Investigation of Chloride Penetration and Steel Corrosion in Repaired Concrete after Exposure to Marine Environment of Thailand

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Abstract

This paper aims to investigate the chloride penetration and the steel corrosion in the repaired concrete specimen after exposure to the marine environment of Thailand. The repaired concrete specimen was made in the laboratory and then exposed to the tidal zone of the marine site. There were two parts in the repaired concrete specimen, which were original concrete (OC) and replaced concrete (RC). Cement-only concrete and fly-ash concrete with water to binder ratio (w/b) of 0.65 were used for making the OC, while the RC was produced from fly-ash concrete with w/b of 0.55. The binder replacement by fly ash was employed at 30% and 50%. From the experimental results, it was found that types of concrete in the OC and RC significantly affected the chloride penetration and steel corrosion in the repaired concrete specimen. Chloride penetration resistance of the repaired concrete specimen that the RC made from fly-ash concrete with 50% of FA was higher than that from fly-ash concrete with 30% of FA, while the steel corrosion level was also lower. In addition, the availability of the initial chloride in the OC influenced the chloride penetration profile and steel corrosion level in the RC.

Keywords: repaired concrete, chloride penetration, steel corrosion, marine, Thailand

1. Introduction

Reinforced concrete is one of the most common construction materials widely used all over the world. However, because it is a porous and heterogeneous composite material, it is often susceptible to damage and deterioration from various physical and chemical factors [1-3]. The corrosion of embedded steel in concrete is one of the major causes of premature deterioration of reinforced concrete structures, leading to structural failure. In general, the corrosion of the embedded steel in concrete can commence with several phenomena such as carbonation, sulfate attack, alkali-silica reaction, acid attack, and so on. However, chloride-induced corrosion is one of the significant deterioration mechanisms of reinforced concrete structures that are subjected to chloride in the marine environment [4-6]. The corrosion process occurs after the concentration of chloride accumulated in concrete near the surface of reinforcement reaches the threshold level with the presence of moisture and oxygen. When steel corrodes, concrete cracking may occur, which reduces the bond strength between concrete and reinforcing steel as well as accelerates future corrosion rate [7]. The corrosion of reinforcement adversely affects the safety and serviceability of the concrete structures and hence shortens their service life; this results in the needs of massive budgets for repairs or maintenance activities to prolong the service life of the concrete structures [8, 9]. To enhance structural integrity, the structure is required an appropriate maintenance or repair strategy. It is needed not only for the existing structures but also for the newly built structures. There are many rehabilitation techniques available to restore the deteriorated concrete structures from the steel corrosion.

In this paper, the performance of the repair material type for concrete cover of the structure was investigated to measure the chloride penetration and steel corrosion after repair work. Types of concrete in the structure before the repair were also studied. The chloride penetration and steel corrosion in the repaired concrete specimens exposed to the marine environment for one year was evaluated. The chloride penetration profiles were compared for the chloride penetration resistance of specimens. The steel corrosion levels were investigated by weight loss of steel.

2. Experimental program

2.1 Materials and mix proportions

Experiments were done to evaluate the effect of the concrete type, which used in the original concrete (OC) and replaced concrete (RC) on the chloride penetration of repaired concrete specimens. Portland cement type I (OPC) was used as a primary binder of the mix proportion, while Mae Moh fly ash (FA) was employed as a partial replacement of the binder. The maximum particle size of coarse aggregate (Rock) was 19 mm, and the fineness modulus of fine aggregate (Sand) was 3.10. The chemical compositions and physical properties of the binder were summarized in Table 1. The mix proportions of concrete were listed in Table 2. The FA was used to replace binder at the ratios (f/b) of 0.30 and 0.50. Water to binder ratio (w/b) was 0.55 for the RC and 0.65 for the OC. The high w/b of OC represented the poor quality of old concrete structure, and the low w/b of RC represented the high quality of material in the repair of damaged structure from chloride-induced corrosion.

Table 1 Chemical compositions and physical properties of cement and fly ash

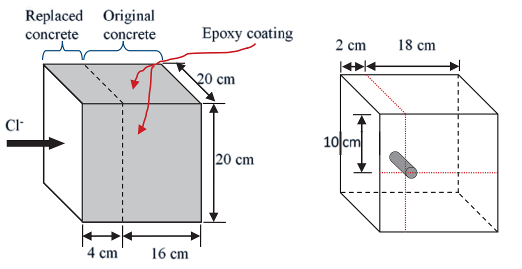
Chemical compositions (%)	Binder types	
	OPC	FA
Silicon oxide (SiO_2)	19.51	40.49
Aluminum oxide (Al_2O_3)	4.97	22.42
Iron oxide (Fe_2O_3)	3.78	13.64
Calcium oxide (CaO)	65.38	13.63
Magnesium oxide (MgO)	1.08	2.93
Sulfur trioxide (SO_3)	2.16	1.92
Sodium oxide (Na_2O)	0.01	0.89
Potassium oxide (K_2O)	0.44	2.28
Free lime	0.79	-
Loss on ignition (LOI)	2.27	0.47
Physical properties		
Blaine fineness (cm^2/g)	3,550	2,836
Specific gravity	3.15	2.29

