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Research Article

Sensitivity of Service Life Extension and CO_2 Emission due to Repairs by Silane Treatment Applied on Concrete Structures under Time-Dependent Chloride Attack

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This paper presents sensitivity of service life extension and CO_2 emission due to silane (alkyltriethoxysilane) treatment on concrete structures under time-dependent chloride attack. The service life is predicted by the Crank–Nicolson-based finite difference approach for avoiding the complexity in solving Fick's second law. The complexity occurs due to time-dependent chloride attack and nonconstant diffusion coefficient of concrete with silane treatment. At the application time of silane treatment, the cumulative CO_2 emission is assessed. The effectiveness of silane treatment is defined as the ratio of the service life extension to the cumulative CO_2 emission assessed within the corrosion-free service life. The service life extension is defined as the difference between corrosion-free service life of concrete structures without and with time-based application of silane treatment. From the study, the diffusion of chlorides in concrete with silane treatment is found to be retarded. In comparison, the strategy without deterioration of silanes during effective duration is more suitable for service life extension but less effective than that with deterioration. In the sensitivity analysis, there are up to eight parameters to be determined. The service life of concrete structures without silane treatment is most sensitive to the water-to-cement ratio and the threshold depth of concrete structures. Considering only five parameters in silane treatment strategies, the service life is most sensitive to the first application time of silane treatment. The cumulative CO_2 emission is most sensitive to either the first application time of silane treatment or the amount of CO_2 emission per application.

1. Introduction

Concrete structures have been used in construction industry for years. After a period of time, those structures deteriorate due to mechanical loading or environmental attack. For concrete structures exposed to chloride attack, the deterioration can be categorized into three forms: reinforcement corrosion, concrete cracking, or a combination of them. In general, the reinforcement corrosion occurs prior to the others. It generally initiates whenever the critical (or threshold) amount of chloride ions at the surface of reinforcement is reached, combining with the condition of having enough oxygen and moisture. This may lead to severe deterioration and even shorten the service life of the concrete structures [1]. However, this process is not allowed due to the risk of structure reconstruction which causes high environmental impacts. In particular, sustainable structures are widely mentioned nowadays because old-fashioned construction to support city expansion due to population increase was found to be the largest consumer of materials [2], and this leads to large environmental impacts, in particular, greenhouse effect gases, for example, CO_2. Hence, a remedial action is required. For this, there can be two main options to be considered. The first option is using sustainable materials, which are both durable and causing low CO_2 emission. However, this option is out of the scope of this study and can be found elsewhere, such as in the study of Pimraksa et al. [3], Chindaprasirt and Rukzon [4], and Nazari and Sanjayan [5]. The second option is applying a proper repair plan to extend the service life of concrete structures prior to severe deterioration [6].

Silane treatment, which is categorized as a kind of surface treatment, is one of the most favorite repair methods applied on concrete surface for retarding the transport of chloride ions for service life extension of concrete structures [7, 8]. For years, several research studies have been conducted so as to determine the effectiveness of the silane treatment as follows. A group of researchers [9] reviewed different engineering aspects of various silane treatments by collecting a set of data. For example, they showed that the penetration depth of silane treatment was between 1 and 9 mm depending on the percentage of silanes and test methods. Their review also showed that silanes could reduce water absorption of concrete by 87.5% [10] and silanes combined with acrylic coating were able to reduce the water absorption of concrete by 75% to 95% [11]. In terms of chloride penetration, they reviewed that silanes could reduce the chloride content within 20 mm from concrete surface by 94% [12] and that silanes combined with acrylic coating were able to reduce the chloride content between 5 and 10 mm from concrete surface by 87% [11]. Moreover, Thompson and Leeming [13] tested the effect of 21 treatments and stated that the treatments could reduce chloride uptake by up to 90%. Regarding the diffusion of chloride ions, Robinson [14] stated that silanes could reduce by 81%. Some researchers studied another benefit of surface treatment. For example, Yoon [15] tested chloride penetration through cracks in high-performance concrete and surface treatment system for crack healing. They concluded that penetrant could not cure cracks; however, coating and combined treatment could prevent chloride from flowing in concrete with maximum crack width of 0.06 mm and 0.08 mm, respectively.

Although a repair is useful to prevent structure reconstruction and extend the service life of structures, it is unavoidable that the environmental impact can occur in the process of the repair, for example, the process of repair material production, repair application, and even repair material degradation. Therefore, all the associated activities in life cycle should accordingly be assessed including the assessment of the environment impact due to the repair. Furthermore, the regulation in the ISO-EN-UNE-14.040 standard defines the word "life cycle assessment (LCA)" as the collection and assessment of the inputs and outputs of any potential environmental impacts caused by the production system throughout its life cycle. From this, the activities, for example, construction, reuse, and demolition, causing environmental impacts should be concerned in the life cycle assessment. For structures in operation, the key aspects needed to assess over service life are repair and maintenance [16].

This study presents assessment of the environmental impact in terms of the CO_2 due to silane (alkyltriethoxysilane) treatment for extending corrosion-free service life extension of chloride-exposed concrete structures. To achieve this, there are two issues to be addressed: prediction of corrosion-free service life extension and assessment of the amount of CO_2 emission. In predicting the service life, the behaviors of chloride diffusion before and after time-based silane treatment are considered by using a self-developed Crank–Nicolson-based finite difference approach. And also, the amount of cumulative CO_2 emission due to silane treatment is calculated. The ratio of the service life extension to the amount of cumulative CO_2 emission is defined as the effectiveness of silane treatment for comparing different repair strategies. Finally, the sensitivity of the service life and the cumulative CO_2 is determined in order to observe the effect of each parameter.

