

Review Article

Chloride-Induced Corrosion of Steel in Concrete: An Overview on Chloride Diffusion and Prediction of Corrosion Initiation Time

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Initiation of corrosion of steel in reinforced concrete (RC) structures subjected to chloride exposures mainly depends on coefficient of chloride diffusion, D_c , of concrete. Therefore, D_c is one of the key parameters needed for prediction of initiation of reinforcement corrosion. Fick's second law of diffusion has been used for long time to derive the models for chloride diffusion in concrete. However, such models do not include the effects of various significant factors such as chloride binding by the cement, multidirectional ingress of chloride, and variation of D_c with time due to change in the microstructure of concrete during early period of cement hydration. In this paper, a review is presented on the development of chloride diffusion models by incorporating the effects of the key factors into basic Fick's second law of diffusion. Determination of corrosion initiation time using chloride diffusion models is also explained. The information presented in this paper would be useful for accurate prediction of corrosion initiation time of RC structures subjected to chloride exposure, considering the effects of chloride binding, effect of time and space on D_c , and interaction effect of multidirectional chloride ingress.

1. Introduction

During the last several decades, a large number of reinforced concrete (RC) infrastructures have been built using steel and concrete. It is estimated that, at present, about 2 billion tons of reinforced concrete is being built every year [1]. However, the deterioration of constructed infrastructures using RC directly affects everyday life in terms of safety, economy, and sustainability. A significant fraction of concrete produced is increasingly being used for repair and rehabilitation rather than new construction and it poses an economic burden on the society [2]. Deterioration of RC structures due to chloride-induced reinforcement corrosion has been reported to be a major durability problem worldwide. A large number of RC infrastructures are affected by reinforcement corrosion, particularly those which are exposed to coastal/marine conditions. In the chloride-laden environment, the fluctuations in the diurnal and seasonal temperature and humidity initiate cycles of expansion-contraction and hydration-dehydration that results into initiation and propagation of reinforcement

corrosion leading to cracking, spalling, and loss of load bearing capacity of the RC structures [3].

In order to protect the reinforcing steel from corrosion, the mechanism of chloride penetration into concrete and the factors influencing it should be understood [4]. Unlike the cases of other porous mediums, the penetration of chloride ions into concrete is a complex nonlinear dynamic phenomenon including several transport mechanisms (ionic diffusion, capillary sorption, permeation, dispersion, etc.) [5, 6]. The ionic diffusion is considered to have the most dominant effect under the assumption that concrete cover is fully saturated [7]. In saturated state, chloride ions enter concrete by ionic diffusion due to concentration gradient between the exposed surface and the pore solution inside concrete. This process is often described by Fick's second law of diffusion [8]. Crank gave the solution of this governing partial differential equation with semi-infinite boundary conditions and assumed the coefficient of chloride diffusion as a constant [9]. However, various researchers have reported that the coefficient of chloride diffusion varies with time and space

[10]. The effects of chloride binding and multidirectional chloride ingress on chloride diffusion coefficient are also reported [9, 11, 12].

Chlorides diffusing inside concrete can be either dissolved in the pore solution or bound to the cement hydrates chemically and physically along the diffusion path [9]. Therefore, we can divide total chloride into bound and free chloride. It is the free chloride that diffuses to the rebar and breaks the passive layer resulting into initiation of reinforcement corrosion [11]. The effect of chloride binding in concrete on the corrosion initiation is twofold: (i) the rate of ionic diffusion of chloride in concrete is reduced, since the amount of available mobile ions (free chloride) is reduced due to binding mechanisms and (ii) the reduction of free chlorides in concrete results in lower amounts of chlorides being accumulated at the reinforcing steel layer [13]. Theoretically, the concrete matrix becomes denser with the passage of time; therefore, the chloride binding ability of concrete should also improve based on the same principle. This makes it necessary to consider the effect of chloride binding with age in chloride diffusion models.

Although many pieces of valuable information on chloride diffusion of concrete have been reported in the past for service life prediction of concrete structures [14], most of these pieces of information are based on the results obtained by studying 1D chloride diffusion in concrete. However, some parts of concrete structures in the field (e.g., edges and corners of beams and columns) are subjected to the 2D and 3D chloride ingress [15], which results into a higher rate of diffusion through the edges and corners of concrete members than the portions subjected to 1D chloride diffusion [16]. Therefore, the effect of multidirectional chloride diffusion should be considered in the modelling of chloride diffusion process.

