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Service life prediction of repaired concrete structures under chloride environment using finite difference method

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ABSTRACT

Service life of concrete structures under chloride environment can be predicted by formulations based on the mechanism of chloride ion diffusion. This mechanism can be mathematically described using the partial differential equation (PDE) of the Fick's second law. One-dimensional PDE can be solved analytically by assuming constant surface chloride ion concentration and constant diffusion coefficient. However, the solution becomes more complicated when two additional conditions are included, i.e., concrete cover repair or replacement and time dependent variation of the surface chloride ion concentration and diffusion coefficient. In this paper, a numerical finite difference based formulation is proposed to effectively accommodate these two additional conditions. By virtue of numerical computation, the nonlinear initial chloride ion concentration can be treated in point-wise manner and both the time dependent surface chloride ion concentration and diffusion coefficient can be iteratively updated. Based on a Crank–Nicolson scheme within the finite difference method, a proper formulation accounting for space-dependent diffusion coefficient was derived; chloride ion concentration profiles are obtained and the service life of repaired concrete structures under chloride environment is predicted. Numerical examples and observations are finally presented.

1. Introduction

Even though concrete structures are considered as durable, some structures deteriorate due to severe environmental conditions during the service life; nevertheless the service life of the structures can be prolonged with proper maintenance actions.

The condition of concrete structures can be assessed in terms of concrete deterioration, reinforcement corrosion or combination of both. Chloride attack is considered as one of the most important factors affecting the service life of concrete structures. Whenever the threshold amount of the chloride ions reaches the surface of reinforcement, along with enough oxygen and moisture, steel corrosion may take place resulting in concrete cracking and spalling of the cover concrete when expansive stress exceeds the tensile strength of the concrete; reduction of steel reinforcement cross-section may also lead to structural failure. The debonding subsequently reduces the flexural or shear strength of structures. As a result, the corrosion of reinforcement adversely affects the safety and serviceability of concrete structures and hence shortens the service life [1].

To prevent structural deterioration an appropriate maintenance strategy is desired. This is required not only for existing structures, but also for newly built structures. There are various corrosion survey techniques available to assess the health of concrete structures. In this study, the strategy to slow down the rate of corrosion by accepting the need for cyclic repairs will be considered for maintaining the remaining service life. Concrete repair by replacing cover concrete with an inert material against chloride-induced corrosion is considered.

In order to study the durability and service life of repaired concrete structures, a quantitative assessment of chloride transport in repaired concrete structures is preferable [2]. There are several mechanisms by which chloride transport can take place in concrete, including diffusion, absorption, migration, pressure-induced flow and wick action. Diffusion is the primary mechanism of chloride transport in concrete under chloride environment where there is no applied electric field and the moisture condition of pore structure in concrete is stable. The Fick's 2nd law of diffusion is widely used to evaluate the behavior of chloride transport in concrete. There are two principal mechanisms of interest: chloride ion penetration in original concrete without repair and in partially repaired cover concrete. The former mechanism has been studied in [3,4], whereas the latter mechanism has been reported in [5–7]. In the former mechanism, the initial surface chloride ion concentration was treated as constant or time dependent, and the diffusion coefficient was treated as constant. By these two assumptions, a one-dimensional partial differential equation

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(PDE) was analytically solved. However, these two assumptions do not hold when considering replacement of the concrete cover. The initial chloride ions consist of two parts: surface chloride ions in repaired cover concrete and remaining chloride ions in the original (un-repaired) concrete. The concentration of remaining chloride ions in the original concrete is nonlinearly space-dependent at the time of repair; these ions generally penetrate into the repair material and further through the original concrete. In addition, the diffusion coefficient is space-dependent due to the difference between the diffusion coefficients of original concrete and repair material. Combining these situations with the time dependency of surface chloride ion concentration [4,8,9] and diffusion coefficient [10], analytical solutions of the PDE are not available. To circumvent this difficulty, a finite difference based formulation has been proposed in this paper. The feasibility of using this method for service life prediction of repaired concrete structures is also studied.

2. Cl^- penetration in concrete structures

2.1. Cl^- penetration in concrete structures without repair

The fundamental one-dimensional PDE for chloride ion diffusion [11–13] can be written as

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

where C is the chloride ion concentration as a function of position x and time t, and D is the chloride ion diffusion coefficient which can either be a constant or a function of x or t. With proper initial and boundary conditions, we can solve Eq. (1) analytically.

After the diffusion of chloride ions combining with enough oxygen and moisture, steel corrosion take place which results in concrete cracking and lead to severe deterioration. Without any maintenance actions, concrete structures will continue to deteriorate leading to failure. However, the phenomenon of such severe condition or failure is not allowed due to safety or the risk of life. Therefore, maintenance actions, for example, concrete repair, must be introduced before severe deterioration, or even before the corrosion initiation.

2.2. Definition of concrete repair

Various authors have studied the maintenance strategy of bridge structures by proposing different approaches [14–16]. In this study, the cover concrete replacement will be of interest. According to the literature [2], concrete cover replacement can be defined as the removal of old concrete and replacement with a new material, e.g., concrete, polymer-based material etc. This action is only suitable for repairing surface concrete. If only concrete and small part of reinforcement deteriorates, this action is effective. Some chemical adhesion can be applied on the interface between the original concrete and repair material. The type of adhesion material should be carefully chosen, because the loss of bond between the original concrete and repair material may cause the total failure of chloride protection from the repair material. However, in this study, the bond between the original concrete and repair material is assumed to be perfect.

