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Energy use in repairs by cover concrete replacement or silane treatment for extending service life of chloride-exposed concrete structures

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Abstract. In this study, the service life of repaired concrete structures under chloride environment is predicted. This prediction is performed by considering the mechanism of chloride ion diffusion using the partial differential equation (PDE) of the Fick's second law. The one-dimensional PDE cannot simply be solved, when concrete structures are cyclically repaired with cover concrete replacement or silane treatment. The difficulty is encountered in solving position-dependent chloride profile and diffusion coefficient after repairs. In order to remedy the difficulty, the finite difference method is used. By virtue of numerical computation, the position-dependent chloride profile can be treated position by position. And, based on the Crank-Nicolson scheme, a proper formulation embedded with position-dependent diffusion coefficient can be derived. By using the aforementioned idea, position- and time-dependent chloride ion concentration profiles for concrete structures with repairs can be calculated and shown, and their service life can be predicted. Moreover, the use of energy in different repair actions is also considered for comparison. From the study, it is found that repairs can control rebar corrosion and/or concrete cracking depending on repair actions.

1. Introduction

The attack of chlorides (Cl^-) is one of the significant phenomenon in the mechanism of concrete structure deterioration. When the quantity of the chlorides (Cl^-) near the circumstance of rebars is equal to its precarious value in addition to plenty amount of O_2 and humidity, rebar corrosion probably occurs causing concrete cracking and reducing the bond strength between concrete and rebar. Later, the debonding may decrease structural concrete strength. So, the corrosion of rebars detrimentally influences the safe and serviceable state, and also shortens the service life of structural concrete.

To prevent the deterioration, a proper repair action is necessary. Here, the action to slow down the rate of deterioration by implementing cyclic repairs; like replacing cover concrete or treating by silanes, is considered in order to extend the deterioration time. To predict the extension of the deterioration time or the service life of structural concrete with repairs, the evaluation of Cl^- penetration by a quantitative approach is recommended [1-3].

For the quantitative assessment, this study shades the light on the Cl^- diffusion determined by the Fick's second law. Two major processes are considered, i.e., chloride penetration through concrete without and with repairs. First, the surface chloride concentration (boundary condition) and the diffusion coefficient (material property) were supposed to be constant. Accordingly, solving one-dimensional partial differential equation (1-D PDE) is straightforward. However, when repairing by cover concrete replacement or silane treatment for service life extension in the second process is implemented, the assumption cannot be kept. To eliminate this problem, the Crank-Nicolson-based finite difference method (FDM) is used. In addition, the environmental impact in terms of energy use in different repairs is compared.

2. Chloride ion penetration in concrete

2.1. Cover concrete replacement

REHABCON [1] defined cover concrete replacement to be an action which aimed to remove original cover concrete and replace it by new materials, for example, concrete, repair material etc. To cope with this, there are two main stages to be considered in chloride ion penetration over exposure time:

2.1.1. Penetration of chlorides (Cl^-) from outer surface toward old (original) concrete. The basic 1-D PDE for explaining the diffusion of chlorides [4] is expressed as

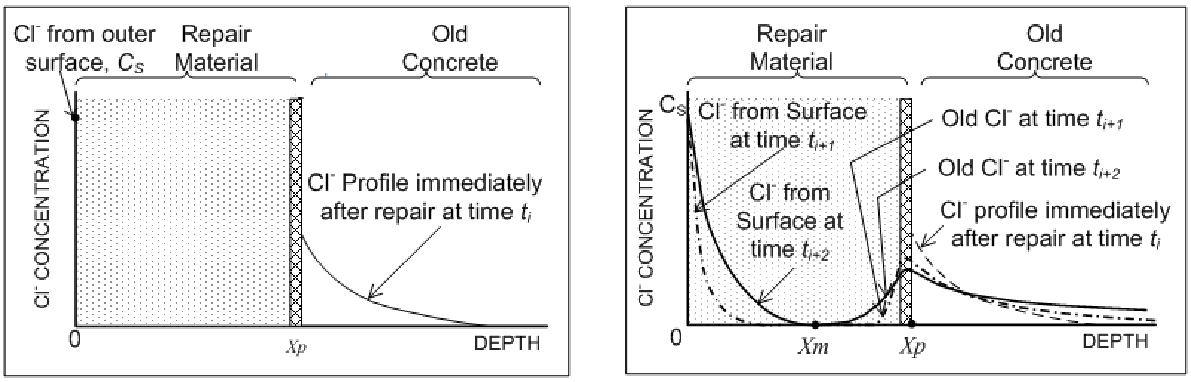
$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} D \frac{\partial C}{\partial x} \tag{1}$$