In this paper, an updated overview of the following aspects of chloride diffusion process in concrete structures is presented so that the prediction of time to initiation of reinforcement corrosion would be made with more degree of accuracy:

- (i) The influence of chloride binding on the coefficient of chloride diffusion in plain and blended cement concrete
- (ii) The effect of time and space on the coefficient of chloride diffusion
- (iii) Models currently available for the prediction of time to initiation of reinforcement corrosion of RC structures considering the effects of chloride binding, time, and space.
- (iv) The utility of chloride diffusion models in predicting time to initiation of reinforcement corrosion.

2. The Influence of Chloride Binding on the Coefficient of Chloride Diffusion in Plain and Blended Cement Concrete

The amount of chloride diffusing into concrete is referred to as total (acid-soluble) chloride. This can be further divided

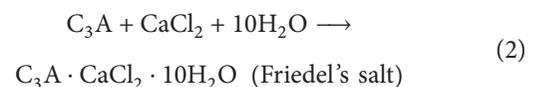
into the free (water soluble) chloride and bound chloride. It is the free chloride that is responsible for the reinforcement corrosion [11, 17]. The bound chloride either is physically adsorbed within the pores or chemically reacts with the hydration products [2]. The chloride binding in concrete affects the rate of chloride ingress, which in turn determines the chloride-induced corrosion initiation. The pore solution concentration, which is the driving agent of chloride diffusion process, is reduced due to the chloride binding reducing the chloride transport process [18]. Not only does this affect the chloride diffusion but the other mechanisms of chloride ingress (chloride transport from the flow of water due to capillary sorption, wick action, permeation, etc.) are also affected due to the binding of chloride [18].

When the binding effect of chloride is considered, the concentration of free chloride is reduced such that the coefficient of chloride diffusion is also reduced simultaneously [19]. Therefore, the diffusion-reaction model would predict a longer corrosion initiation time than the models that do not consider the effect of chloride binding during the chloride diffusion process [9]. The chloride binding chemical reaction occurs between chloride ions and the C_3A , C_4AF , and their hydration products that results in the formation of Friedel's salt as the product of the reaction [10]. It is also reported that chloride binding will be higher with high chloride concentration in the pore solution because chloride ions will have access to the more binding sites [20]. The reduction in chloride diffusion coefficient of blended cement concrete over plain cement concrete has been reported [15]. A 10 to 20% replacements of microsilica in cements showed a reduction of 2 to 11 times in chloride diffusion coefficient than that of OPC concrete and this significant reduction in silica fume concrete may be attributed to the densification of microstructure due to the development of secondary calcium silicate hydrate in result of pozzolanic reaction [2].

It is significant to consider the effect of chloride binding due to the following:

- (1) Only free chlorides (water soluble chlorides) are responsible for corrosion of reinforcement [17, 21]
- (2) The chemical binding of chloride ions with C_3A and C_4AF results in the formation of Friedel's salt, which has a less porous structure and slows down the transport of chloride ions [2]
- (3) Retardation in the diffusion of chloride and reduction of free chloride ions concentration in the vicinity of the reinforcement due to chloride binding reduces the corrosion risk [2, 22].

The chemical reaction between C_3A , C_4AF , and chloride ions, which leads to the formation of Friedel's salt, is given below:



A study on the relative importance of C_3A , C_4AF , C_3S , water/cement ratio, and so forth shows that C_3A has the most

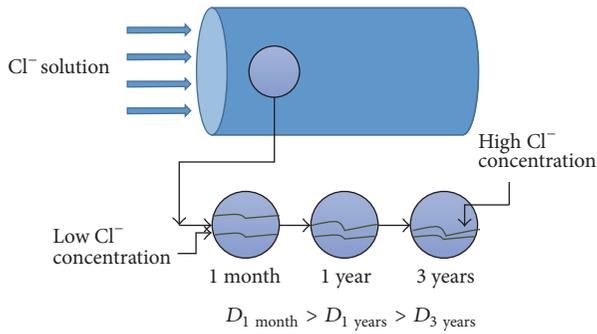


FIGURE 1: Effect of time on chloride diffusion coefficient [9].