2. Finite Difference Approach for Predicting Corrosion-Free Service Life

2.1. Without Silane Treatment. Concrete structures under chloride attack by diffusion can be assessed based on the partial differential equation (PDE) of Fick's second law [17] as follows:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} D \frac{\partial C}{\partial x}, \tag{1}$$

where C is the chloride content as a function of position x and time t and D is the chloride diffusion coefficient which can be either constant or in a function of time t. With proper initial and boundary conditions, (1) can analytically be solved and used to predict the diffusion of chloride ions in concrete (e.g., [18]), and the service life of concrete structures can be predicted accordingly.

2.2. With Silane Treatment. Fundamentally, the physical model for predicting chloride diffusion through concrete with surface treatment could be classified into three types [19–21], that is, penetrating, coating, and sealing. Zhang et al. [22] explained that a penetrant penetrated through concrete for lining or blocking pores, whereas a coating could be seen as an additional physical layer on concrete. Last, a sealer acted as a combination of both penetrating and coating.

Silane treatment was categorized as one kind of penetrants for hydrophobic treatment aiming to slow down the diffusion of chloride ions in concrete structures [23]. Moreover, Pan et al. [24] stated that silanes operated through penetrating concrete pores, enlarging the contact angle, and could inhibit penetration of water and water-born ions, but allowed water vapor to enter or exit. There are two main steps to model the diffusion of chloride ions in concrete with silane treatment as follows.

2.2.1. Chloride Ion Penetration from the Outer Surface through the Original Concrete. For this, the Crank–Nicholson numerical scheme can be used. Because the diffusion coefficient D for the original concrete can be considered as constant, the finite difference approximation for (1) [25] can be written as follows:

$$\frac{c_{i,j+1} - c_{i,j}}{\Delta t} = \frac{D}{2}\left[\frac{\left(c_{i+1,j+1} - 2c_{i,j+1} + c_{i-1,j+1}\right) + \left(c_{i+1,j} - 2c_{i,j} + c_{i-1,j}\right)}{(\Delta x)^2}\right], \tag{2}$$

where $c_{x,t}$ is, in a general form, the chloride content at a mesh point x at time t. In addition, Δt and Δx are the incremental time step (1 week) and the size of the mesh point (1 mm), respectively.

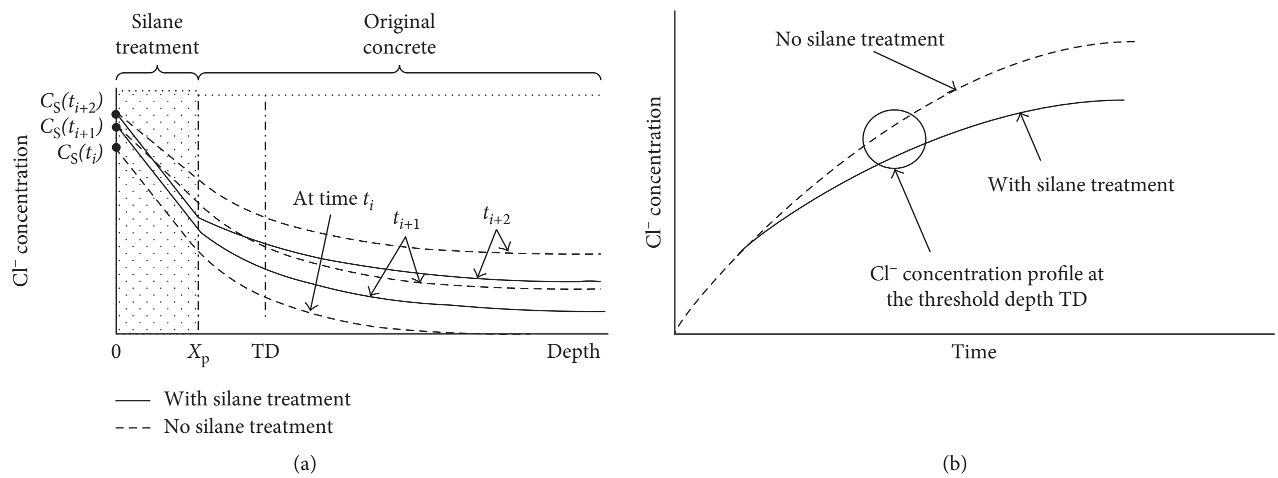


Figure 1: Chloride profile: with and without silane treatment. (a) Chloride-depth profile. (b) Chloride-time profile.

2.2.2. Chloride Ion Penetration through Silane-Treated Concrete and Original Concrete. For chloride penetration through concrete with silane treatment, let us consider Figure 1 [26]. After the time passes by, the chloride ions penetrate through concrete structures, and the amount of chloride ions at concrete surface increases with time because of time-dependent surface chloride. At time t_i, silane treatment is applied at the surface of concrete, so silanes react with the pore structure within hardened concrete to create a nonwettable or hydrophobic surface as deep as the distance x_p (or effective depth) within concrete. Hence, within the effective depth, concrete becomes composite. This results in the problem involving space-dependent diffusion coefficient, or $D(x)$, due to the difference of diffusion coefficients between the silane-treated concrete and the original concrete. In addition, the diffusion coefficient is also time dependent, or $D(t)$, because the continuous process of cement hydration results in connection and condensation of concrete pore structures. Mathematically, the PDE for the space- and time-dependent diffusion coefficients can be rewritten as follows:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} D(x,t) \frac{\partial C}{\partial x}, \quad (3)$$