2.3. Numerical scheme for Cl^- penetration in concrete structures with repair

For repairing concrete structures, complicated mathematical formulation in solving partial differential equations (PDEs) in each step of repair will occur. As a result, it should be more appropriate to use a numerical scheme to solve the problem. There are two main steps for chloride ion penetration involving lifetime concrete repair as follows:

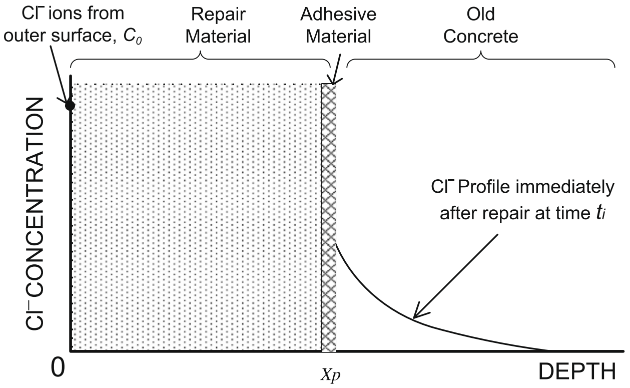
1. Chloride ion penetration from the outer surface through the original concrete. For this, a numerical method based on the Crank–Nicholson numerical scheme can be adopted. As the diffusion coefficient D can be considered constant in the original concrete, the finite difference approximation of Eq. (1) [17,18] can be written as

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

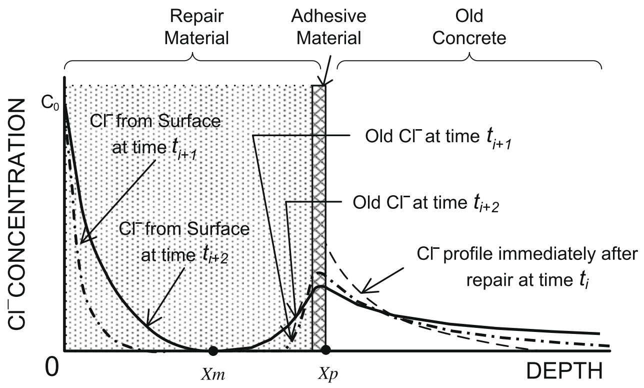
where $c_{x,t}$, in a general form, is the chloride ion concentration at a mesh point x and time t. It is noted that the key point of the Crank–Nicolson numerical scheme [17] is to apply differencing at the halfway between the known and the unknown time levels, i.e., averaging between the times j and $j + 1$.

2. Chloride ion penetration and redistribution after repair [2]. Let us consider Fig. 1a. At time t_i, concrete cover is initially taken as deep as the distance of x_p (or repair depth), and consequently the chloride ions inside the cover are also taken-off. After that, an adhesive material is applied on the surface of the original/old concrete and a repair material is subsequently replaced for the taken-off concrete.

After repair, there are three principle stages. Let us consider Fig. 1b. Firstly, when the chloride ions in the original concrete are about to redistribute, the problem will be involved in solving the PDE with nonlinear initial chloride profile or $C(x)$. Secondly, when the redistributing chloride ions penetrate through the origi-



(a) Immediately after repair



(b) After repair

Fig. 1. Chloride concentration profile after concrete repair [2]: (a) immediately after repair and (b) after repair.

Table 1
Time dependent surface chloride ion concentration C_s.

Standard speciation	Parameter	Distance from the sea (m)		
		0	100	250
$C_S(t) = \alpha[\ln(\beta t + 1)]$ (Song et al. [4])	α	1.52	0.76	0.51
	β	3.77		
JSCE [20] MOCT [21]	C_S (kg/m^3)	9	4.5	3

nal (old) concrete, adhesive material and repaired material, the problem involving space and time dependent diffusion coefficient, or $D(x,t)$, will be encountered. The space-dependent property is due to the different diffusion coefficient among the original concrete, adhesive material and repair material, whereas the time dependent property is due to aging of concrete structures. Mathematically, the PDE for this diffusion problem based on the Fick's second law can be written as

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

Thirdly, when the penetrating surface chloride ions merge with the redistributing chloride ions at the point x_m, the problem in solving PDE will again be faced. It will be even more complicated, if the number of repairs is more than one. In order to avoid all the aforementioned difficulties, a Crank–Nicolson based numerical scheme is proposed for computation.

Let us consider these three stages as a whole. It is observed that the problem only involves the diffusion of chloride ions through the materials having different diffusion coefficients. From the Crank–Nicholson based scheme [18], the solution for the problem with different diffusion coefficients can be formulated as

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

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 coefficient in Eq. (4) is constant, the equation reduces to Eq. (2). When the concrete cover is replaced over the depth x at time t, the diffusion coefficient of concrete cover will be updated, for instance, $(D_{0,t})_0 = (D_{0,0})_{rep}$ at concrete surface, and $(D_{x,t})_0 = (D_{x,0})_{rep}$ at repair depth x. $(D_{x,t})_0$ and $(D_{x,t})_{rep}$ are defined as the diffusion coefficient of original concrete and repair material at the depth x and time t, respectively.

Furthermore, taking advantage of the finite difference method, the time dependent surface chloride ion concentration may be iteratively updated as $c_{s(x=0),t} = C(t)$, and nonlinear chloride ion concentration can be treated point-wise.