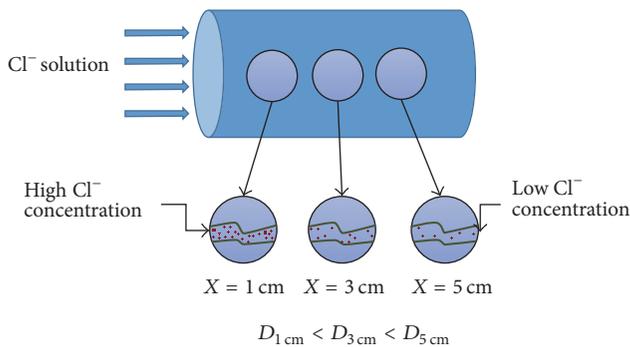


FIGURE 2: Effect of depth (space) on chloride diffusion coefficient [9].

dominant effect in chloride binding [23]. Various researchers [18, 23–25] have suggested models for estimating the chloride binding isotherms with C_3A content depending upon different isotherms (Langmuir isotherm and Freundlich isotherm) and concluded that C_3A content, which has an influence on the chloride binding capacity, changes the chloride diffusion coefficient [10]. It is reported that no single binding isotherm can accurately express the relationship between free and bound chloride within the complete concentration range [14].

3. The Effect of Time and Space on the Coefficient of Chloride Diffusion

The capillary pore structure of concrete depends mainly on water/cement ratio, degree of hydration, type of cement, and so forth. Microstructure of concrete also changes with time at various locations. Therefore, both the chloride ion concentration and chloride diffusivity vary with time and space [9]. The coefficient of chloride diffusion decreases with time because the capillary pore structure is altered due to the continuous formation of hydration products [26, 27]. Figures 1 and 2 show schematically the relationship between chloride ion concentration, age, and depth with the progress of chemical and hydration reactions [7].

As shown in Figure 1, at a certain depth inside concrete, the chloride concentration increases with time. However, due to continuation of hydration reactions, the porosity and pore

connectivity decrease, reducing the coefficient of chloride diffusion with the age of concrete. As shown in Figure 2, at a certain time, with increasing depth there is a decrease in chloride ion concentration and increase in the coefficient of chloride diffusion. This can be attributed to the fact that, at a shallow depth from the surface, chloride ion concentration is higher and therefore concentration gradient is lower that results into a lower coefficient of chloride diffusion. On the other hand, at a higher depth from the surface, the chloride ion concentration is lower and therefore there is higher concentration gradient that causes a higher coefficient of chloride diffusion.

The error function solution of Fick's second law of diffusion, given by Crank [28], is valid when both the coefficient of chloride diffusion (D_c) and the concentration of chloride on the surface (C_s) are assumed constant in time and space. However, it is known that D_c varies with space and time due to the variation in chloride concentration itself, temperature, moisture, and exposure conditions [2]. D_c determined by Crank's solution is specific to certain maturity of concrete and chloride exposure period. For example, D_c determined after 28 days of curing and 50 days of exposure to chloride solution will reflect the average concrete properties regarding transportation by diffusion (i.e., from 28th day to 78th day). However, this cannot be taken as a representative value because as the concrete matures, hydration decreases the ability of chloride ions to penetrate concrete, thereby changing D_c during the exposure period. The diffusivity of concrete made using the cement blended with supplementary cementing materials (fly ash, silica fume, etc.) is considerably more sensitive to the aging than plain cement concrete. Diffusivity of fly ash concrete may be one order of magnitude lower than plain cement concrete after approximately 2 years and it is predicted that it may decrease to two orders of magnitude lesser after 100 years [29].

Liang et al. [26] reported a study on the relationship between chloride diffusion coefficients for total and free chloride. They also reported the variations of coefficient of chloride diffusion with time for free as well as total chloride, as shown in Figures 3 and 4, respectively.

It can be observed from Figures 3 and 4 that both total and free chloride diffusion coefficients decrease with time. Initially, the reduction in coefficient of chloride diffusion is very high; however, it approaches to steady state after a longer exposure period. Liang et al. [26] also reported the change of coefficient of chloride diffusion with increasing penetration depth. It was reported that the free and total chloride diffusivities are proportional to the square of chloride penetration depth, as shown in Figures 5 and 6, respectively. It is therefore imperative to consider the effect of time and depth to prevent error in the prediction of reinforcement corrosion initiation using a constant coefficient of chloride diffusion [29].