where $D(x,t)$ is the chloride diffusion coefficient in a function of space x and time t. It is complicated to solve for a closed-form solution of (3); hence, a Crank–Nicolson-based numerical scheme is introduced as follows [27]:

$$\frac{c_{i,j+1} - c_{i,j}}{\Delta t} = \frac{1}{2}\left(\frac{\left[D_{i+1/2}(c_{i+1} - c_i) - D_{i-1/2}(c_i - c_{i-1})\right]_{j+1}}{(\Delta x)^2} + \frac{\left[D_{i+1/2}(c_{i+1} - c_i) - D_{i-1/2}(c_{i,} - c_{i-1,})\right]_j}{(\Delta x)^2}\right), \quad (4)$$

where $D_{i+1/2} = (D_i + D_{i+1})/2$ and $D_{i-1/2} = (D_{i-1} + D_i)/2$. If the diffusion coefficients in (3) and (4) are constant, these equations are reduced to (1) and (2), respectively. In computation, when the original concrete is treated with silanes over the depth x_p at time t, the diffusion coefficient of silane-treated concrete will be updated, for instance, $(D_{0,t})_o = (D_{0,t})_{rep}$ at concrete surface and $(D_{x_p,t})_o = (D_{x_p,t})_{rep}$ at effective depth x_p. In general, $(D_{x,t})_o$ and $(D_{x,t})_{rep}$ are defined as the diffusion coefficients of original and silane-treated concrete, respectively, at the depth x and time t.

Figure 1(b) shows the chloride content at a threshold depth of TD (see also Figure 1(a)) plotted with time. With silane treatment, the increase of the chloride content is retarded resulting in reducing penetrating chloride ions, and consequently extending the initiation time of reinforcement corrosion and structural deterioration.

3. Time-Dependent Surface Chloride and Diffusion Coefficient

3.1. Time-Dependent Surface Chloride. The surface chloride represents the extent of chloride ions around concrete structures and depends on many factors, for instance, the distance from the sea and the properties of concrete [28]. Several researchers have proposed closed-form solutions for both constant and time-dependent surface chloride models [29–31]. In this study, the surface chloride for original concrete is time dependent as shown in the following equation [32]:

$$C_S(t) = C_0 + k\sqrt{t} = 10^{[0.814(w/c) - 0.213]} + 2.11\sqrt{t}, \quad (5)$$

where C_0 is the initial surface chloride (% wt. of binder), and "k" is a constant related to the rate of increase of surface chloride per square root of the exposure time (t, years). Figure 2 represents the time-dependent surface chloride for concrete with the water-to-cement ratio (w/c) of 0.45, 0.55, and 0.65.

3.2. Time-Dependent Diffusion Coefficient. The corrosion of concrete structures under chloride attack is related to the resistance of chloride diffusion in concrete and can be represented in terms of the diffusion coefficient of concrete. The diffusion coefficient depends on materials, for example, concrete and silane-treated concrete. The diffusion coefficient was found to be time dependent, because the process of

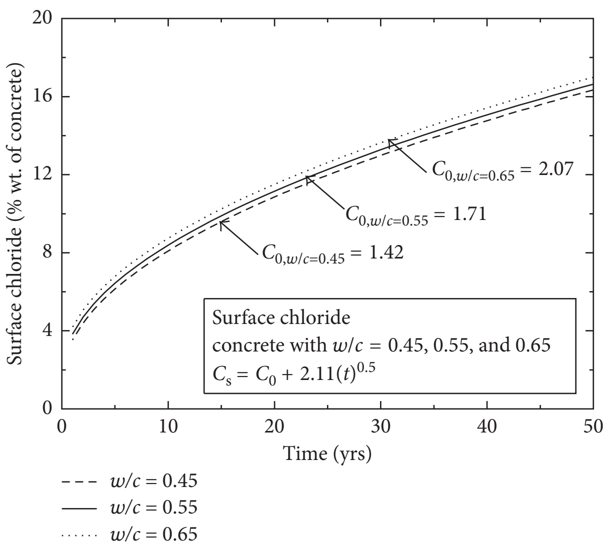


Figure 2: Time-dependent surface chloride.

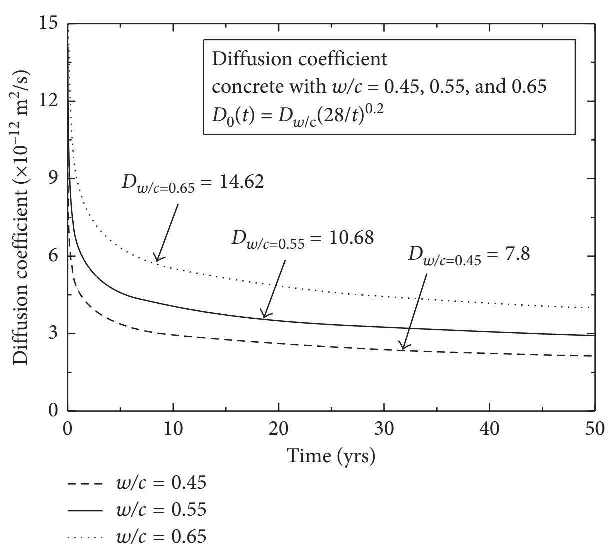


Figure 3: Time-dependent diffusion coefficient.

cement hydration resulted in connection and condensation of concrete pore structures [33]. In this study, the time-dependent diffusion coefficient (in mm^2/year) at the exposure time (t, in years) is represented in terms of a decay function [32] as follows:

$$D_0(t) = 10^{[1.776+1.364(w/c)]} \left(\frac{t_{\text{ref}}}{t}\right)^{0.2}, \quad (6)$$

in which t_{ref} is a reference time which is equal to 28 days. The time-dependent diffusion coefficients for concrete with w/c of 0.45, 0.55, and 0.65 are shown in Figure 3.