2.2 Specimen preparation

The cube specimens with a dimension of 20x20x20 cm were cast for evaluating chloride penetration resistance under the marine environment. The details of the specimen preparation were illustrated in Figure 1. There were two parts in the cube specimen, of which the original concrete part with 16-cm depth and the replaced concrete part with 4-cm thickness (see Figure 1a). Cube specimens were cast in steel molds and compacted by using a vibrating table. For the OC contaminated with chloride, the 0.35% (% by weight of binder) of initial chloride was added into the OC during the concrete mixing. The round bar with 1.2 cm in diameter (RB12) and 5 cm in length was embedded in the specimen with the 2-cm covering depth in the RC part at the middle of the 20-cm width (see Figure 1b) for assessing the steel corrosion level in the RC part. The reason for embedding the steel inside the RC part is to simulate the real repair work that the removal of the original concrete exceeds the position of the outer reinforcing steel in the reinforced concrete structure is required. The RC was poured after the OC about six hours. This time lag was done to prevent the contamination between RC part and OC part during casting. An example of the repaired concrete specimen preparation was presented in Fig. 2. After 24 hours, the specimens were removed from the molds and wrapped by plastic sheets for self-curing. After six days of curing, all sides of the specimen were coated by epoxy, except one end surface, in order to allow one-dimensional chloride penetration, as seen in Figure 1a. Then, specimens were left in the laboratory for three days to allow the full set of epoxy coating. After that, the specimens were exposed to the marine site. The site was located on the eastern shoreline of Thailand (Thailand gulf) in Tambon Ang-Sila, Amphoe Muang, Chonburi Province. The specimens were put in the tidal zone of the marine environment for one-year exposure. The specimens exposed to the cyclic wetting and drying periods. The drying period was nearly the same as the wetting period, which was about 12 hours each in a day.

Table 2 Mix proportion of concrete

No.	Mix id.	w/b	Cement (kg/m^3)	Fly ash (kg/m^3)	Water (kg/m^3)	Sand (SSD) (kg/m^3)	Rock (SSD) (kg/m^3)	Initial chloride content (% by wt. of binder)
		Original concrete (OC)						
1	C350W65	0.65	350	-	228	734	970	-
2	C350FA30W65		245	105	228	730	964	-
3	C350W65-CL		350	-	228	734	970	0.35
4	C350FA30W65-CL		245	105	228	730	964	0.35
Replaced concrete (RC)								
5	C350FA30W55	0.55	245	105	192	770	1,017	-
6	C350FA50W55		175	175	192	768	1,015	-



(a) Concrete specimen (b) Detail of embedded steel

Figure 1 Schematic diagram of cube specimen and embedded steel

(a) Casting the OC part (b) Casting the RC part

Figure 2 Specimen preparation

(a) Marine site (b) Repaired concrete specimens

Figure 3 Specimens in marine site

2.3 Investigation of chloride content and steel corrosion

After one year of marine exposure, the specimens were collected from the marine site and moved to the laboratory for investigating the chloride penetration and steel corrosion.

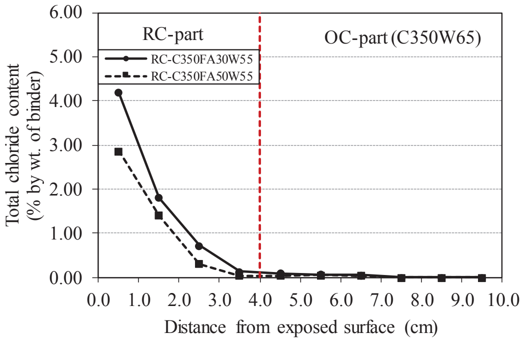
The 5-cm diameter concrete sample was cored from the exposed surface (uncoated surface) of the specimen by using the coring machine in order to determine the chloride penetration profile in concrete. The cored sample was sliced into disc samples at every 1- cm thickness from the exposed surface up to the depth of 10 centimeters. Then, the disc samples were ground into powder, which passed sieve No. 20. The method to determine the total chloride content of concrete was followed by the ASTM C1152 (Acid-soluble chloride) [10]. Then, the remaining cube specimen was broken down to pick the embedded steel in the concrete. The steel corrosion level was measured by the determination of the weight loss of steel, followed by the ASTM G1 [11].