Andrade et al. [30] proposed an approach to use the electrical resistivity of concrete to represent porosity and pore connectivity in modelling chloride penetration into concrete. This approach also considers the effect of concrete age on reduction of the coefficient of chloride diffusion. Farahani et al. [31] developed a model for estimating the service life of RC structures under chloride exposure by considering the

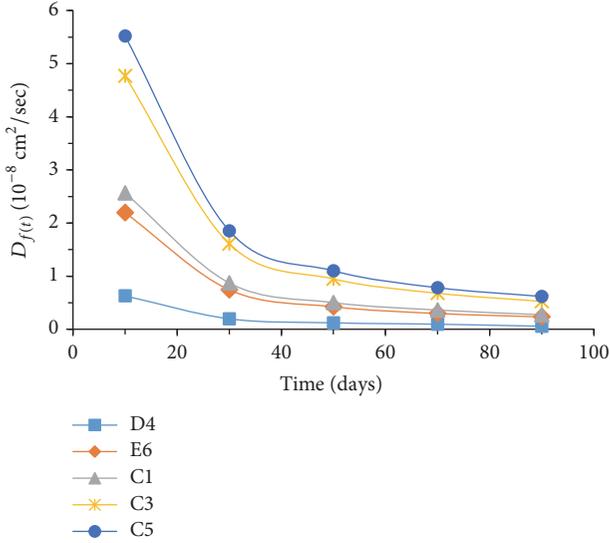


FIGURE 3: Effect of time on free chloride diffusion coefficient [26].

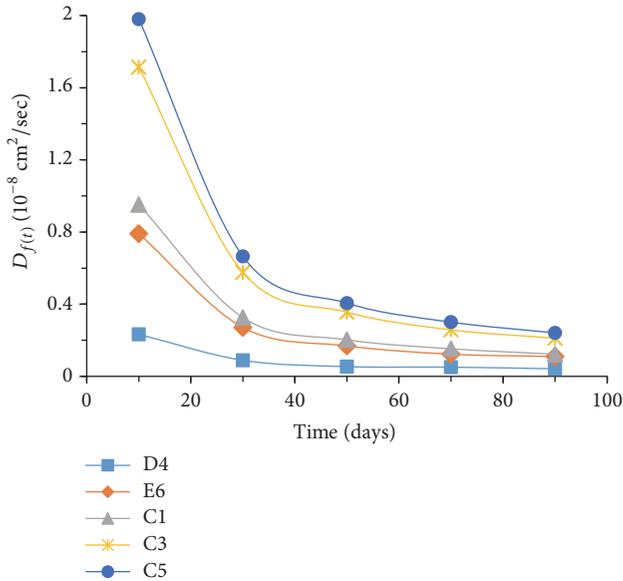


FIGURE 4: Effect of time on total chloride diffusion coefficient [26].

effects of temperature and time on the coefficient of chloride diffusion.

4. Modelling of Chloride Diffusion in Concrete

4.1. Basic Fick's Chloride Diffusion Model. A simple model that describes the chloride concentration as a function of time and distance under nonsteady state is given by Adolf Fick and it is popularly known as Fick's second law of diffusion [8], as given below:

$$\frac{\partial C}{\partial t} = D \frac{\partial}{\partial X} \left(\frac{\partial C}{\partial X} \right). \quad (3)$$

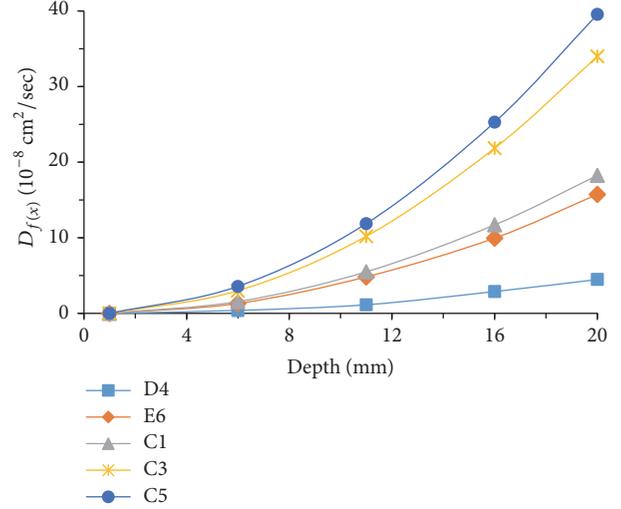


FIGURE 5: Effect of penetration depth on free chloride diffusion coefficient [26].