in which C is the quantity of chlorides in terms of location x and time t, and D is the concrete diffusion coefficient. According to (1), a Crank-Nicholson scheme for (1) is in the following form [5]

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

where $c_{x,t}$ is the quantity of chlorides at a mesh point x and time t. And, Δx is the mesh size (2 mm) and Δt is the time step (1 week).

2.1.2. Penetration and re-penetration of chlorides (Cl^-) after cover replacement. From figure 1(a), cover concrete is removed up to the cover replacement depth of x_p (or concrete cover depth), so the chlorides within the cover concrete are removed as well. Then, a repair material is replaced up to removed concretes (shaded area). The amount of unremoved chlorides (Cl^-) inside old concrete is shown by the Cl^- profile at time t_i. Then, three major steps occur as shown in figure 1(b). In the first step at time t_i, the chlorides inside old concrete are ready for re-penetrating toward the repair material, the problem involving solving the PDE with position-dependent Cl^- profile, or C(x,t), is met.



(a) Instantly subsequent to replacement (b) Subsequent to replacement

Figure 1. Cl^- profile subsequent to cover replacement [1].

In the second step at time $t_{i+}1$, the re-penetrating chlorides diffuse from old concrete toward the repair material, the problem involves position-dependent diffusion coefficient, or D(x), because the diffusion coefficients of old concrete is different from that of the repair material. Therefore, the partial differential equation in (1) can mathematically be updated as

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

In the third step at time t_{i+2}, when the newly diffused Cl^- from concrete surface meet with the re-penetrating chlorides (Cl^-) at the location x_m, the problem in solving the partial differential equation will again be met. If the number of repairs is more than one, it is even more complex. To avoid these problems, the Crank-Nicolson numerical scheme is introduced in calculation. By considering the three steps simultaneously, the problem solely deals with the transport of chlorides (Cl^-) toward concretes comprising dissimilar diffusion coefficients. Using [6], the numerical solution for (3) is written as

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

where $D_{i+1/2}$ and $D_{i-1/2}$ is equal to $(D_i + D_{i+1})/2$ and $(D_{i-1} + D_i)/2$, respectively. In calculation, whenever the cover is replaced within the location of x, its diffusion coefficient is updated, e.g., $(D_x)_0$ is $(D_x)_{CR}$. Moreover, $(D_x)_0$ is the diffusion coefficient of old concrete at the location of x, and $(D_x)_{CR}$ is the diffusion coefficient of repair material at x. Taking advantage of the FDM, the position-dependent Cl^- profile is considered location by location, hence this problem can simply be solved. Moreover, if the diffusion coefficients become constant, (3) and (4) reduces to (1) and (2), respectively.

2.2. Silane treatment (SL)

Silane treatment could be classified to be a type of penetrating sealers that reacted with hardened concrete within concrete pore to create a hydrophobic or non-wettable surface [7]. Hence, two stages occurs over the exposure time of concrete structures with silane treatments as:

2.2.1. Penetration of chlorides (Cl^-) from outer surface toward old concrete. To consider this, (1) and (2) are applicable as explained in Section *2.1.1*.

2.2.2. Penetration of chlorides (Cl^-) toward silane-treated and old concrete. At time t_i in figure 2, silanes are treated at concrete surface. By this treatment, silanes react with the hardened concrete within concrete pore up to the treating depth of x_p.

