^3) is higher than that in specimen repaired by polymer cement mortar (2.37 kg/m^3). Polymer cement mortar has a denser structure than does cement mortar. Therefore, chloride ion transfer in the specimen was affected by the porosity of the repair material [15]. Chloride ions were not detected in PCM-2F because polymer cement mortar has a highly dense structure and prevented chloride ion infiltration into concrete. Under both exposure conditions (Case 1 and Case 2) with PCM, chloride ion contents in the concrete parts (3F and 4F) increased. In particular, in Case 1 with PCM, the chloride ion content of 3F + 4F increased from 0 kg/m^3 (1stD) to 9.10 kg/m^3 (3W) (see Figure 1: processing of 1stD and 3W, Fig. 4: chloride ion contents). Therefore, chloride ions in the specimen moved from the patch material to the concrete (3F and 4F). Conversely, the chloride ion content in CM-2F–4F increased because of the high permeability in Case 2.

In all specimens, the chloride ion content increased from the start of the redeterioration test. However, the chloride ion content decreased in 4W, except for Case 1 with PCM. Chloride ion content increase is generally predicted because of the sodium chloride solution supply, as shown in Fig. 4(b) (Case 1 with PCM). However, in this study, this phenomenon did not occur clearly. Two factors are associated with the chloride ion decrease. First, water did not move due to the freezing of the sodium solution during the freezing process. Second, the increasing chloride ion concentration in the unfrozen part led to a high-concentration sodium solution, which caused moisture movement to the opposite direction. However, these factors are insufficient to explain the reduction of chloride ion contents after 4W. Further research is necessary to investigate the reason for this phenomenon.

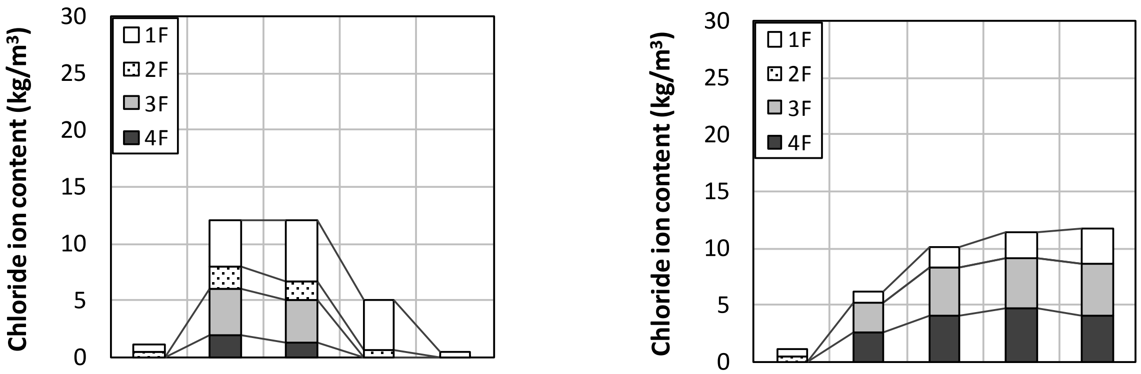
3.2 Moisture content

The moisture content of the specimen was measured to evaluate the effect of moisture on chloride ion transfer. Figure 6 shows that some of the moisture contents of the specimens were 0% because Eq. (1) was based on a previous study [13].

The moisture content of the cement mortar and polymer cement mortar was generally higher in Case 2 than in Case 1. Additionally, the moisture content in 1F of the specimens in Case 2 showed a gradual increase. The increase of moisture content can be explained by micro-ice-lens formation [16]. Micro-ice-lens formation generates microscale ice crystals (about 150 nm). The process of ice crystal production is as follows: 1) gel water and a cement matrix initiate frost shrinkage in the gel pores during freezing; 2) the gel water moves to the ice crystal; 3) the gel water in the ice crystal increases. This phenomenon (micro-ice-lens formation) is one of the causes for the moisture increases of the specimens [16, 17].

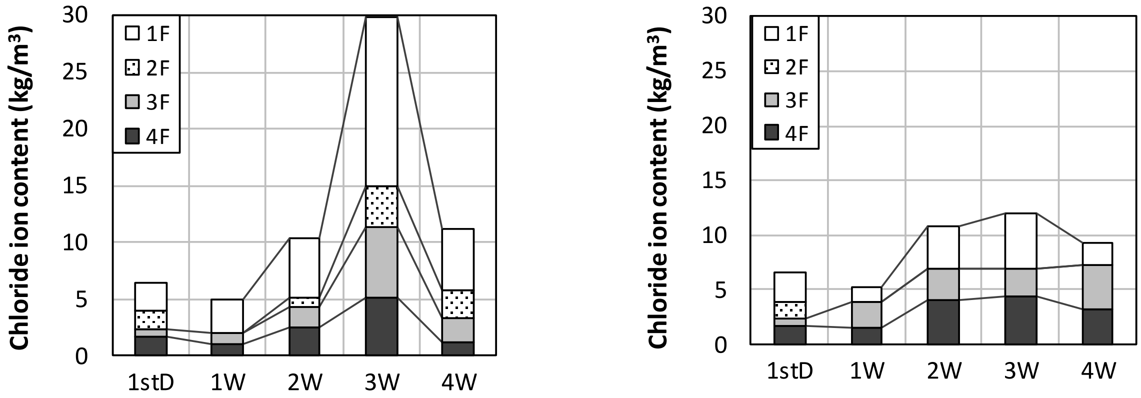
The moisture contents of the specimens repaired with cement mortar were higher than those of the specimens repaired with polymer cement mortar. The highly dense polymer cement mortar prevented moisture transfer to the specimens. Low moisture content was also observed in 3F for each specimen in Case 1 because this portion dried when the repair material was added.