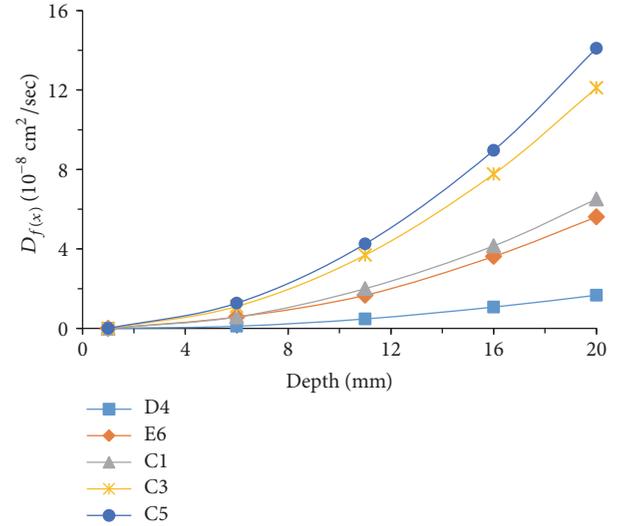


FIGURE 6: Effect of penetration depth on total chloride diffusion coefficient [26].

The initial condition (I.C.) and boundary conditions (B.C.) used to solve (3) are given by (4) through (6):

$$\text{I.C.: } C(x, 0) = 0 \quad (4)$$

$$\text{B.C.: } C(0, t_m) = C_s \quad (5)$$

$$C(x \rightarrow \infty, t_m) = 0. \quad (6)$$

The mathematical solution of (3) given by Crank [28] assuming D and C_s as a constant is given as

$$C_{x,t} = C_s \left(1 - \operatorname{erf} \left(\frac{x}{2\sqrt{Dt}} \right) \right), \quad (7)$$

where $C_{x,t}$ is chloride concentration at depth x and time t , C_s is chloride concentration at the surface, x is depth

from surface, t is time, and D is apparent chloride diffusion coefficient.

$$\operatorname{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2} dt. \quad (8)$$

The above model for chloride penetration may be simplified by using a parabola function, as follows:

$$C_{x,t} = C_s \left[1 - \frac{x}{2(3Dt)^{0.5}} \right]^2. \quad (9)$$

The values of C_s and D are found by best-fitting of the diffusion model ((7) or (9)) using the least squares method and best-fitted values of C_s and D are considered as constant [32]. However, as mentioned earlier, values of C_s and D vary with following factors:

- (i) Time
- (ii) Space
- (iii) Chloride binding during diffusion
- (iv) Damage in concrete cover due to loads

Therefore, various researchers have attempted to develop modified chloride diffusion models considering the above factors [7, 9, 29, 33–38].

4.2. Chloride Diffusion Model considering Effect of Time. A model reported by Maage and Helland [29] considering the effect of time on the chloride diffusion coefficient is as follows:

$$D_t = D_{28} \cdot \left(\frac{t_{28}}{t} \right)^m, \quad (10)$$

where D_t is chloride diffusion coefficient at time t , D_{28} is chloride diffusion coefficient at time t_{28} (28 days), and m is constant.

Value of m depends upon the concrete mix variables. The value of m tends to be lower for ordinary Portland cement mixtures than those incorporating mineral additives [33].

4.3. Chloride Diffusion Models considering Effect of Chloride Binding. Martö [7] proposed a modified Fick's second law which considers the effect of chloride binding by making changes in the computation of chloride diffusion coefficient.

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} \left(D^* \frac{\partial C}{\partial x} \right) \quad (11)$$

$$D^* = \frac{D}{1 + (1/\omega_c)(\partial C_b / \partial C_t)} \quad [\text{m}^2/\text{s}],$$

where D^* is apparent diffusion coefficient (m^2/s) and $\partial C_b / \partial C_t$ is binding capacity of the concrete binder (m^3 of pore solution/ m^3 of concrete).

The relationship between bound chloride concentration (C_b) and total chloride concentration (C_t) is to be obtained from various isotherms. The solution of (11) can be obtained in the same way as (3).