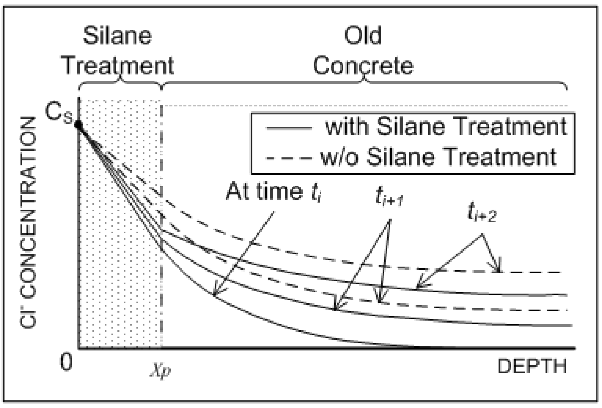


Figure 2. Chloride profile for concretes without and with treating by silanes.

Silane treatment such as that shown in figure 2 will result in the problem involving position-dependent diffusion coefficient, or D(x), because the diffusion coefficient of silane-treating concretes is dissimilar to the diffusion coefficient of old concrete. For this, the partial differential equation is

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identical with (3), so (4) is appropriate. In computation, the diffusion coefficient of concretes with silane treatment is updated after treatment. But, the unremoved chlorides in concrete with treatment are not set as zero, because they are not taken off by treatment (see figure 2).

2.3. Surface chlorides
In computation, the surface chloride could be treated as a boundary condition. Its value relies upon several factors, for instance, concrete mix or properties, the condition of exposure, and the distance of structural concretes from the source of chloride ions [8]. Due to these factors, the surface chloride functions were proposed in several forms [9]. Here, the constant surface chloride is given as 13 kg/m^3 for evaluating structural concretes situated in rigorous zone of the sea [10].

2.4. Diffusion coefficient
The diffusion coefficient of concrete could be treated as a material property. Its value relies on material types, for instance, normal concrete, repair concrete, silane-treating concretes and so on. Here, the diffusion coefficient of old concretes and repair materials is selected to be 1×10^{-8} cm^2/s [11] and 90% of the original concrete (0.9×10^{-8} cm^2/s), respectively, whereas the diffusion coefficient of silane-treating concretes is given as 0.29×10^{-8} cm^2/s [11]. In comparing, the diffusion coefficient for silane-treating concretes according to [11] is compatible a literature [12].

2.5. Time of repair implementation and lifetime for repairing
Cover replacement is utilized when the quantity of chlorides (Cl^-) on a monitoring (threshold) depth is equal to its precarious value (threshold-based). JSCE [13] specified the precarious value of 1.2 kg/m^3 for rebar corrosion initiation, whereas a researcher [14] specified the precarious value of 2.0 kg/m^3 for concrete cracking initiation. Here, the precarious value is given to be 1.2 kg/m^3 so as to control rebar corrosion (CR1) and 2.0 kg/m^3 so as to control concrete cracking (CR2). These two types of repair action are implemented whenever its precarious value is reached as shown in table 1.

Table 1. Time of repair implementation and lifetime for repairing.