2.4. Surface chloride ion concentration

Several researchers have proposed close-formed solutions for both time independent and dependent surface chloride ion concentration. The surface chloride depends on many factors, for example, the distance of structures from the sea, the region of structures (i.e., atmospheric, tidal, splash, or submerged zones), and concrete properties [26]. Costa and Appleton [19] presented an experimental study where the parameters used in the penetration model were calibrated to allow the prediction of long term chloride content in concrete. In the study, the surface chloride models were considered depending on concrete mix and exposure condition. Kassir and Ghosen [3] recently developed a new close-formed solution to predict the corrosion initiation time of reinforced concrete bridge decks using measured time varying surface chloride accumulations and the data base for the surface chlorides were cored at a shallow depth below the surface of 15 bridge decks in the snow belt region. Other surface chloride close-formed solutions were found elsewhere [4,8,9]. All of these close-formed solutions can simply be implemented to the finite difference based program and the chloride ion diffusion through concrete structures can subsequently be predicted. In this study, the time independent and dependent surface chloride ion concentration based on the standard specifications, i.e., JSCE [20] and MOCT [21], and on the close-form solution developed by Song et. al. [4], respectively will be considered as shown in Table 1.

2.5. Time dependent diffusion coefficient

The corrosion of concrete structures is directly related to the resistance or diffusion coefficient of concrete; hence a precise formulation of the diffusion coefficient is of importance in predicting chloride transport. The diffusion coefficient is recently found to be time dependent, because the process of cement hydration results in connection and condensation of concrete pore structures [4]. The time dependent form of the diffusion coefficient at time t in years, $D_{w/c}(t)$, is represented as a decay function of the following equations [10]

$$D_{w/c}(t) = D_{w/c}\left(\frac{t_R}{t}\right)^m \quad t \leqslant 30 \text{ years} \quad (5)$$

$$D_{w/c}(t) = D_{w/c}\left(\frac{t_R}{t_{\lim}}\right)^m \quad t > 30 \text{ years} \quad (6)$$

in which the limit time of these two equations, $t_{\lim}$, is of 30 years. $D_{w/c}$ is the diffusion coefficient at a reference time t_R which is equal to 28 days [10], and can be represented in terms of the water to cement ratio w/c as

$$D_{w/c} = 10^{(-12.06+2.4*w/c)}. \quad (7)$$

The value of m is a constant which represents the rate of diffusion coefficient decay and depends on the content of fly ash and slag [10]. However, in this study the amount of fly ash and slag is assumed to be zero, hence the value of m is set to 0.2. The diffusion coefficient for the water to cement ratio of 0.3, 0.4 and 0.5 is shown in Fig. 2.

2.6. Critical chloride ion concentration and threshold depth

The critical chloride ion concentration or the chloride threshold level, C_{crit}, is one of the main parameters in predicting the service life of concrete structures. Schiessl and Raupach [22] stated that the critical chloride ion concentration or content could be defined as the chloride content that was necessary to sustain local passive film breakdown at the steel depth before the process of corrosion initiation. The critical value can be defined as the value which corrosion initiation of concrete structures occurs at 0.2–0.4% by weight of cement [23]. Yokota and Iwanami [24] stated that the corrosion of reinforcement will start and progress rapidly, whenever the chloride ion concentration reached a threshold value at the position of reinforcement. JSCE [25] defined the critical value of 1.2 kg/m^3 to initiate reinforcement corrosion. Moriwake [26]