Another model proposed by Tumidajski [34] considered first-order chemical reaction to include the effect of simultaneous chloride diffusion and chloride binding by introducing reaction term in Fick's second law of diffusion. The model proposed by Tumidajski [34] is given by (12), as follows:

$$\frac{\partial C_t}{\partial t} = \frac{\partial}{\partial x} \left(D_t^* \frac{\partial C_t}{\partial x} \right) - kC_t, \quad (12)$$

$$\text{I.C.: } C(x, 0) = 0, \quad (13)$$

$$\text{B.C.: } C(0, t_m) = C_s, \quad (14)$$

$$C(x \rightarrow \infty, t_m) = 0, \quad (15)$$

where k is rate of reaction, C_t is total chloride concentration, and D_t^* is total chloride diffusion coefficient.

Danckwerts [35] obtained the solution of Tumidajski's model [34] as expressed by (12). The solution of (12) is given by (16), as follows:

$$C_{t(x,t)} = \frac{1}{2}C \left[\exp \left(-x \sqrt{\frac{k}{D}} \right) \operatorname{erfc} \left(\frac{x}{\sqrt{4Dt}} - \sqrt{kt} \right) + \exp \left(x \sqrt{\frac{k}{D}} \right) \operatorname{erfc} \left(\frac{x}{\sqrt{4Dt}} + \sqrt{kt} \right) \right]. \quad (16)$$

Danckwerts [35] reported that (16) predicts the experimental data well and the fitting of model against experimental data was improved for longer exposure durations.

4.4. Chloride Diffusion Models considering Effect of Time, Space, and Chloride Binding. Sun et al. [9] developed a model that considers the effects of time, depth, and chemical reaction on chloride diffusion coefficient. They considered three different models:

- (i) Simple model
- (ii) Time/depth dependent diffusion model
- (iii) Time/depth dependent diffusion-reaction model

(i) *The simple model* is the solution given by Crank [28] for Fick's second law of diffusion (3).

(ii) In *the time/depth dependent diffusion model*, Sun et al. [9] considered chloride diffusion coefficient to be the function of space and time and they proposed a model given by (17) considering initial and boundary conditions as given by (18) through (20):

$$\frac{\partial C(x,t)}{\partial t} = \frac{\partial}{\partial x} \left(D_{xt} (C(x,t)) \frac{\partial C(x,t)}{\partial x} \right), \quad (17)$$

$$\text{I.C.: } C(x, 0) = 0, \quad (18)$$

$$\text{B.C.: } C(0, t_m) = C_s, \quad (19)$$

$$C(x \rightarrow \infty, t_m) = 0, \quad (20)$$

where $C(x, t)$ and $D_{xt}(x, t)$ are the chloride concentration and chloride diffusion coefficient, respectively, that can be determined by fitting the experimental data into (17) nonlinearly using suitable software.

(iii) *Time/depth dependent diffusion-reaction model* presented by Sun et al. [9] also considers the effect of chemical reaction along with the effect of space and time. According to Sun et al. [9], the diffusing chloride ions are assumed to be immobilized by an irreversible first-order chemical reaction and it is given as

$$\ln [C_{xt}^F] = -kt + \ln [C_{xt}^T], \quad (21)$$

where k is a constant, and the rate of removal of diffusing chloride ions is k times the free chloride concentration.

Following is the 1D model given by Sun et al. [9] along with the initial and boundary conditions given by (23) through (25):

$$\begin{aligned} \frac{\partial C^F(x, t)}{\partial t} \\ = \frac{\partial}{\partial x} \left(D_{xt,k}^F(C^F(x, t)) \frac{\partial C^F(x, t)}{\partial x} \right) - kC^F(x, t), \end{aligned} \quad (22)$$

$$\text{I.C.: } C^F(x, 0) = 0, \quad (23)$$

$$\text{B.C.: } C^F(0, t_m) = C_S^F, \quad (24)$$

$$C^F(x \rightarrow \infty, t_m) = 0, \quad (25)$$

where $C^F(x, t)$ is free chloride concentration at various depths and time and $D_{xt,k}^F$ is the free apparent diffusion coefficient of diffusion-reaction equation that can be determined by fitting the experimental data into (16) nonlinearly using suitable software.

4.5. Chloride Diffusion Models considering Effect of Multidimensional Chloride Ingress. In real life scenario, RC structures are exposed to multidirectional chloride diffusion. The synergic effect of simultaneous exposure from more than one side can lead to a faster rate of deterioration and the critical members may show signs of distress much earlier than predicted. Hence, it is necessary to consider this effect in order to mimic the true behavior of chloride diffusion. However, these effects cannot be considered by one-dimensional chloride diffusion analysis. Figure 7 shows the schematic diagram of the interaction of chloride diffusion at the corners of a structural member and the path of maximum interaction is represented by dots.