4. Silane Treatment Strategies

In this study, there are two silane treatment strategies (SL1 and SL2), as shown in Table 1. For each strategy, there are four parameters as explained in the following.

4.1. Application Time and Effective Duration of Silane Treatment. Carter and McGettigan [34] stated that sealers such as silanes should not be applied to concrete until cement had hydrated sufficiently, and most manufacturers recommended that they should not be applied until at least 28 days after concrete placement. From literatures [35, 36], the first application of silane treatment was within 15 years after concrete placement, and the subsequent one should be applied every 3 to 15 years from prior application. From these literatures, the first and subsequent applications for SL1 and SL2 are chosen to be at the year 5 and every 7.5 years after previous application, respectively, as shown in Table 1.

The report of NCHRP-558 [23] indicated that the lifetime of silane treatment relied on the condition of exposures, for instance, ultraviolet and moisture. Moreover, Weyers [37] stated that the lifetime of silane treatment fell between 5 and 7 years after application for highway bridges. In this study, the lifetime is called the effective duration and chosen to be 5 years after application, as shown in Table 1. It is noted that the time difference between the subsequent application time of silane treatment and the effective duration is equal to 2.5 years. This difference indicates that the silane treatment is reapplied after the effect of the previous silane treatment vanishes for 2.5 years.

4.2. Diffusion Coefficient and Effective Depth for Silane-Treated Concrete. Schuereman et al. [38] performed site surveys on the quay wall of the new container terminal at Zeebrugge Harbor, Belgium. On the quay wall, a water-repellent agent known as alkyltriethoxysilane was applied immediately after construction in order to protect against chloride ingress. It was also claimed that such a kind of silane type had the smallest hydrolysis reaction speed, which enabled its maximum penetration. They determined the chloride profiles and estimated the effective diffusion coefficient of concrete without and with treating by alkyltriethoxysilane. From their study, the ratio of the diffusion coefficient of original concrete to that of silane-treated concrete (α) can be calculated in this study and is found to be 0.12 and 0.17, depending on the time of site surveys. Moreover, they also determined the penetration depth (effective depth) of alkyltriethoxysilane by both site surveys and laboratory tests. The effective depth (x_p) was found to be 1–6 mm for site survey and 6–9 mm for laboratory tests. Moradllo et al. [39] found that the performance of surface coatings using different materials deteriorated at different rate and proposed an exponential function to represent the deterioration of the materials. In this study, the ratio of the diffusion coefficient of original concrete to that of silane-treated concrete and the effective depth are chosen as 0.12 and 9 mm, respectively. During the effective duration, the silanes are considered to deteriorate either immediately (step wise) or exponentially which is denoted as SL1 or SL2, respectively, as shown in Table 1.

Considering the parameters in Table 1, the diffusion coefficient of original and silane-treated concrete for SL1 and SL2 can be compared, as shown in Figures 4(a) and 4(b), respectively. The black and white dots show the starting and the end times of silane treatment, respectively. The period between

Table 1: Application time, effective duration, and effect of silane treatment.

Silane treatment strategy	Application time First (t_{FIRST})	Application time Sub. (t_{SUB})	Eff. duration (yrs) (t_{DUR})	Diffusion coefficient of silane-treated concrete during effective duration	Eff. depth (mm) (x_p)
SL1	At year 5	Every 7.5	5	$D_{SL}(t) = \alpha \cdot D_0(t)$	9
SL2				$D_{SL}(t) = (\alpha \cdot e^{\beta[t-t_{APP}]})\, D_0(t)$	

Note. α is the ratio of diffusion coefficient of original concrete to that of silane-treated concrete and is equal to 12%. t_{APP} is equal to the years 5, 12.5, 20, 27.5, 35, and so on. β is the rate of the deterioration of silane treatment.

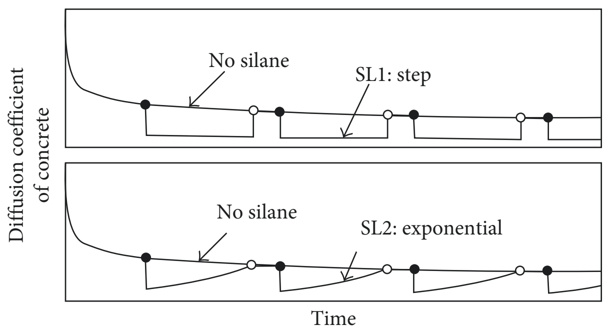


Figure 4: Diffusion coefficient of original and silane-treated concrete: (a) SL1 and (b) SL2.

the black and white dots represents the effective duration. When SL1 or SL2 is applied, the diffusion coefficient of original concrete $D_0(t)$ is suddenly reduced to $D_{SL}(t)$ or to 12% of the original concrete. After that, $D_{SL}(t)$ for SL1 is kept equal to $0.12D_0(t)$ without the deterioration of silanes until the end of the effective duration. However, $D_{SL}(t)$ for SL2 exponentially increases until the end of the effective duration because of the deterioration of silanes. It is noted that $D_{SL}(t)$ of SL2 is determined by solving for the silane treatment deterioration parameters, that is, β (in Table 1) which satisfy the starting and the end times of the silane treatment.