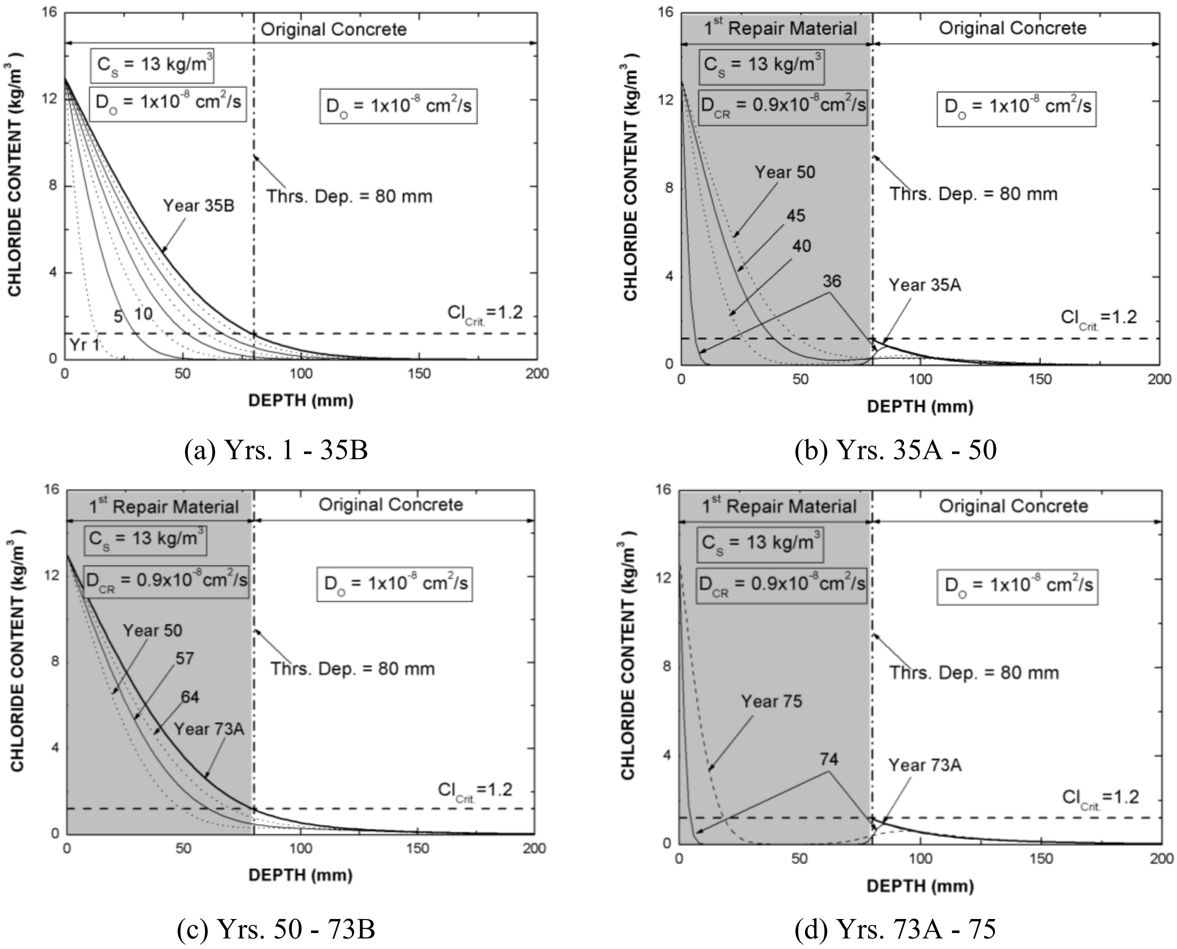
Repairs	Notation	Time of repair implementation	Lifetime
Cover replacement	CR1	whenever $Cl_{TH,T}$ = 1.2 kg/m^3	whenever $Cl_{TH,T}$ = 1.2 kg/m^3. again
	CR2	whenever $Cl_{TH,T}$ = 2.0 kg/m^3	whenever $Cl_{TH,T}$ = 2.0 kg/m^3. again
Silane Treatment	SL1	every 7 yrs	5 yrs after treatment
	SL2	every 5 yrs	5 yrs after treatment

Silane treatment is utilized according to a defined cyclic time (time-based). NCHRP-558 [7] claimed that the lifetime of silane treatment relies on the condition of exposures, for instance, ultraviolet, moisture, and etc. Moreover, its lifetime felt between 5 and 7 years prior to re-implementation. According to these, the time of treating by silanes is selected at every 7 years or 5 year (SL1 or SL2, respectively), whereas its lifetime is determined as 5 years after treatment (see table 1). SL2 is utilized every 5 years or after the end of lifetime of the former treatment in order for restoring the quality of treatment continuously.

3. Illustrative case studies
Illustrative case studies are given here; structural concretes with replacing cover and that with treating by silanes. In computation, the monitoring depth to evaluate the critical time is found to be 80 mm for structural concretes situated within seawater [13].

3.1. Cover concrete replacement (CR)

Using the aforementioned data, the diffusion of chlorides (Cl^-) toward the depth of structural concretes is determined in figures 3(a) to 3(d). In figure 3(a), the outer chlorides (Cl^-) transport toward the old (original) concretes with the surface chloride of 13 kg/m^3, when the time passes by. At the 42nd week after 35 years, the Cl^- profile hits the precarious value of 1.2 kg/m^3 (CR1) at the monitoring depth as presented by the profile at year 35B (B: Prior to repair), so-called critical time. With cover replacement (shown by the shaded area within cover concrete in figure 3(b)), the Cl^- profile converts the profile at year 35A (A: Subsequent to repair). At year 36, chlorides (Cl^-) from the surface transport to the concretes (shown by the profile near concrete surface), and the unremoved chlorides inside old concretes both re-penetrate to the repair material and penetrate to old concretes (shown by the profile near the monitoring depth). The diffusion process of chlorides (Cl^-) still lasts. At year 73 in figure 3(c), the Cl^- profile at the monitoring depth again becomes equal to the precarious value, the repair identical with the former one is re-implemented, so the behavior of chloride diffusion is similar. At year 75, the design service life [15] is reached, the computation is terminated as shown in figure 3(d).