As shown in Figure 7, the chloride front is diffusing inside the concrete from both faces. At the edges, the concentration from both sides is interfered and increased. Due to the synergic effect, the threshold chloride concentration will be attained at the corner reinforcements much earlier than the side reinforcements (although the cover depth is more at the corner reinforcement). This phenomenon of interaction cannot be evaluated while considering the unidirectional chloride ingress.

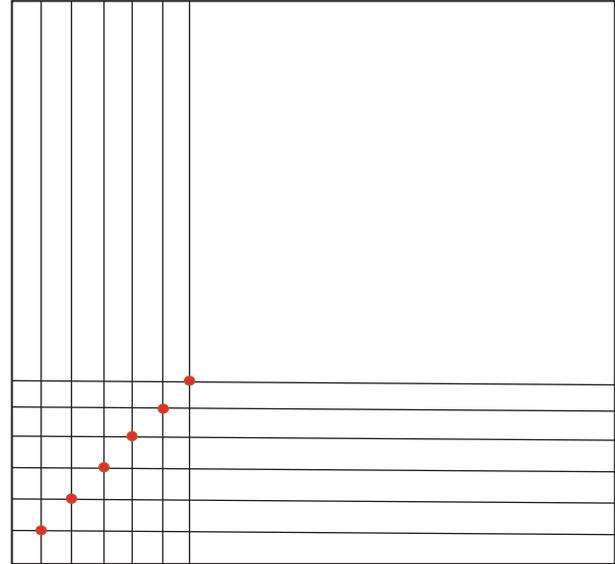


FIGURE 7: Interaction effect of chloride diffusion from 2 sides.

A very few literatures are available on 2D or 3D chloride diffusion of concrete. Zhang et al. [15] studied the effect of multidimensional ingress on chloride diffusion of fly ash concrete by exposing concrete cubes to chloride solution. The multidimensional ingress of chloride was simulated in a similar manner as that of 1D, with the difference that in 2D exposure four faces of the cubes were epoxy coated and two faces were left open and similarly for 3D exposure, three faces were epoxy coated and three faces were left open. It was reported that the chloride concentration at the same distance of concrete was in order $3D > 2D > 1D$ and the values of coefficient of chloride diffusion obtained from 2D and 3D exposure were 2.01 and 2.27 times higher than that of 1D, respectively. This suggests that more attention should be paid to the chloride ingress of the edge and corner concrete [15].

4.6. Chloride Diffusion Model considering Effect of Damage in Concrete. Concrete structures are subjected to the loadings that initiate damage of various degrees. Therefore, it is expected that the diffusivity of chloride will be higher in damaged concrete than virgin concrete [35–37]. Al-Kutti [2] considered a two-dimensional diffusion model and coupled it with mechanical damage and chloride binding. It was reported that, for undamaged concrete, the coefficient of chloride diffusion was $2.1 \times 10^{-6} \text{ mm}^2/\text{sec}$ while there was an increase of diffusivity of up to 9 times for the damaged concrete [2].

5. Application of Software in Modelling of Chloride Diffusion in Concrete

Apart from these mathematical models, types of special purpose software like Life-365 and STADIUM are now also available. These software types allow the designers to perform 1D and 2D analysis of chloride exposures with a

variety of user-defined parameters such as material options (inclusion of silica fume or corrosion inhibitors, etc.) and steel coating. These types of software have an extensive database for different exposure conditions and are gradually proving to be a handy tool for the design engineers [38]. Moreover, service life prediction of concrete structures subjected to chloride exposure can also be performed by general-purpose software, that is, COMSOL. These types of software are now equipped with specific modules that can simulate transport/reaction with mechanical/thermal response. Bentz et al. [38] performed 1D chloride diffusion using COMSOL, and they compared the predicted service life by the solution based on simple Fick's second law and service life obtained by using specific available modules in COMSOL for binding/reaction of ingressing chlorides. The variables considered were the cover thickness, threshold chloride concentration at rebar level, and material parameters (silica fume, corrosion inhibitors, and epoxy coated reinforcing bars). It was reported that, in all cases, solution based on Fick's second law was conservative and it predicted lower service lives. For a concrete cover thickness of 50 mm, the differences were 21%, 18%, 19%, 24%, and 27% for plain cement, plain cement partially replaced by 5 and 7% silica fume, corrosion inhibitor, and epoxy coated reinforcing bars, respectively [38].