3. Experimental results and discussion

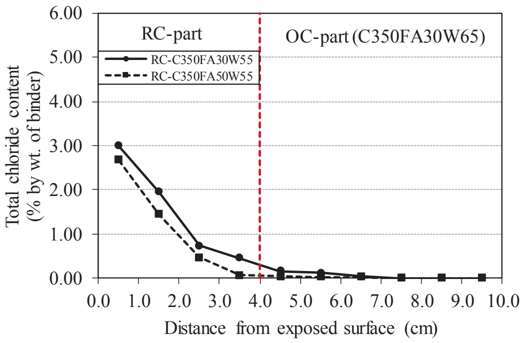
3.1 Chloride penetration profile

Chloride penetration profiles presented chloride penetration resistance of concrete, as shown in Figures 4 to 9.

Figures 4 and 5 illustrate the effect of the replaced concrete (RC) type on the chloride penetration profile of the repaired concrete specimen without and with initial chloride, respectively. It was noted that the RC type significantly affects chloride penetration of concrete. The chloride penetration of the repaired concrete specimen that the RC made from concrete containing 50% of FA (C350FA50W55) was lower than the one made from concrete containing 30% of FA (C350FA30W55). The decrease was due to the more pozzolanic reaction between FA and $Ca(OH)_2$ forming more pozzolanic products (C-S-H and C-A-H). These products make finer pore of paste, resulting in low chloride penetration. Furthermore, the filler effect of concrete with a higher amount of FA makes the concrete denser. This performance can be seen in both cases without and with initial chlorides in the OC parts.

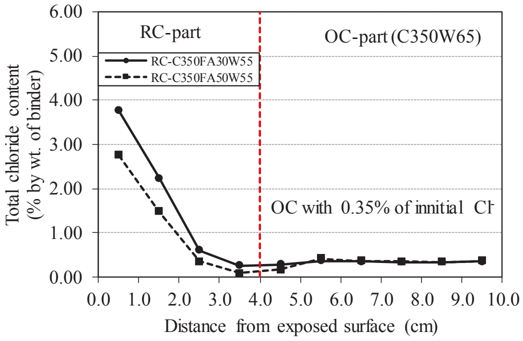


(a) OC made from cement-only concrete

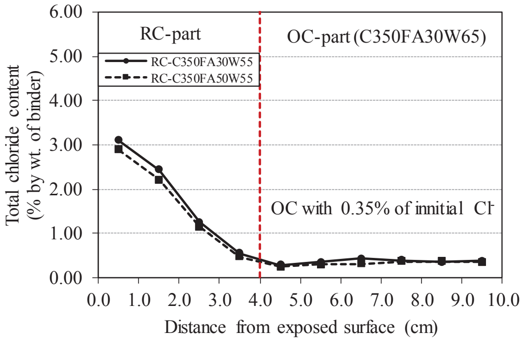


(b) OC made from concrete with 30% of FA

Figure 4 Chloride penetration profile of concrete with different RC type (No initial Cl^- in OC)

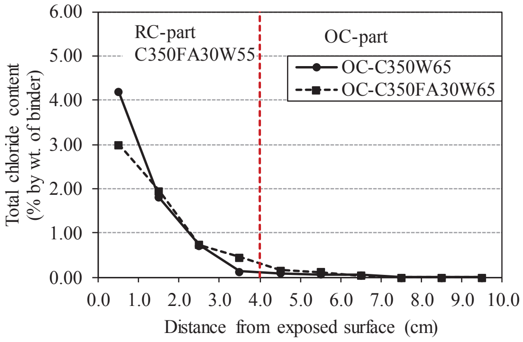


(a) OC made from cement-only concrete

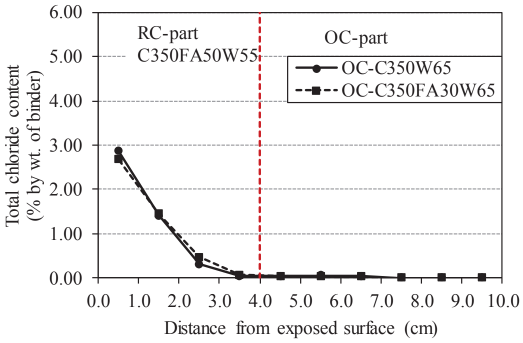


(b) OC made from concrete with 30% of FA

Figure 5 Chloride penetration profile of concrete with different RC type (0.35% initial Cl^- in OC)