4.3. Critical Chloride and Repair Application Time. Schiessl and Raupach [40] stated that the critical chloride content could be defined as the content that was necessary to break down local passive film at the steel depth before the process of corrosion initiation. Yokota and Iwanami [41] stated that the corrosion of reinforcement started and progressed rapidly whenever the chloride content at the position of reinforcement reached a critical value. Chalee et al. [42] stated that the critical chloride value for reinforcement corrosion initiation was equal to 0.9% wt. concrete for normal concrete.

In this study, the critical chloride value at the threshold depth (TD) for the original concrete is chosen equal to 0.9% wt. of concrete [42]. This value is used to compare the service life of concrete structures without and with silane treatment. In addition, the service life is defined as the time at which the chloride content at the position of reinforcement (or the threshold depth, TD) reaches the critical value.

4.4. Environmental Impacts in Terms of CO_2 due to Silane Treatment. The environmental impacts of silane treatment were studied by Arskog et al. [43] and can be classified into several categories. In this study, the global warming impact in terms of equivalent CO_2 emission is considered. The CO_2 is derived from four processes: production of silane agent, surface preparation for treatment, transportation and treatment process, and long-term degradation. The estimation of the CO_2 per application or the annual CO_2 (ACD) for the four processes is shown in Table 2. It is noted that the unit of the annual CO_2 is in equivalent grams of CO_2 per m^2 of silane treatment per application.

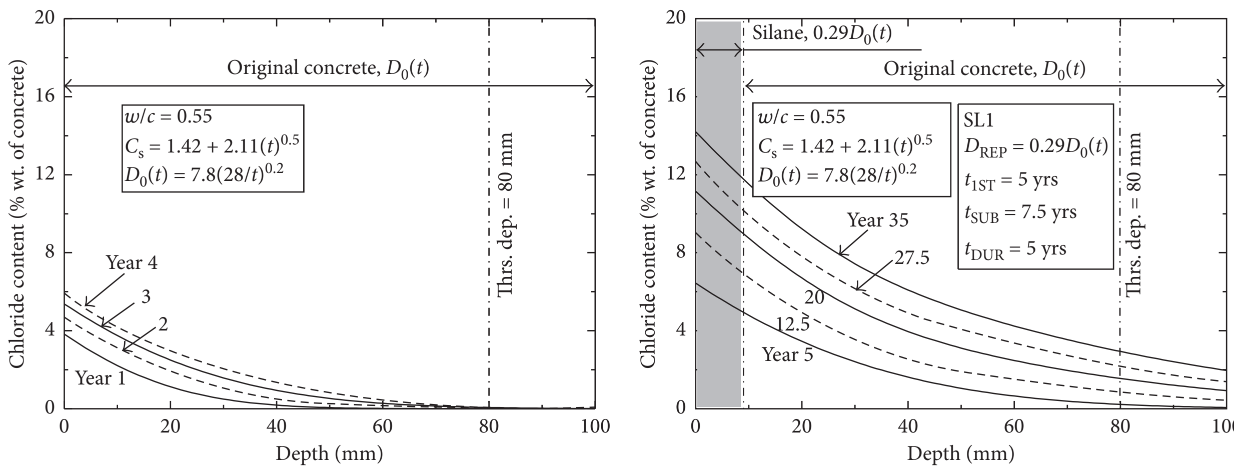
Table 2: Environmental impacts for each silane treatment.

Process	Annual CO_2 (eq. g/m^2/application, ACD)
Production of silane agent	295
Surface preparation	10
Transportation and silane treatment process	80
Long-term degradation	2171
Total	2559

5. Numerical Assessment and Sensitivity Analysis

A Crank–Nicolson-based finite difference approach was developed based on the aforementioned idea and data. There are two main examples to study the service life extension and the cumulative CO_2 due to silane treatment on concrete structures and the sensitivity of service life and CO_2 to several parameters. In these examples, the concrete cover or threshold depth (TD) to monitor the chloride content is equal to 80 mm for concrete structures exposed to chloride environment [44].

5.1. Service Life Extension and CO_2. In this example, an original concrete structure with w/c of 0.55 is repaired with SL1. The chloride content in the structure is computed and plotted with concrete depth, as shown in Figures 5(a) and 5(b). From Figure 5(a), chloride ions penetrate through the original concrete time-dependently. At the surface, the chloride content increases with time because of the effect of time-dependent surface chloride. Moreover, the rate of chloride diffusion is slower with increasing time because of the effect of time-dependent diffusion coefficient. From Figure 5(b), SL1 is first applied at the year 5; hence, the diffusion coefficient of the original concrete is updated to that of the silane-treated concrete or $0.12D_0(t)$ as deep as 9 mm from concrete surface. It is noted that the shaded area represents the zone of silane-treated concrete. At the year 10 (5 years after the first treatment), the effect of silanes vanishes due to the end of its



(a) (b)

FIGURE 5: Chloride content versus depth for original concrete of $w/c = 0.55$ with SL1. (a) Years 1 to 4 (before silane treatment). (b) Year 5 to year 35 (with silane treatment).

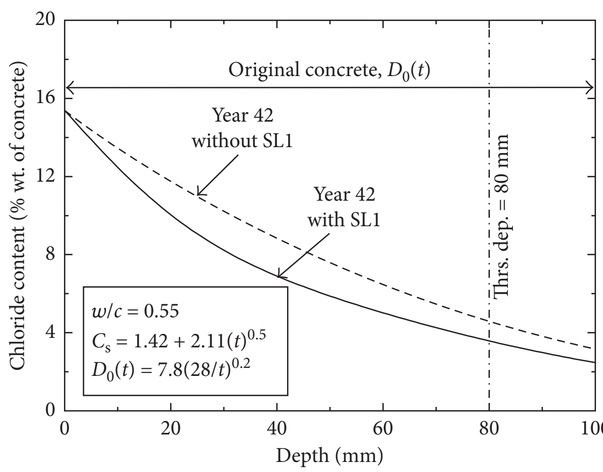


FIGURE 6: Chloride content versus depth for concrete without and with SL1 at year 42.