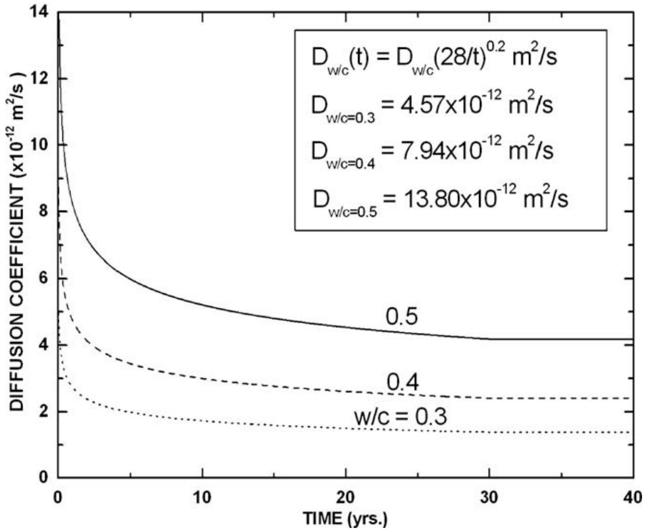


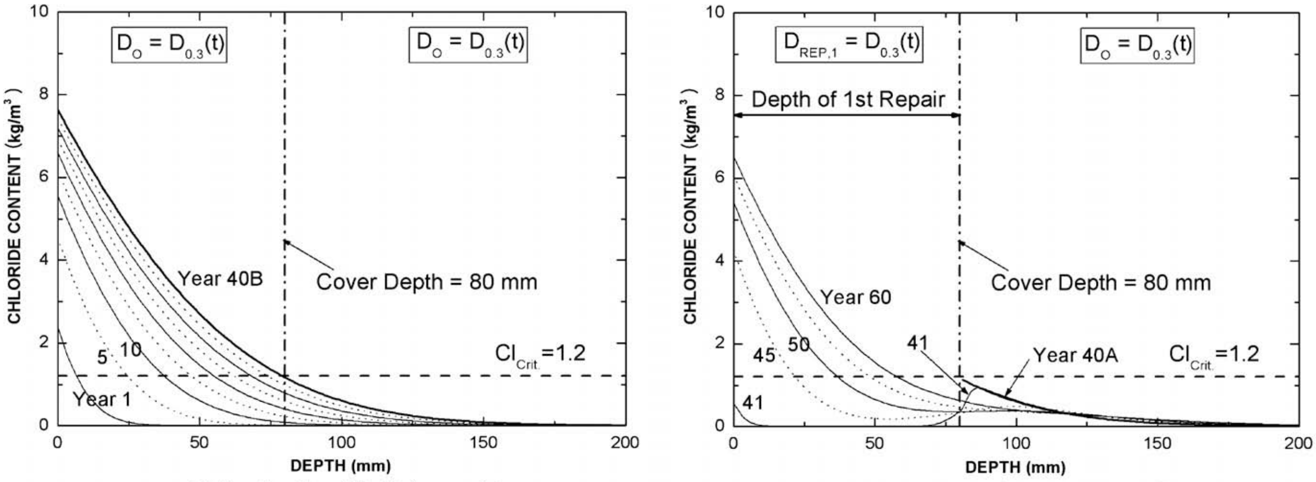
Fig. 2. Time dependent diffusion coefficient.

defined the critical value of 2.0 kg/m^3 to initiate concrete cracking. Alonso et al. [27] stated that the critical chloride value depends on the roughness of steel surface, concrete properties, and the aggressiveness of the environment. Ann and Song [28] extensively studied the critical threshold level.

In this study, application of concrete repair is performed, whenever the chloride ion concentration reaches a critical value at a specific threshold depth which is defined as a distance from the concrete surface to the front surface of reinforcement. Both 1.2–2.0 kg/m^3 will be used depending on the criteria to control the condition of concrete structures.

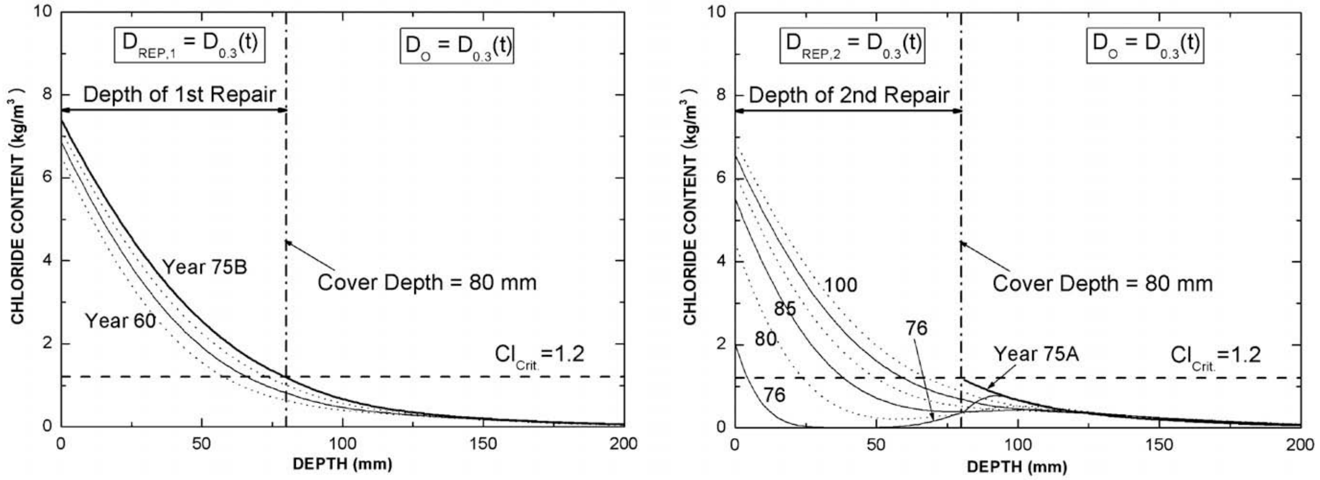
3. Numerical examples

The chloride ion penetration through concrete structures with and without repair can be calculated based on the previously derived equation implemented in a finite difference based program. In this study, there are two numerical examples; the first example with time dependent surface chloride ion concentration $C_S(t)$ and diffusion coefficient, $D_{w/c}(t)$, and the second example with constant surface chloride ion concentration C_S and time dependent diffusion coefficient $D_{w/c}(t)$. In selecting a repair material, it is assumed that the quality of the repair material must be equal to or higher than that of the original concrete. On the other hand, the water to cement ratio of new repair concrete material must be equal to or lower than that of the original concrete. In this study, the adhesive material and the effect of interfacial zone between the original concrete and repair material are neglected. However, these two



(a) Year 1 to Year 40B (Before repair)

(b) Year 40A (After repair) to Year 60



(c) Year 60 to Year 75B (Before repair)

(d) Year 75A (After repair) to Year 100

Fig. 3. Chloride ion-depth profile with 80 mm concrete cover repair.

parameters could be included if more precise information is required. It should also be noted that the size of the mesh point and the incremental time step in computation are 1 mm and 1 week, respectively. Moreover, it is assumed that the amount of oxygen and moisture is enough to cause corrosion, whenever the critical value is reached.

