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Effectiveness of Small Amount of Surface Penetrant against Chloride Ion Penetration †

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Abstract: To increase the durability of concrete structures, surface coating is widely used as a preventive maintenance strategy against de-icing salts. We investigated the effectiveness of a small amount of surface penetrant for chloride-induced corrosion on concrete structures exposed to low NaCl concentrations. The diffusion coefficient of mortar specimens with and without coating was determined using the electric migration test. The results indicated that even a small amount of Silane-based penetrant was effective against chloride ion penetration.

Keywords: surface penetrant; chloride ion penetration; apparent diffusion coefficient

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1. Introduction

Concrete structures play a vital role in modern infrastructure, from highways and bridges to buildings and parking structures. These structures, however, are often exposed to harsh weather conditions, particularly during the winter when de-icing salts are often used to ensure safe traffic on roads and walkways. The de-icing salts, particularly chloride-based compounds, harm the durability and condition of concrete with chloride attack and eventual deterioration. Therefore, to avoid premature deterioration, the use of surface treatment is required, and related research has been conducted to secure excellent workability and effective preventive measures [1].

The application of surface coatings to concrete structures considerably increased concrete's resistance to freezing, thawing, and chloride ion penetration [2]. Swamy and Tanikawa investigated the effect of surface penetrant coating on concrete durability and concluded that applying a surface coating to concrete is an efficient strategy for protecting new and old concrete structures as the coating makes concrete impervious [3]. The application of silicate-type surface penetrants significantly slows the initiation of corrosion in concrete structures located in coastal areas [4]. Ibrahim et al. showed that Silane with a topcoat had the best performance in terms of the effectiveness of acrylic and Silane coatings [5].

In Bhutan, light deicer products are often sprayed during the winter months to prevent vehicles from sliding due to ice formation on the road surface. The use of surface penetrants on concrete structures prevents chloride ion penetration induced by the application of deicers. However, there is limited information about the effectiveness of the surface penetrants against chloride ion penetration when concrete structures are exposed to normal and low sodium chloride (NaCl) concentrations.

2. Material and Methods

2.1. Properties of Fine Aggregate and Binding Materials

Fine aggregate/land sand was used for preparing mortar specimens that had a particle size of less than 4.75 mm and a density of 2.57 g/m^3 following the ASTMC33 standard as stated in Table 1. In this experiment, Ordinary Portland Cement (OPC) of a density of

3.16 g/m^3 meeting the ASTM C150 requirement, which is widely used in the construction of various concrete structures around the world, was adopted.

Table 1. Proportion of mortar mixture.

W/C	S/C	Unit Weight (kg/m^3)		
		W	C *	S **
0.50	2.5	12.296	24.591	61.5

* Ordinary Portland Cement (density of 3.16g/m^3); ** Land Sand (density of 2.57g/m^3).

2.2. Research Methodology

The proportion of the mixture of mortar specimens (20 cm in length × 10 cm in diameter) is shown in Table 1. The specimens were cured in water for 28 days at 20 °C. After that, the test specimens (3 cm in length × 10 cm in diameter) were obtained from prepared mortar specimens. The specimens were coated with the surface penetrant as shown in Table 2 for 7 days at 20 °C and a relative humidity of 60%. Then, the diffusion coefficient of the coated specimens for normal and low concentrations of NaCl was calculated based on JSCE G 571. Figure 1 shows an overview of the electric migration test method used. For testing, test specimens of 3 cm in thickness with and without coating were exposed to 3, 1, and 0.5% NaCl at a constant 15 V during the test duration. A steady state was assumed to be reached once the rate of chloride concentration in the anode became constant. The flux of chloride ions in the pore solution was determined as shown in Figure 2.

Table 2. Types of surface penetrant.

Case	Classification-Type	Application Quantity (g/m^2)
Case No.	No penetrant	0
Case A	Silane-type	200
Case B		100
Case C		50

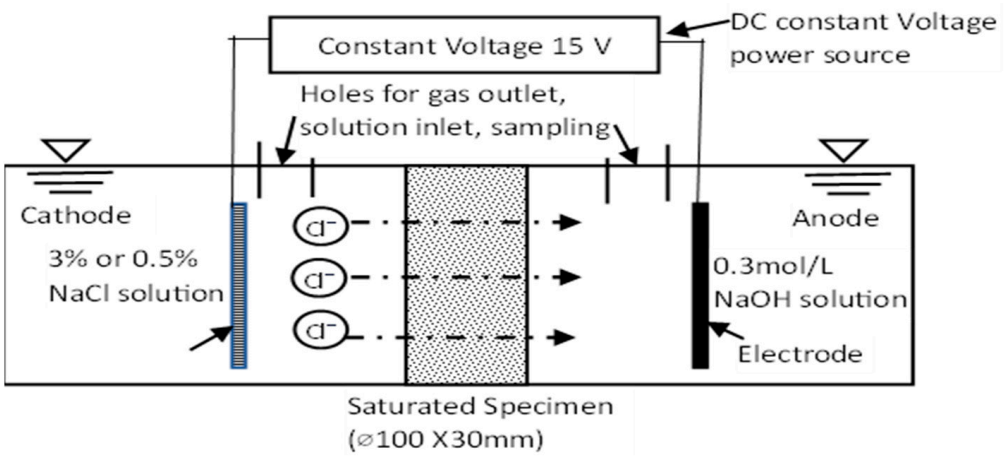


Figure 1. Overview of the electric migration test.