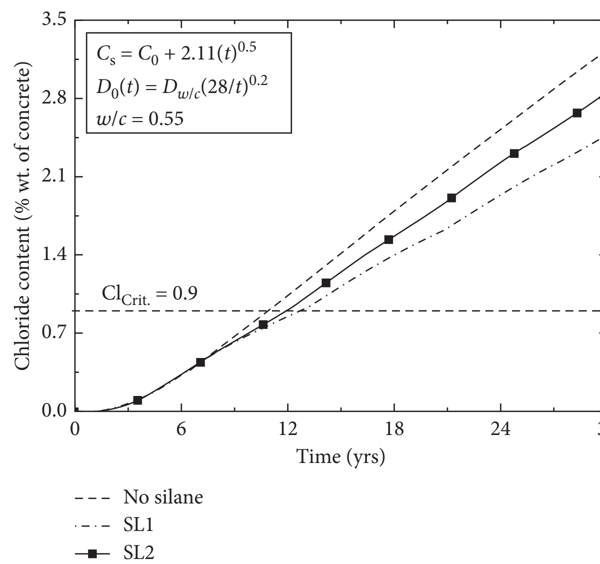


FIGURE 7: Chloride content versus time for concrete without and with SL1 and SL2.

effective duration. However, at the year 12.5 (7.5 years after the first treatment, as shown in Table 1), SL1 is reapplied. Its effect lasts for 5 years. After that, the same silane treatment is cyclically applied at the years 20, 27.5, 35, and so on.

Figure 6 shows the comparison of the chloride content for concrete without and with SL1 at the year 42. It is found that the diffusion of chloride ions through the depth of concrete with SL1 is slower. At the year 42, the effect of silane treatment on concrete with SL1 vanishes because it is the time which falls between the end of silane treatment effect and the start of the next silane treatment. On the other hand, the effective duration of the previous silane treatment applied at the year 35 ends at the year 40 before the subsequent application at the year 42.5.

Figure 7 represents the time-dependent profiles of chloride diffusion through the original concrete without and with silane treatment (SL1 and SL2) at the threshold depth (TD) of 80 mm. Without silane treatment, the chloride content increases, causing continuous deterioration of the concrete structure. If the time that the chloride profile crosses the critical chloride value denoted as 0.9% wt. of concrete for corrosion initiation is defined as the corrosion-free service life of the structure, its service life is about 10.92 years. However, if SL1 or SL2 is applied, the effect of silanes on the diffusion of chloride ions starts to appear around the year 8 as shown by the profiles which start to deviate from the profile with no silane treatment. And, the service life of the structure with SL1 or SL2 is extended to 12.75 or 11.92 years, respectively. The service life of the structure with SL1 is longer than that with SL2 because the effect of SL1 during the effective duration is different from that of SL2. On the other hand, the diffusion coefficient for SL1 is kept equal to $0.12D_0(t)$ without the deterioration of silanes until the end of the effective duration. However, $D_{SL}(t)$ for SL2 exponentially increases until the end of the effective duration because of

Table 3: Service life extension and CO_2 due to silane treatment.

Strategy	Service life extension (yrs)	Number of silane treatment within service life	Cumulative CO_2 (eq. kg/m^2)	Effectiveness (yr/eq. kg/m^2)
SL1	1.83	2	5.118	0.358
SL2	1	1	2.559	0.391

the deterioration of silanes (Figure 4(b)). Hence, the shape of the deterioration during the effective duration also plays an important role in predicting the service life.

Table 3 represents the influence of SL1 and SL2 on the service life extension and the amount of cumulative CO_2 emission. Since the service life extension is defined as the time difference between the corrosion-free service life of concrete structures without and with silane treatment, the service life extension of concrete structures with SL1 and SL2 is equal to 1.83 (=12.75 – 10.92) and 1 (=11.92 – 10.92) years, respectively. The amount of cumulative CO_2 depends on the amount of annual CO_2 due to silane treatment (2559 eq. g/m^2) and the number of silane treatment applications before the end of corrosion-free service life. For example, there are two applications of SL1 within the corrosion-free service life (12.75 years) because the treatment is applied at the years 5 and 12.5. The cumulative CO_2 for extending the service life is equal to 5.118 eq. kg/m^2 (=2 × 2.559 eq. kg/m^2). It is noted that the annual CO_2 due to applying silane treatment after the year 12.75 is not included in consideration because the time of those treatments is beyond the corrosion-free service life. If the ratio of the service life extension to the cumulative CO_2 produced within the corrosion-free service life is defined as the effectiveness of silane treatment, the effectiveness for SL1 and SL2 can be calculated, as shown in Table 3. It is found that SL2 is more effective than SL1, although the service life extension by SL2 is shorter. This is because the service life extension by SL2 per one kg of CO_2 produced due to silane treatment is higher.

5.2. Sensitivity Analysis. The sensitivity analysis is performed to test the effect of each sensitivity parameter on the corrosion-free service life and the cumulative CO_2 emission. In this study, the sensitivity of any quantity X is defined as the percent difference from the original value of X as follows:

$$\text{Sensitivity} = \left(\frac{X_{\text{DIS}} - X_{\text{UND}}}{X_{\text{UND}}}\right) \times 100, \quad (7)$$

in which X can be the service life or the cumulative CO_2 due to silane treatment and X_{DIS} and X_{UND} are disturbed and undisturbed values of X, respectively. In the analysis, each sensitivity parameter is disturbed by ±15%.