3.1. Time dependent $C_S(t)$ and $D_{w/c}(t)$

In the first example, a concrete structure is located near the sea or 0 m far from the sea, hence, the time dependent surface chloride ion concentration can be selected from Table 1, i.e., $C_S = 1.52\ln(3.77t + 1)$. Because the structure is close to the sea, the quality of the original concrete must be as high as the concrete in marine environment with low water to cement ratio as 0.3, or $D_0 = D_{0.3}(t)$, in order to reduce its porosity. Therefore, the applicable repair material must have the diffusion coefficient equivalent to the material with the water to cement ratio of 0.3, or $D_{rep} = D_{0.3}(t)$. Based on the recommendation from the Korean standard, the cover depth or threshold depth of concrete should be at least 80 mm for concrete structures in the marine environment [19]. With this data, the chloride ion diffusion through the depth of the concrete structure up to 100 years can be predicted as shown in Fig. 3a–d.

From Fig. 3a, the chloride ions penetrate through the original concrete, after the time passes by. It should be noted that at the surface, the chloride ion concentration increases with time, because of the effect of time dependent chloride ion concentration. The rate of chloride ion diffusion is slower with increasing time, because of the effect of diffusion coefficient decay with time. At 40 years, the chloride profile reaches the critical value at the threshold depth as shown by the profile at the year 40B (B means before repair). In fact, the chloride profile is found to reach the critical value (at 46th week) after 40 years. With the repair, the concrete cover is replaced by the repair material. Immediately after repair, the chloride profile with repair at 40 years 40A is shown (A means after repair) in Fig. 3b. After 41 years, the chloride ions from the surface will penetrate through the concrete (as shown in the left-handed side), and the remaining chloride ions in the original concrete will both redistribute through the repair material and penetrate through the original concrete (as shown in the right-handed side). When the chloride profile again reaches the critical value (at the 14th week) after 75 years as shown in Fig. 3c, the same repair cycle will be applied again as shown in Fig. 3d, until 100 years.

The application of the concrete repair can prolong the service life. The chloride profiles plotted with time has been shown in Fig. 4. The chloride ion concentration is measured at 80 mm cover depth. Without repair, the chloride ion concentration will cause corrosion initiation as well as propagation of corrosion in concrete structure. If the service life of the structure is defined as when the chloride concentration at the cover depth reaches the value of 1.2 kg/m^3, its service life is approximately of 40 years.

But if the repair material is applied after 40 years, the service life can be prolonged. It should be noted that the chloride ion concentration at repair decreases to zero due to the removal of old concrete replaced with new repair material. However, the chloride ion concentration suddenly increases, because of immediate redistribution of chloride ions from the un-repaired original concrete. After the effect of the first repair, the service life was found to be prolonged by approximately 35 years. At the end of 75 years, the chloride profile reaches the critical value again, the same kind of concrete repair as the first repair is reapplied. Two layers of repair result in prolonging the service life of the structure over 100 years.

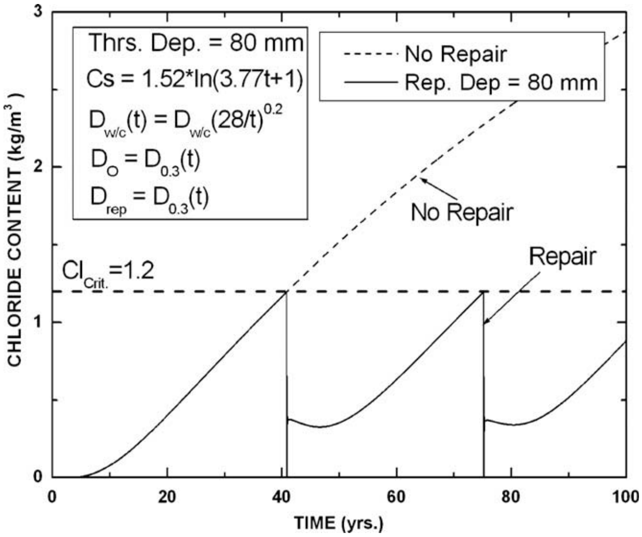


Fig. 4. Chloride ion-time profile with 80 mm concrete cover repair.

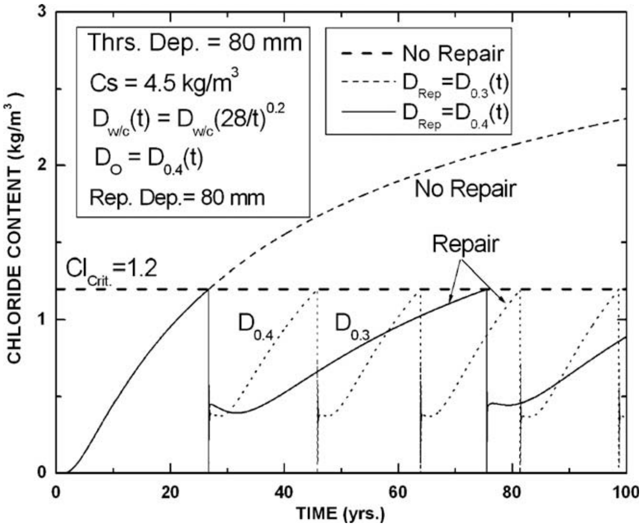


Fig. 5. Chloride ion-time profile with different repair materials.

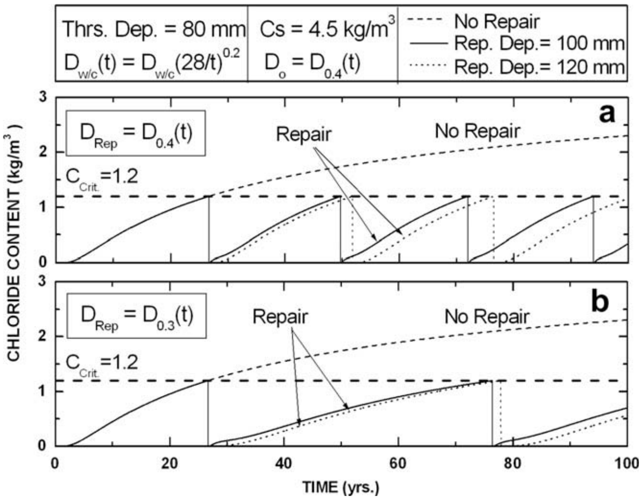


Fig. 6. Chloride ion-time profile with different repair depths and materials.