The effective diffusion coefficient of the chloride ion (Table 3) was calculated from the flux using the Nernst–Planck Equation. The effective diffusion coefficient was converted to the apparent diffusion coefficient (shown in Table 3 and Figure 3) using Equation (1).

$$D_{ae} = K_1 \cdot K_2 \cdot D_e \quad (1)$$

(D_{ae}: apparent diffusion coefficient, D_e: effective diffusion coefficient obtained in the migration test (cm^2/year), K_1: coefficient reflecting the equilibrium concentration of chloride ions on the cathode side and at the concrete surface, and K_2: coefficient reflecting the effect of immobilization of chloride ions in the hydrated cement system).

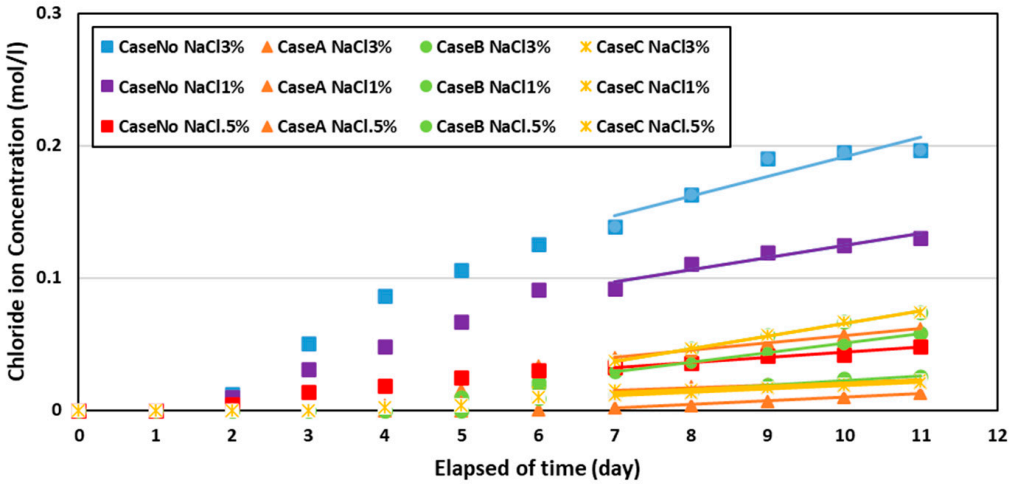


Figure 2. Change in chloride ion concentrations on the anode side.

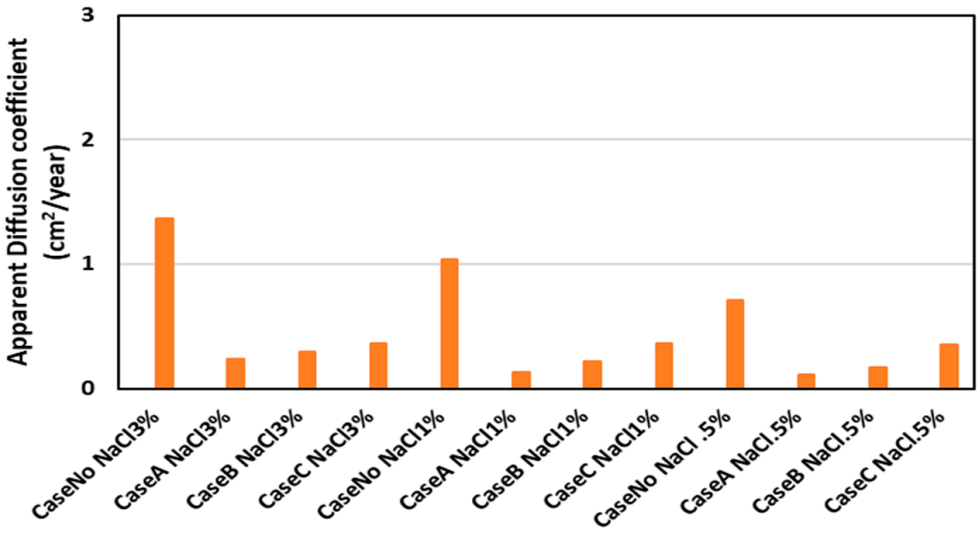


Figure 3. Apparent chloride ion diffusion coefficient of all experiment specimens.