Without silane treatment, two parameters, that is, the water-to-cement ratio of the original concrete (w/c) and the threshold depth (TD) of concrete structures, can be considered in the sensitivity analysis on the service life. Figures 8(a) and 8(b) show the chloride profiles with no disturbance and ±15% disturbance on w/c and TD, respectively. It can be estimated that the increase and decrease of w/c by 15% lead to the reduction of the service life by 25% and the extension by

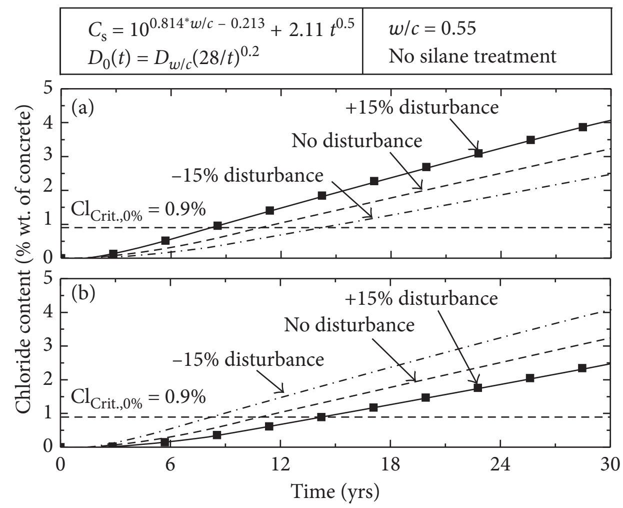


Figure 8: Chloride content for original concrete without and with disturbance on (a) w/c and (b) "TD."

32%, respectively. However, the increase and decrease of TD by 15% lead to the service life extension by 31% and reduction by 27%, respectively. Therefore, the service life is more sensitive to the decrease of w/c and the increase of TD.

With SL1 and SL2, there are two groups of sensitivity parameters relevant to the service life: two for original concrete (w/c and TD) and five for silane treatment strategies in Table 1. The five parameters are composed of the first and subsequent application of silane treatment (t_{FIRST} and t_{SUB}), the effective duration of silane treatment (t_{DUR}), the ratio of diffusion coefficient of original concrete to that of silane-treated concrete (α), and the effective depth of silane treatment (x_{p}). By ±15% disturbances on these sensitivity parameters, the service life and the cumulative CO_2 within the corrosion-free service life can be calculated, as shown in Table 4.

From (7) and Table 4, the sensitivity of the service life of concrete structures with SL1 and SL2 to each sensitivity parameter can be shown in Figures 9(a) and 9(b), respectively. It is found that the service life with SL1 and SL2 is most sensitive to both the water-to-cement ratio of the original concrete (w/c) and the threshold depth (TD) of the concrete structures. However, it is not sensitive to the subsequent application time of silane treatment (t_{SUB}). To explain this, let us consider the chloride profiles for concrete with SL1 and SL2 without and with 15% disturbance on t_{SUB}, as shown in Figure 10. The effect of t_{SUB} in the case of no disturbance starts to appear almost at the same time as the time which the chloride profile crosses the critical value (12.75 and 11.92 years for SL1 and SL2, resp.). With disturbance, the effect of t_{SUB} on the service life extension

Table 4: Service life and cumulative CO_2 for ±15% disturbances on sensitivity parameters.

Sensitivity parameters	Disturbance	SL1		SL2	
		Service life (yrs)	CO_2 (eq. kg/m^2)	Service life (yrs)	CO_2 (eq. kg/m^2)
w/c	+15%	8.56	2.556	8.5	2.556
	−15%	16.94	5.112	15.71	5.112
TD	+15%	16.58	5.112	15.48	5.112
	−15%	8.4	2.556	8.35	2.556
t_{FIRST}	+15%	12.08	2.556	11.65	2.556
	−15%	13.17	5.112	12.1	2.556
t_{SUB}	+15%	12.75	5.112	11.92	2.556
	−15%	12.75	5.112	11.92	2.556
t_{DUR}	+15%	12.89	5.112	12.02	2.556
	−15%	12.52	5.112	11.79	2.556
α	+15%	12.62	5.112	11.85	2.556
	−15%	12.89	5.112	11.98	2.556
x_p	+15%	12.89	5.112	11.98	2.556
	−15%	12.62	5.112	11.85	2.556
ACD	+15%	12.75	5.886	11.92	2.943
	−15%	12.75	4.35	11.92	2.175

Note. The service life of concrete structures with SL1 and SL2 for no disturbance is equal to 12.75 and 11.92, respectively.

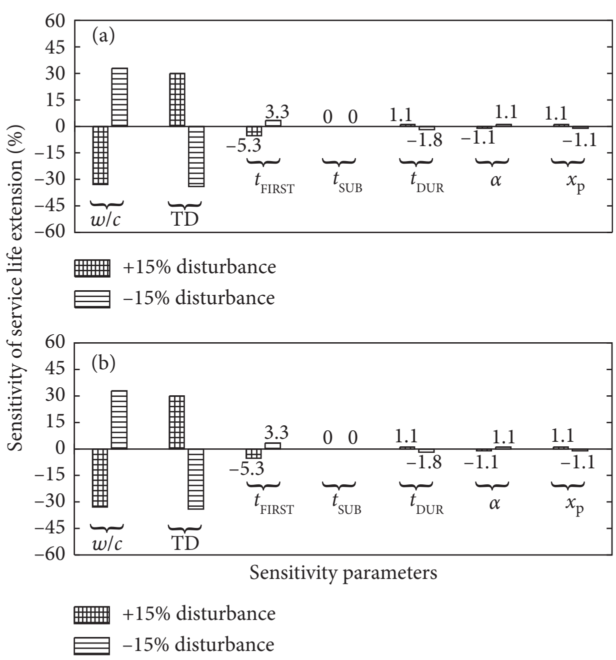


Figure 9: Sensitivity of the service life of concrete structures with SL1 and SL2.