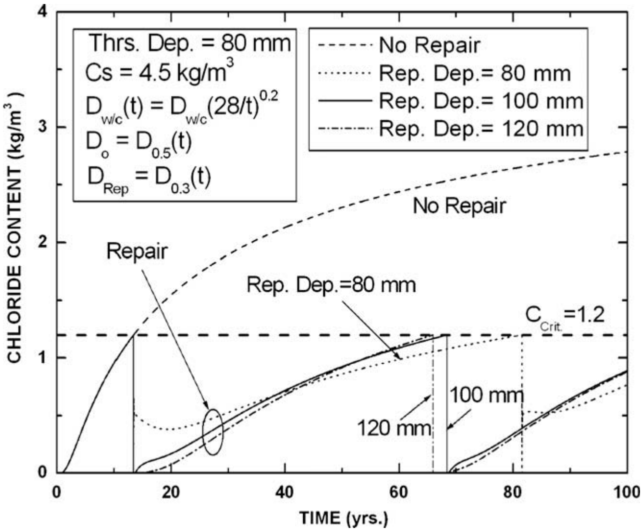


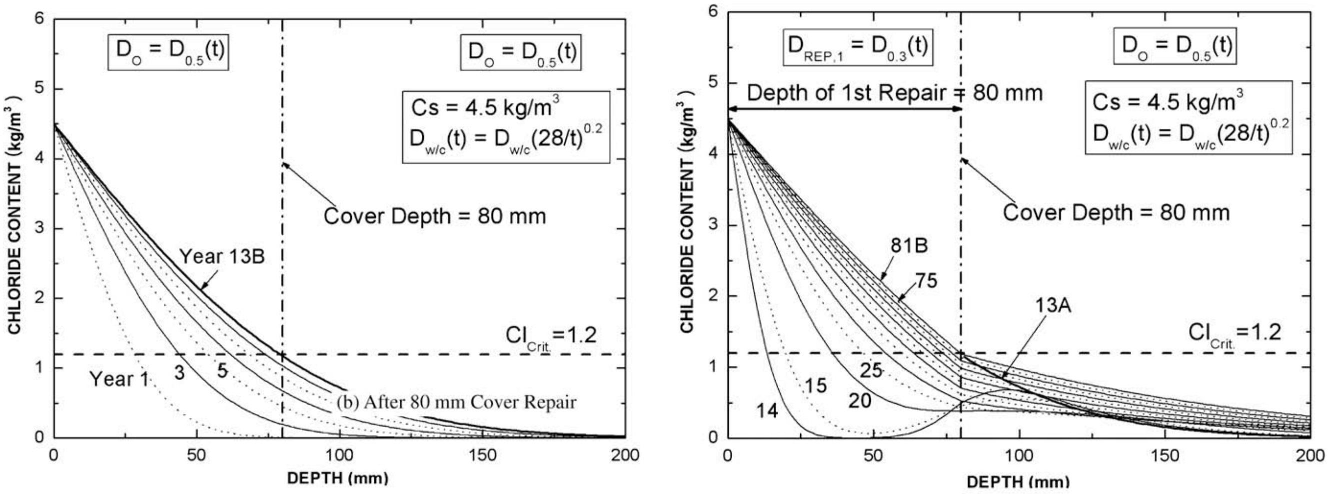
Fig. 7. Chloride ion-time profile with different repair depths.

It is worthwhile mentioning that accurate calculations of chloride transport for repaired structures in this study provide optimum time and period for prolonging the service life of the structure.