These results, when compared with the chloride ion content results, show that specimens experiencing a moisture content increase also



(a) Cement mortar (Case 1)

(b) Polymer cement mortar (Case 1)



(c) Cement mortar (Case 2)

(d) Polymer cement mortar (Case 2)

Fig. 4 – Chloride ion contents by deterioration environment and repair material

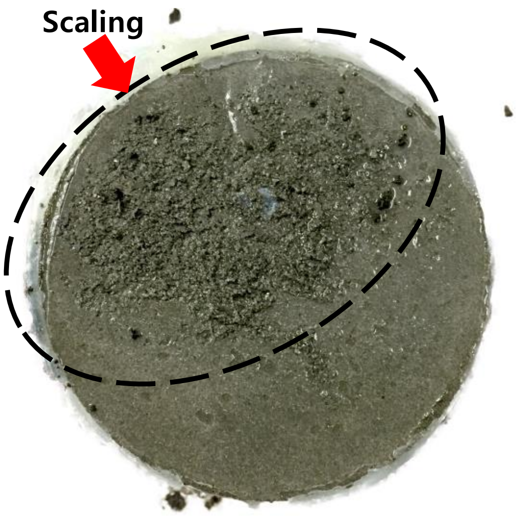


Fig. 5 – Scaling in polymer cement mortar due to freezing and thawing

experienced a greater chloride ion increase. Therefore, the chloride ion concentration in the repair material moved with the transfer of moisture content.

4. Conclusions

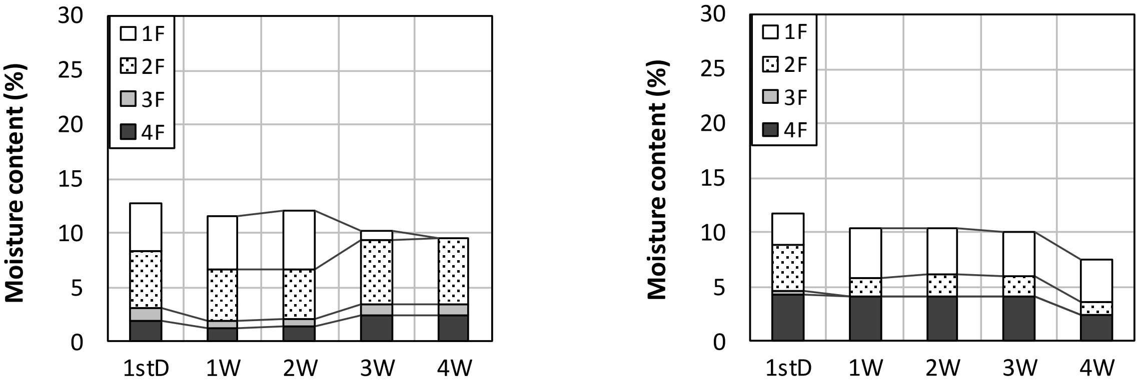
This study experimentally investigated the cause of short-term re-deterioration in repaired concrete subjected to chloride-induced damage and complex deterioration (chloride-induced damage and frost damage) environments. The conclusions are as follows:

(1) The permeability of chloride ions into concrete was higher in the complex deterioration environment than in the chloride-induced damage environment.

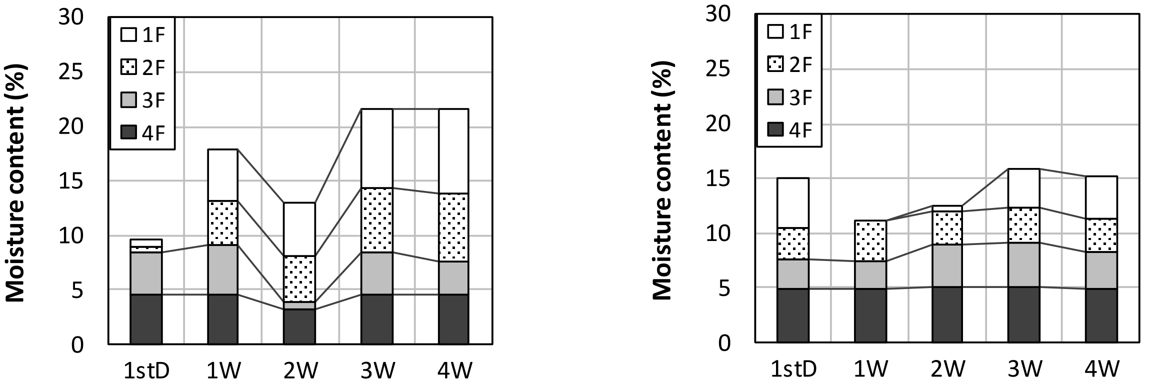
(2) Chloride ions in the concrete and repair material moved with the transfer of moisture content.

(3) The preventive effect of polymer cement mortar as a repair material against the transfer of chloride ions and moisture was higher than that of cement mortar.

The initial chloride ion contents of the concrete were neglected because this study focused on the differences of chloride ion content associated with deterioration environment and patch material. However, this initial chloride ion concentration of



(a) Cement mortar (Case 1) (b) Polymer cement mortar (Case 1)



(c) Cement mortar (Case 2) (d) Polymer cement mortar (Case 2)

Fig. 6 – Moisture content by deterioration environment and repair material

the original concrete may bring about short-term redeterioration. Therefore, future works should focus on the cause of increased chloride ion content in the initial concrete and investigate the diffusion velocity of chloride ions by water.

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