6. Prediction of Corrosion Initiation Time

The chloride diffusion models can be used to predict the initiation time of chloride-induced corrosion of reinforcing bars by considering t is corrosion initiation time, x is concrete cover thickness, and $C(x, t)$ is threshold chloride concentration.

For example, (9) can be used to predict the corrosion initiation time, t_p , as follows:

$$t_p = \frac{1}{12D} \left[\frac{C_v}{1 - (C_{th}/C_s)^{1/2}} \right]^2, \quad (26)$$

where D is chloride diffusion coefficient, C_s is chloride concentration on concrete surface, C_v is concrete cover thickness, and C_{th} is threshold chloride concentration.

Sun et al. [9] typically reported the values of corrosion initiation time at different cover depths calculated using their three different chloride diffusion models, as discussed in Section 4.4. Plots of the predicted values of corrosion initiation time are shown in Figure 8. It can be observed from Figure 8 that the time/depth diffusion-reaction model predicted the highest corrosion initiation time as it considers the chloride binding occurring due to the chemical reaction, and expectedly the simple model predicted the lowest values of corrosion initiation time as it considers the chloride diffusion coefficient without considering the effect of chloride binding.

7. Conclusions

Based on the findings from this review, the following conclusions can be drawn:

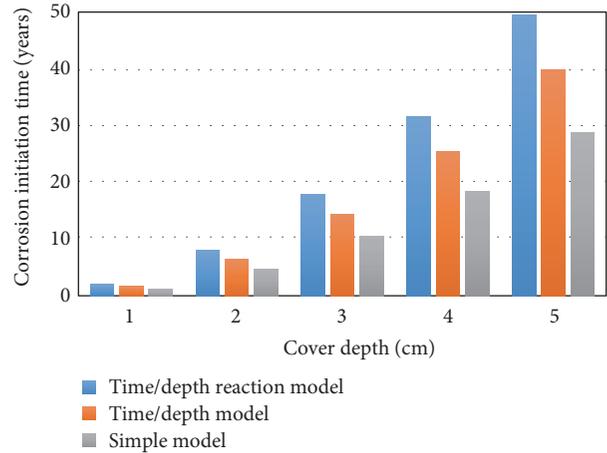


FIGURE 8: Comparison of corrosion initiation time by different diffusion coefficients [9].

- (1) The chloride diffusion parameters obtained from simple Crank's solution of Fick's second law of diffusion represents average concrete properties regarding transportation by diffusion and this cannot be taken as representative because as the concrete matures the ability of chloride ions to penetrate concrete decreases.
- (2) Since the coefficient of chloride diffusion decreases with time and chloride binding inside concrete, the model that consider the effect of chloride binding and the time on coefficient of chloride diffusion predicts higher service life of RC structures than that obtained using the solution based on simple Fick's second law of diffusion.
- (3) The synergic effect of simultaneous exposure from more than one side can lead to a faster rate of deterioration and the critical members may show signs of distress much earlier than predicted. Hence, it is necessary to consider this effect in order to mimic the true behavior of chloride diffusion.
- (4) With the advancement in computational capabilities and availability of special and general-purpose software, corrosion based service life models can be validated and verified. In addition, these types of software can be used for performing the parametric studies to determine the most influencing factors that affect the service life of RC structures.
- (5) The updated information presented in this paper can be useful for the estimation of time to initiation of reinforcement corrosion with higher degree of accuracy.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

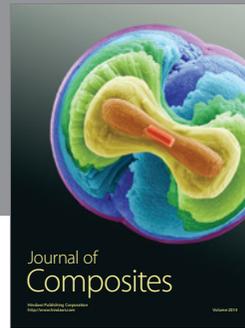
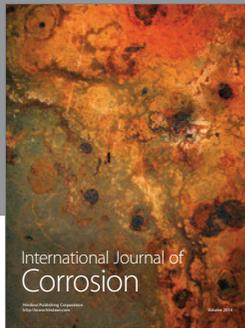
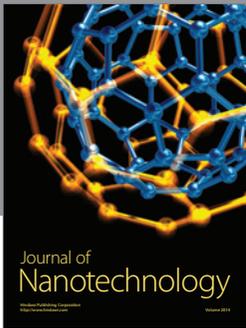
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