3.2. Constant C_S and time dependent $D_{w/c}(t)$

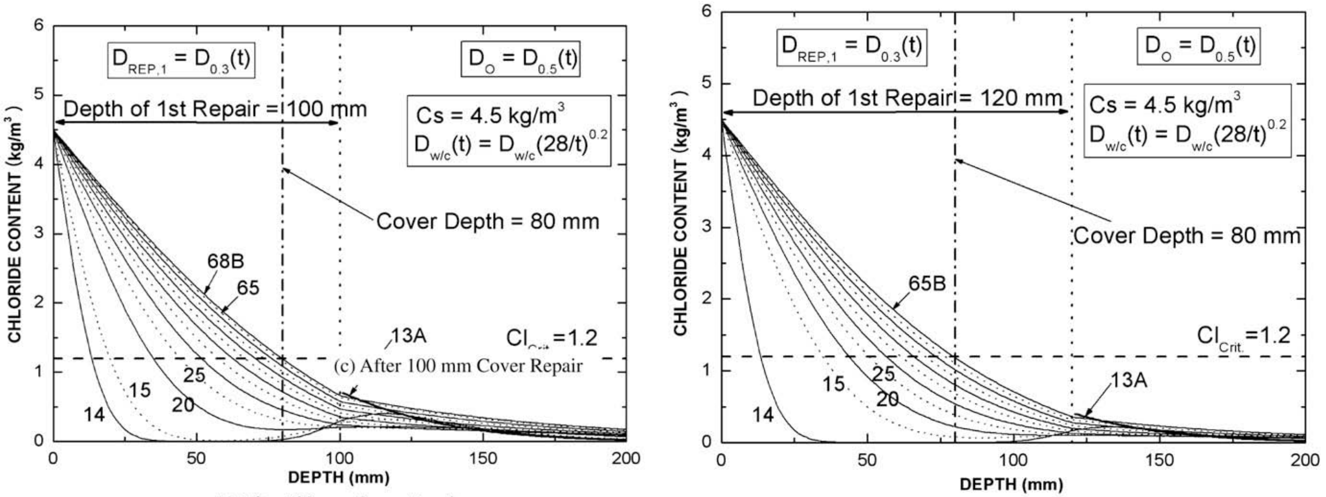
In the second example, a concrete structure is assumed to be 100 m far away from the sea. From Table 1, C_S is chosen to be constant and equal to 4.5 kg/m^3. The water to cement ratio of the original concrete is 0.3, 0.4, or 0.5 depending on strength requirement. Therefore, the applied repair material must have the diffusion coefficient equivalent to the material with water to cement ratio of 0.3, 0.4, or 0.5. However, the water to cement ratio of the repair material must be equal to or lower than that of the original concrete. The cover depth is equal to 80 mm and the critical chloride ion concentration is equal to 1.2 kg/m^3 as otherwise specified. With this information, the chloride ion diffusion through the depth of the concrete structure was predicted to investigate the effect of repair materials. The influence of different repair materials is shown in Fig. 5. In this case, D_0 is equal to $D_{0.4}(t)$, and D_{rep} is chosen to be equal to $D_{0.3}(t)$ or $D_{0.4}(t)$. It is found that the compatibility between original concrete and the repair material is good and then the service life is considered to be longer. On the other hand, the number of repairs required to satisfy the designed service life become less, if high quality repair material is used.

The effect of repair depths is shown in Fig. 6. It is found that the depth of repair is deeper, the service life is longer. This occurs, because the distances of chloride ion redistribution from 80 mm cover depth to 100 mm repair depth is shorter than that of the



(a) Before Repair

(b) After 80 mm Cover Repair



(c) After 100 mm Cover Repair

(d) After 120 mm Cover Repair

Fig. 8. Chloride profile with different repair depths.

120 mm repair depth. On the other hand, the distance between 80 mm cover depth and 100 mm repair depth is 20 mm, while the distance between 80 mm and 120 mm is 40 mm. Therefore, the time of chloride ion penetration in case of 100 mm repair depth is shorter than that of the 120 mm.

In some special cases, although the depth of repair is higher, the service life of concrete structures is not more prolonged as indicated in Figs. 7 and 8. In this case, D_0 is equal to $D_{0.5}(t)$, and D_{rep} is equal to $D_{0.3}(t)$. The depth of repair is varied from 80, 100, to 120 mm. From Fig. 7, in case of 80 mm repair depth, the chloride ion concentration decreases to zero immediately after repair and then jumps up with a specific value due to chloride ion redistribution. And then, it slowly increases with time. In case of 100 mm and 120 mm repair depths, the chloride ion concentration decreases to zero. Then, it increases slowly at the beginning, and later it increases suddenly due to high differential diffusion coefficient between the original concrete and repair material.

Fig. 8 shows the chloride profiles with different repair depths. The diffusion coefficient of the original concrete ($w/c = 0.5$) is higher than that of the repair material ($w/c = 0.3$) as shown in Fig. 2, hence the chloride ions tend to quickly redistribute from the repair material to the original concrete. As a result, the large extent of chloride ions moves towards the original concrete, as shown in the tail of the chloride profile in Fig. 8b, leading to reduction of chloride ion penetration in repair material. In case of 100 mm repair depth as shown in Fig. 8c, the same mechanism occurs, but the resultant chloride ion profile is not the same. This happens, because the chloride ion profile tends to behave as a decay profile. Therefore, the amount of chloride ions passing through the original concrete is limited leading to the accumulation of chloride ions in the repair material. As a result, the chloride ion concentration at the threshold depth increases faster than the case of 80 mm. Furthermore, as comparing the tail of the chloride ion profile in Fig. 8b and c, it is observed that the amount of chloride ions in the original concrete in case of 80 mm repair depth is larger than that of 100 mm. In case of 120 mm repair depth as shown in Fig. 8d, the same observation for 100 mm can be obtained. This leads to the increase of chloride ion concentration faster 80 mm than in 100 mm. This example shows that both quality and depth of repair material should be considered carefully for efficient repairing.

In terms of durability design, if it is able to select the water to cement ratio between 0.3, 0.4, and 0.5 while controlling the repair material having the same water to cement ratio and the same depth of repair, for example, $w/c = 0.3$–80 mm, respectively. Some observations from the design can be drawn.

From Fig. 9, with the repair depth of 80 mm, it is found that the original concrete with higher quality is more beneficial in prolonging the period after the first repair. However, after the first repair, the period between the application of first and second repair for the original concrete with $w/c = 0.3$ is shorter than that with 0.4 and 0.5, because the original concrete with $w/c = 0.3$ acts as a barrier to protect the chloride ion to move from the repair material to the original concrete. As a result, the chloride ions accumulate in the repair material and quickly increase. The same comparison can be drawn for the original concrete with $w/c = 0.4$–0.5.