(a) Yrs. 1 - 35B

(b) Yrs. 35A - 50

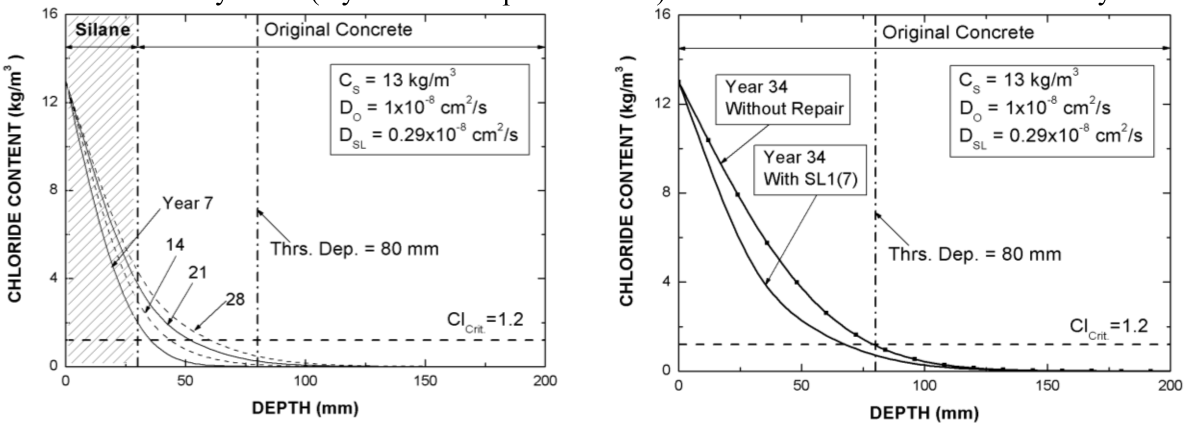
(c) Yrs. 50 - 73B

(d) Yrs. 73A - 75

Figure 3. Space-dependent chloride profile with replacement over 80 mm concrete cover.

3.2. *Silane treatment (SL)*

In the second case study, treating by silanes is used instead of cover replacement. The position-dependent Cl^- profiles could be presented in figures 4(a) and 4(b). Figure 4(a) shows the profiles for concretes with silane treatment utilized every 7 years (SL1). It is noted that the shaded area which covers over 30 mm from concrete surface shows the silane-treated zone (x_p). By comparing at year 34 in figure 4(b), the quantity of chlorides (Cl^-) at the monitoring depth for concretes with treating by SL1 is lower than that without. This shows the benefit of SL1 for extending the critical time. It is also noted that there is no silane-treated zone in this figure, because the quality of silanes implemented at year 28 vanishes at year 33 (5 years after implementation). The next silane treatment occurs at year 35.