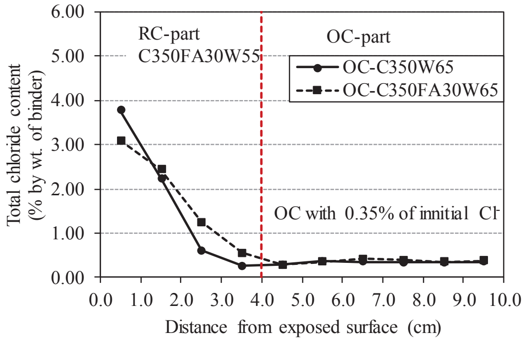


(a) RC made from concrete with 30% of FA

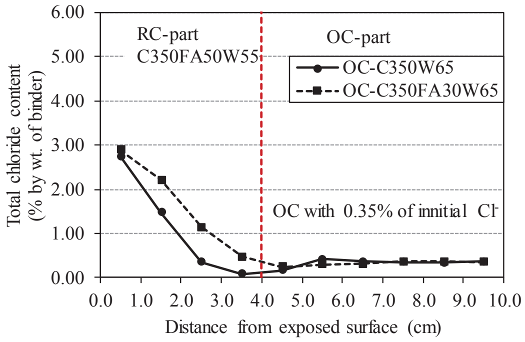


(b) RC made from concrete with 50% of FA

Figure 6 Chloride penetration profile of concrete with different OC type (No initial Cl^- in OC)



(a) RC made from concrete with 30% of FA

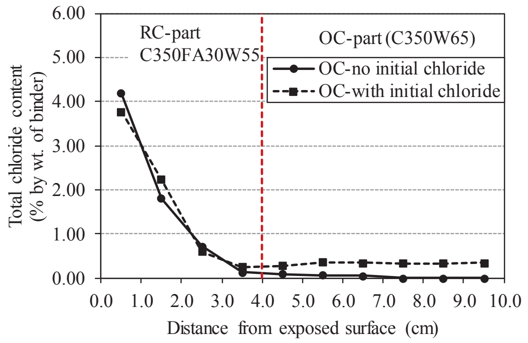


(b) RC made from concrete with 50% of FA

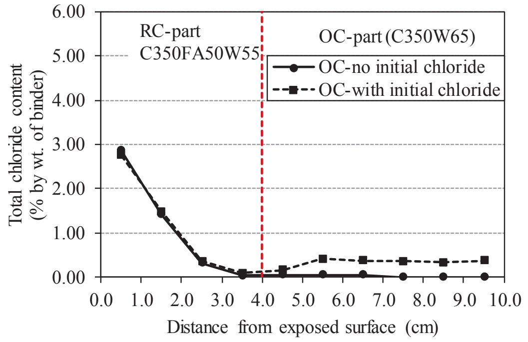
Figure 7 Chloride penetration profile concrete with different OC type (0.35% initial Cl^- in OC)

Figures 6 and 7 show the effect of the original concrete (OC) type on the chloride penetration profile of the repaired concrete specimen without and with initial chloride, respectively. It indicates that the OC type also affected chloride penetration in the concrete. When RC was the same fly-ash concrete, the chloride penetration of concrete with the OC made from fly-ash concrete was lower in OC part and higher in RC part than that one made from cement-only concrete. It was clearly observed in the condition of having the initial chloride in OC part. The reason was the denser of fly-ash concrete in the OC part prevented the chloride ions penetrating inside, resulting in higher accumulation of chloride ions in the RC part.

Figures 8 and 9 show the effect of initial chloride in the OC made from cement-only concrete and fly-ash concrete on the chloride penetration profile in the RC part. In Figure 8, the chloride penetration profiles in the RC part were nearly equal for both without and with initial chlorides in the OC parts. These chlorides were mostly from chloride ions penetrating from the seawater outside concrete. Very few chloride ions can move from the OC cement-only concretes. While, the chloride penetration profiles in the RC part were significantly different for without and with initial chlorides in the OC parts, as seen in Fig. 9. A large number of chloride ions moved out from the OC parts with initial chlorides. The large amount of chloride was due to the short curing time of 7 days considerably affected the pozzolanic reaction in OC fly-ash concrete, resulting in more diffusion of chloride ions.