When Ordinary Portland Cement was used, $(K_1 \cdot K_2) = 0.2 \exp(1.8\ (W/C))$ $(0.3 \leq W/C < 0.55)$ [6]. As shown in Table 3, the diffusion coefficient (D_s) of surface penetrants was estimated using Equation (2) [7]. The impregnation depth surface penetrant was 3 mm for a full coating, 2.3 mm for a half coating, and 1.7 mm for a quarter coating.

$$\frac{C'}{\sqrt{D'}} = \frac{C_c}{\sqrt{D_c}} + \frac{C_s}{\sqrt{D_s}} \tag{2}$$

(C': thickness of coated specimens (mm), D': diffusion coefficient of coated specimens (cm^2/year), D_c: diffusion coefficient of uncoated specimens (cm^2/year), C_c: thickness of uncoated specimens (mm), C_s: penetrating depths (mm), D_s: diffusion coefficient of penetrant (cm^2/year), and S: converted cover depth (mm)).

$$S = C'\left[\frac{\sqrt{D_c}}{\sqrt{D'}} - 1\right] = C_s\left[\frac{\sqrt{D_c}}{\sqrt{D_s}} - 1\right] \tag{3}$$

The converted cover depth [7] in Table 4 was calculated from the diffusion coefficient (D_s) of the surface penetrant, the apparent diffusion coefficient (D_c) of uncoated mortar specimens, and the apparent diffusion coefficient (D′) of coated mortar specimens using Equation (3) [7].

Table 3. Result of migration test.

Cases	Effective Diffusion (cm^2/Year)	Apparent Diffusion (cm^2/Year)	Diffusion Coefficient (D_s) Penetrant (cm^2/Year)
Case No NaCl 3%	2.67	1.36	
Case A NaCl 3%	0.47	0.24	0.0062
Case B NaCl 3%	0.59	0.30	0.0055
Case C NaCl 3%	0.71	0.36	0.0025
Case No NaCl 1%	2.03	1.04	
Case A NaCl 1%	0.26	0.13	0.0029
Case B NaCl 1%	0.43	0.22	0.0040
Case C NaCl 1%	0.71	0.36	0.0035
Case No NaCl 0.5%	1.40	0.71	
Case A NaCl 0.5%	0.21	0.11	0.0025
Case B NaCl 0.5%	0.34	0.17	0.0034
Case C NaCl 0.5%	0.69	0.35	0.0059

Table 4. Equivalent cover depth.

Case	Converted Cover Depth (mm)
Case A NaCl 3%	41.50
Case B NaCl 3%	39.94
Case C NaCl 3%	28.08
Case A NaCl 1%	48.84
Case B NaCl 1%	37.27
Case C NaCl 1%	18.84
Case A NaCl 0.5%	47.27
Case B NaCl 0.5%	36.25
Case C NaCl 0.5%	12.73

3. Result and Discussion

Figures 2 and 3 show that the chloride ion concentration and the apparent diffusion coefficient of the mortar specimens were higher for the specimens exposed to the high NaCl concentration and lower for the specimens exposed to the low NaCl concentration. Also, the concrete surface coated with a Silane-based surface penetrant significantly reduced the chloride ion concentration on the anode side and the apparent diffusion coefficient. As shown in Table 4 and Figure 4, the equivalent cover depth of full and half coatings increased significantly when exposed to NaCl concentrations of 0.5 to 3%, whereas quarter coatings showed an increase in cover depth. The converted cover depth remains roughly the same when the application amount is increased from half to full coating regardless of specimens exposed to 0.5% to 3% NaCl solution; however, quarter application shows a less increase in equivalent cover depth as illustrated in Table 4 and Figure 5. It indicated that quarterly-coated concrete structures with a surface penetrant did not allow chloride ion penetration when exposed to low NaCl concentrations.

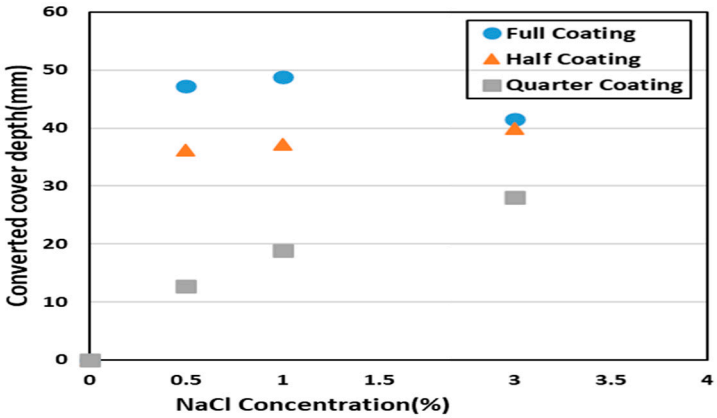


Figure 4. Equivalent cover depth over increase in NaCl concentration.