In concrete repair, there are different criteria to decide the necessity of repairing to maintain the condition of concrete structures via the critical chloride ion concentrations as shown in Fig. 10. The critical chloride ion concentration of 1.2 kg/m^3 is defined as the chloride threshold value, i.e., a value to initiate corrosion, whereas that of 2.0 kg/m^3 can be defined as a value to initiate concrete cracking. This means the critical values of 1.2–2.0 kg/m^3 can be used to define corrosion-free and crack-free concrete, respectively. If we apply the same kind of repair but at different criteria, the condition of concrete structures will be different. The case with the critical value of 2.0 kg/m^3 allows more severe deterioration; therefore more careful attention and higher cost due to the risk of failure must be paid in spite of lower repair cost due to less number of repairs.

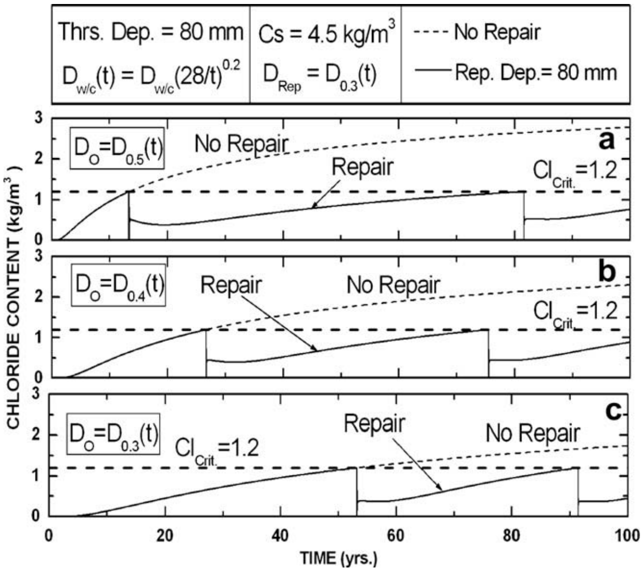


Fig. 9. Chloride-time profile with different original concrete.

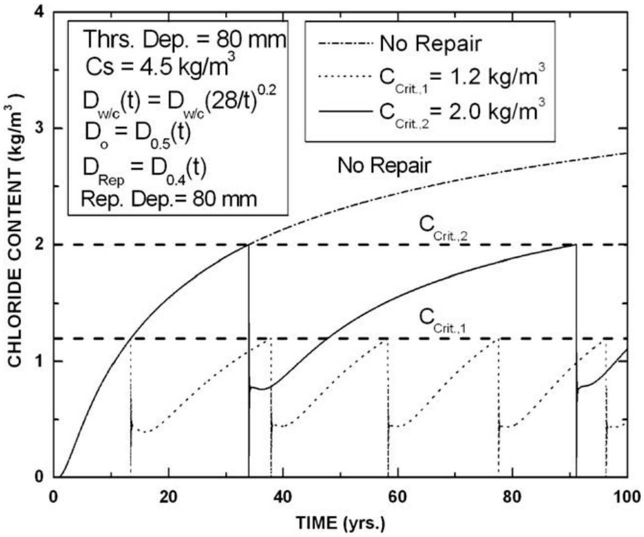


Fig. 10. Chloride-time profile with different critical chloride contents.

4. Conclusion

In this study, a numerical finite difference based formulation is proposed for predicting the service life of repaired concrete structures considering the mechanism of chloride ion diffusion through repaired concrete structures. By virtue of numerical computation, the nonlinear chloride ion concentration can be treated point-wise and time dependent surface chloride ion concentration and time dependent diffusion coefficient can be included. Based on the Crank–Nicolson scheme, a proper formulation embedded with space-dependent diffusion coefficient can be derived. By the aforementioned idea, the chloride ion concentration profiles can further be shown and the service life of repaired concrete structures under chloride attack can be predicted. The following conclusions are obtained.

1. It is quantitatively found that with different repair materials, the service life of concrete structures is prolonged depending on the quality of repair materials used. In other words, the quality of repair materials is higher; the service life of the structure gets extended. And also, if the repair material is of higher quality, the number of application of repair will be less.
2. In general, if the repair depth is higher the service life is also found to be higher. This occurs, because of longer distance and time of chloride ion redistribution to the threshold depth. However, in some specific case, if the differential diffusion coefficient between the original concrete and repair material is comparatively high, the smaller repair depth is more effective. The chloride ions tend to move from the repair material to the original concrete; hence the chloride ions at the threshold depth or cover depth are reduced resulting in prolonging the service life. Therefore, it is recommended that both the quality of the original concrete and repair material and the depth of repair should be considered carefully.
3. In design of new concrete structures, it is found that the original concrete with higher quality is more beneficial in prolonging period of the first repair. However, after the first repair, the original concrete with higher quality acts as a barrier to prevent the chloride ions to move from the repair material to the original concrete. As a result, the chloride ions accumulate in the repair material and increases quickly leading to shortening the service life of concrete structures.
4. In terms of durability, concrete structures can be repaired based on different criteria, for example, corrosion-free or crack-free by controlling the critical chloride ion concentration. It is also found that with different repair criteria, the same kind of repair causes different condition of repaired concrete structures. The higher critical chloride ion concentration will allow more severe concrete deterioration, hence more careful attention should be paid in spite of repair application. This also involves the cost of repair, because more possible deterioration leads to higher possible failure cost in spite of lower cost of concrete repair. Therefore, more study in this subject is recommended. The effect of the adhesive material and the interface between the original concrete and the repair material were neglected due to the lack of precise information, hence the research in these subjects is also recommended.

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