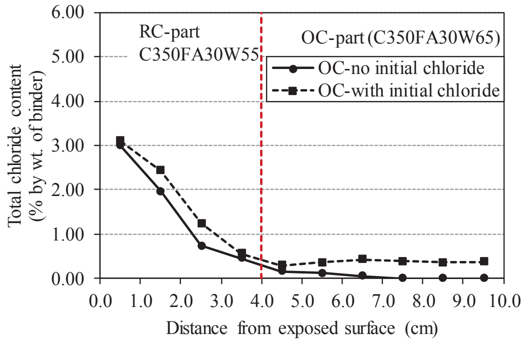


(a) RC made from concrete with 30% of FA

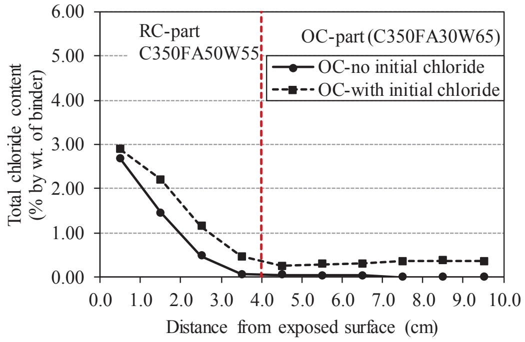


(b) RC made from concrete with 50% of FA

Figure 8 Chloride penetration profile of concrete with cement-only concrete in OC part

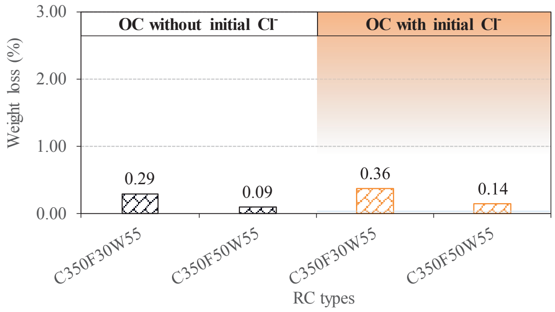


(a) RC made from concrete with 30% of FA

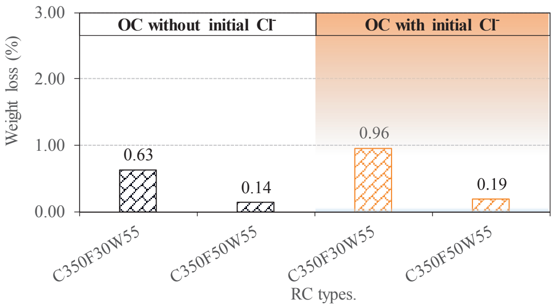


(b) RC made from concrete with 50% of FA

Figure 9 Chloride penetration profile of concrete with fly-ash concrete in OC part



(a) OC made from cement-only concrete (C350W65)



(b) OC made from concrete with 30% of FA (C350FA30W65)

Figure 10 Weight loss of embedded steel in concrete

3.2 Corrosion of embedded steel

The corrosion levels of embedded steels in concrete after exposure to the marine environment were presented in terms of the percentage of weight loss. Figure 10 indicates that the weight loss of steel with initial chloride in concrete was higher than that without initial chloride in concrete. The use of a higher binder replacement by FA in RC resulted in a lower weight loss of steel. This result was because the chloride penetration resistance of concrete with a high content of FA was better than that with a low content of FA, as seen by Figures 4 and 5. However, after the steel corrosion initiation, the steel corrosion level mainly depended upon the chloride concentration in concrete around the steel surface. Higher chloride content resulted in higher steel corrosion. In addition, the OC with FA had higher weight loss than OC with cement-only concrete. The high steel corrosion was due to the incorporation of FA in the OC provided microstructure densification and lower chloride diffusivity, leading to higher accumulation of chloride ions in the RC part and higher weight loss of steel.

4. Conclusions

Based on the experimental results obtained in this investigation, the following conclusions can be drawn:

1. The type of concrete in the OC and the RC significantly affected the chloride penetration and steel corrosion in the repaired concrete specimen. The availability of the initial chloride in the OC also influenced the chloride penetration profile and steel corrosion level in the RC.

2. The chloride penetration resistance of the repaired concrete specimen that the RC made from fly-ash concrete with 50% of FA was higher than that from fly-ash concrete with 30% of FA.

3. The chloride penetration resistance of the repaired concrete specimen that the OC made from fly-ash concrete with 30% of FA was lower than that from cement-only concrete at a short curing time of 7 days.

4. The chloride penetration profile in the RC with initial chloride in the OC tended to be higher than that without initial chloride in the OC.

5. The steel corrosion level in the repaired concrete specimen that RC made from fly-ash concrete with 50% of FA was lower than that RC made from fly-ash concrete with 30% of FA. Besides, the steel corrosion level in the repaired concrete specimen with OC containing initial chloride was higher than that OC without initial chloride.

5. Acknowledgments

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