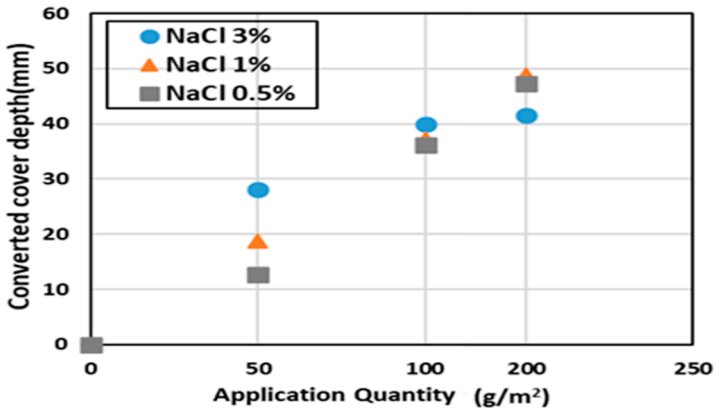


Figure 5. Equivalent cover depth over application rate of coating.

4. Simulation of Corrosion Initiation Time

To evaluate the delay in corrosion initiation time when concrete structures were coated with the Silane-based surface penetrant, the concrete cover depth was set to 5 cm, and the surface chloride ion concentration was fixed to be 1.80 kg/m^3, assuming that the amount of application of deicers was relatively low. The converted cover depth shown in Table 4 and the apparent diffusion coefficient of the uncoated specimens shown in Figure 3 were calculated following Fick's law of diffusion (Equation (4)) to estimate the time for the total chloride ion concentration around the steel bars to reach a threshold value of 1.2 kg/m^3 [8].

$$C_{(x,t)} = C_0\left\{1 - \mathrm{erf}\left(\frac{x}{2\sqrt{D_{ae}\cdot t}}\right)\right\} \quad (4)$$

($C_{(x,t)}$: chloride ion concentration at depth x (cm) and time t (years) (kg/m^3), C_0: chloride ion concentration at the concrete surface (kg/m^3), D_{ae}: apparent chloride ion diffusion coefficient (cm^2/year), and erf error function).

As shown in Figure 6, the time required for corrosion without a surface penetrant was calculated as 49 years for specimens exposed to 3% NaCl, 64 years for 1% NaCl, and 96 years for 0.5% NaCl. However, when specimens were coated with a quarter amount of Silane-based surface penetrant, the time for corrosion was delayed to 120 years for 3% NaCl, 160 years for 1% NaCl, and 230 years for 0.5% NaCl concentrations. The performance deterioration of surface penetrants was not considered in this calculation. However, it was obvious that using only a small quantity of the Silane-based penetrant on concrete structures significantly delayed the onset of rebar corrosion when concrete structures were exposed to normal to low NaCl concentrations.

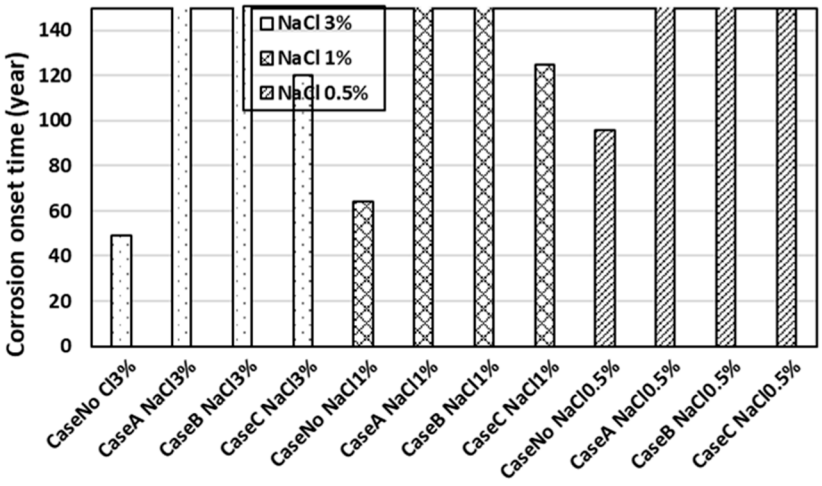


Figure 6. Onset corrosion time of all experiment specimens.

5. Conclusions

In this study, it was found that the chloride ion concentration and the apparent diffusion coefficient of the mortar specimens were higher than those of the specimens exposed to high and low NaCl concentrations. The concrete surface coated with the Silane-based surface penetrant significantly reduced the apparent diffusion coefficient of the chloride ion on the anode side. Even a small amount of the surface penetrant was effective in delaying the corrosion initiation of concrete structures exposed to any concentration of de-icing salts.

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