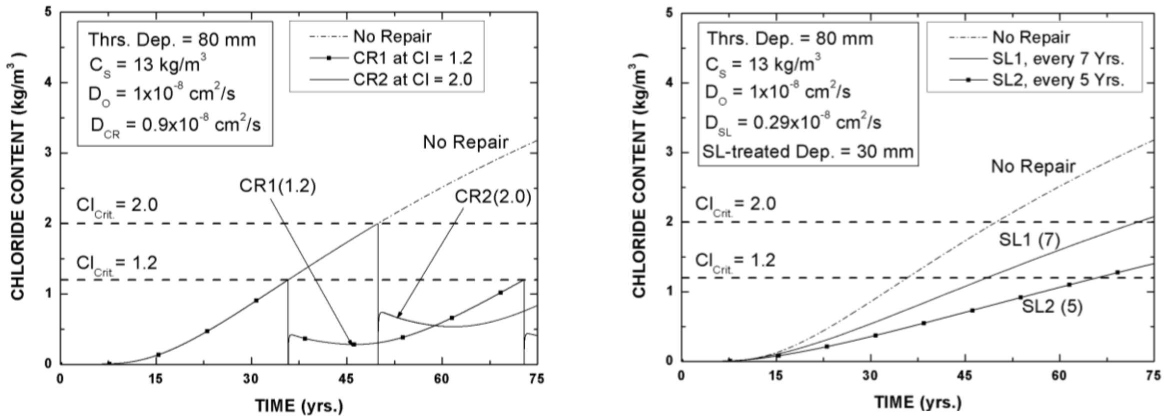


(a) Profiles: Yrs. 7 to 28 w/ SL1 (b) Profiles: Yrs. 35 w/o and w/ SL1

Figure 4. Space-dependent chloride profile with and without silane treatment.

3.3. Comparison

The Cl^- profiles for concretes with replacing cover at 80-mm monitoring depth is depicted with time as presented in figure 5(a). With no replacement, the chlorides unceasingly rise possibly causing rebar corrosion. When the service life of structural concretes is specified to be the time that the Cl^- at the 80-mm monitoring depth hits 1.2 kg/m^3 (CR1) or 2.0 kg/m^3 (CR2), the service life is about 35 years for corrosion control or 50 years for crack control, respectively.



(a) Cover concrete replacement (CR1 or CR2) (b) Silane treatment (SL1 or SL2)

Figure 5. Time-dependent chloride profile with repairs.

If cover replacement is utilized for controlling rebar corrosion at the time that the Cl^- profile hits 1.2 kg/m^3 in year 35, the service life becomes extended for 38 years before hitting the precarious value again at year 73 in figure 5(a). At the repair time (year 35), the quantity of Cl^- reduces to zero because of removing the chlorides with concretes, but the quantity of chlorides (Cl^-) instantly rises owing to abrupt re-penetration of Cl^- from old concretes. Then, the diffusion process of chlorides still lasts. At year 73, the Cl^- profile hits the precarious value one more time, the repair identical with the former one is re-implemented (see figures 3(c) and 3(d)). Hence, the cover replacements at years 35 and 73 extends the service life of structural concretes over 75 years. If CR2 is instead implemented for controlling crack, there is only one repair within 75 years due to the precarious value of 2.0 kg/m^3. It should be notices that the transport of chlorides in concretes with corrosion control (CR1) is different from that with crack control (CR2) in spite of the same repair. This implies that the concrete structure with crack control needs fewer repairs but allows higher risk of deterioration due to rebar corrosion.

With treating concrete by SL1 or SL2 as presented in figure 5(b)), the service life of corrosion-control structural concretes could be extended to year 48 or 66, respectively. With SL1 or SL2, the service life of crack-control structural concretes can however be extended to year 73 or more than year 75, respectively. Thus, concrete structures with SL2 are free of crack for 75 years.

Cover replacement result in eliminating the chloride ions in concrete cover, while silane treatment retards the penetration of chlorides as shown in figures 5(a) and 5(b), respectively. The question is which repair is more environment-friendly. Based on literatures [16,17], the energy use is found to be 1194 and 76 MJ per m^2 for cover replacement and silane treatment, respectively. For 75 years, the energy use for repairs by CR1 and CR2 is equal to 2388 (twice) and 1194 (once) MJ/m^2, respectively, while that by SL1 and SL2 is equal to 760 (10 times) and 1140 (15 times) MJ/m^2, respectively. So, if the energy use and corrosion control for 75 years is desirable, an optimum repair is CR1. But if the energy use and crack control is desirable, an optimum one becomes SL2.

4. Conclusions

Concrete cover replacement is used to control rebar corrosion or concrete cracking by controlling the quantity of chlorides (Cl^-) at the monitoring depth, while treating by silanes is used to extend the time that the Cl^- at the monitoring depth hits the precarious value. Moreover, the optimum repair action relies on what to control (corrosion or crack). And, concrete structures with crack control need fewer repairs leading to lower energy use, but allow more rebar corrosion leading to higher risk of failure.

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