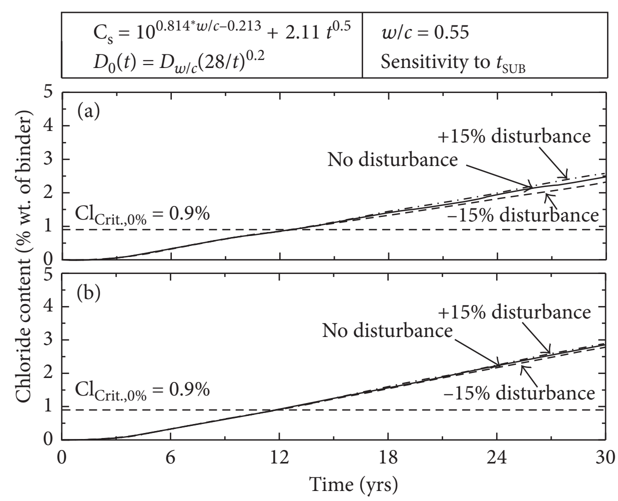


Figure 10: Chloride content for silane-treated concrete without and with disturbance on t_{SUB}.

cannot be fully active within the corrosion-free service life. It is also observed that if only five sensitivity parameters in Table 1 are considered, the service life is most sensitive to the first application of silane treatment (t_{FIRST}).

Figure 11 shows the sensitivity of the cumulative CO_2 within the corrosion-free service life for concrete structures with SL1 and SL2 to eight sensitivity parameters. Seven of the parameters are similar to those for considering the sensitivity of service life and the other one is the annual CO_2 due to silane treatment (ACD) as defined in Table 2. It is found that the cumulative CO_2 for SL1 is most sensitive to w/c, TD and t_{FIRST}, and quite sensitive to ACD. However, the cumulative CO_2 for SL2 is most sensitive to w/c and TD and quite sensitive to ACD. It is also noted that the sensitivity of the cumulative CO_2 in Figure 11 does not tend to be the same as that of the service life in Figure 9. This is due to the fact that the cumulative CO_2 depends on whether the application of silane treatment is within the corrosion-free service life or not, while the service life does not.

5. Conclusion

A Crank–Nicolson-based finite difference approach is used to assess corrosion-free service life of chloride-exposed concrete structures before and after repairs by time-based silane (alkyltriethoxysilane) treatment on concrete structures exposed to time-dependent chloride attack. The environmental impact in terms of the cumulative CO_2 emission due to silane treatment is also considered. From the study, it is concluded as follows:

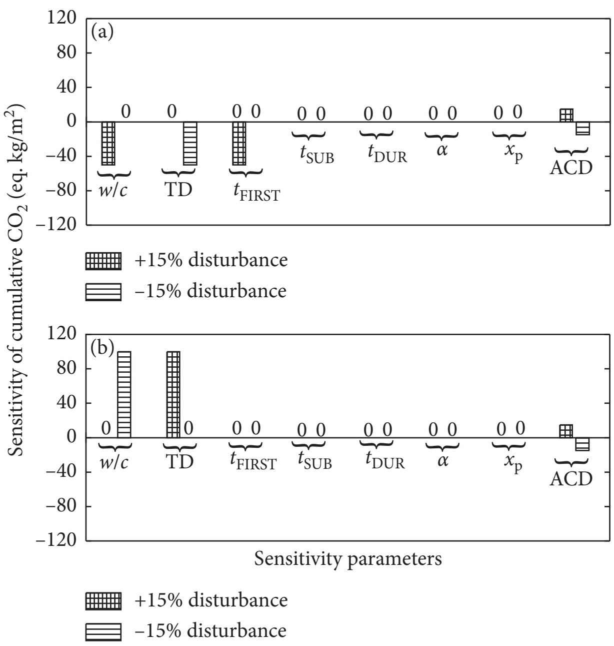


Figure 11: Sensitivity of cumulative CO_2 for concrete structures with SL1 and SL2.

(1) The diffusion of chloride ions in concrete with silane treatment is slower than that without. The strategy with the deterioration of silanes during the effective duration leads to lower service life than that without; hence, the shape of the deterioration during the effective duration also plays an important role.

(2) When comparing SL1 and SL2, the effect of SL1 leads to longer service life extension, but its effectiveness is lower. This occurs because the effectiveness considers both the service life extension and the cumulative CO_2 together.

(3) Without silane treatment, the service life of concrete structures is most sensitive to the decrease of the water-to-cement ratio and the increase of threshold depth of concrete structures.

(4) By considering only the sensitivities parameters in silane treatment strategies, the service life is most sensitive to the first application of silane treatment. The cumulative CO_2 for SL1 is most sensitive to the first application time of silane treatment, but that for SL2 is most sensitive to the amount of CO_2 emission per application.

(5) There are two recommendations for further study. First, the probabilistic study on assessing service life and CO_2 emission should be studied due to the randomness of chloride attack, concrete properties, and workmanship. Second, different kinds of surface treatment, such as polyurethane and cementitious coating, should also be evaluated.

Conflicts of Interest

The author declares that there are no conflicts of interest.

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