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Closed-form solutions for bilinear surface chloride functions applied to concrete exposed to deicing salts

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ABSTRACT

This study proposes new closed-form solutions for a mixed form of linearly increasing and constant surface chloride functions to remedy the inconsistency in predicting chloride diffusion in a previous study. The inconsistency occurs due to treating diffusion coefficient by using two redundant factors. To remedy the consistency, this study proposes to treat surface chloride by including a superposition term in the proposed solutions. To show the applicability, three examples are studied. The predictions of chloride diffusion in concrete by the proposed solutions are found consistent. To ensure the generality, the predictions by the proposed solutions are compared to those by the finite difference approach. From field data of concrete exposed to deicing salts, two bilinear surface chloride functions are compared for showing the importance of selecting an appropriate function. The sensitivity analysis reveals high influence of each parameter in the proposed solutions. The limitations of the proposed solutions are discussed.

1. Introduction

Chloride transport is known as one of the main phenomena accounting for the deterioration of concrete structures. For a period of time after the transport of chloride ions through concrete, the passive layer on reinforcing steel can be broken down. This occurs, whenever the amount of chloride ions at the steel surface is sufficient. In combination with chloride ions acting as catalysts [1], the corrosion of the steel initiates. After that, a continuous process of the corrosion may lead to severe deterioration of concrete structures in form of concrete cracking, and possibly the reduction of the flexural or shear strength of concrete structures. This is related to shortening the service life of concrete structures. Corresponding to this situation, Bouteiller et al. [2] reviewed the study of Angst et al. [3], and stated that the service life could be divided into two phases: in phase I referred as initiation phase (contaminants penetrate into the concrete cover), and in phase II referred as propagation phase (corrosion takes place). Nevertheless, the time identification between both phases still needed to be ascertained. Alexander and Thomas [4] outlined that performance specifications should permit concrete to be produced with the required properties to meet the desired service-life requirements in the specific environment. These reveal the importance of predicting not only the transport of chloride ions in concrete but also the service life of concrete structures under chloride environment.

If the transport of chloride ions by diffusion is focused in the service life prediction, the one-dimensional partial differential equation (1-D PDE) of the Fick's second law for predicting the diffusion of chloride ions can be written as

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

where C and D are defined as the chloride content as a function of position x and time t, and the chloride diffusion coefficient, respectively. In predicting the service life of concrete structures under chloride diffusion, a closed-form solution for Eq. (1) is necessary. For this, many researchers applied the mass transport model derived based on Eq. (1) by Crank [5]. For example, Collepardi et al. [6] used the closed-form solution for constant surface chloride C_S to predict the diffusion of chloride ions in concrete as follows

$$C(x,t) = C_S \, erfc \frac{x}{2\sqrt{Dt}} \tag{2}$$

where D is a constant diffusion coefficient, while erfc(·) is the complementary error function. It is noted that C_S and D are used as the boundary condition and the material property in numerical analysis. To predict the transport of chloride ions, the value of C_S and D are required, and can be determined by curve fitting with experimental data.

In many cases, both the surface chloride and the diffusion coefficient are found to be time-dependent [7–11]. For example, Kassir and Ghosn [12] proposed a closed-form solution for predicting the corrosion initiation time of reinforced concrete bridge decks in snow belt regions. The surface chloride function was proposed as exponential, i.e., $C_S = k$

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$(1 - e^{-\gamma t})$, and the corresponding closed-form solution was derived as follows

$$C(x,t) = k\left(1 - erfc\,\frac{x}{2\sqrt{Dt}} - e^{-\frac{x^2}{4Dt}}\ Re\left[e^{-z^2} erfc(-iz)\right]\right) \tag{3a}$$

$$z = \sqrt{\gamma t} + ix/\sqrt{4Dt} \tag{3b}$$

where k is a constant, and γ is a parameter related exposure time. Re[·] represents the real part in the parenthesis. It is observed that if the closed-form solution in Eqs. (3a) and (3b) is used, the imaginary number will be taken into account.

Another kind of time-dependent surface chloride is in a linear form, i.e., $C_S = kt$, as observed in a literature [13]. In 2015, Petcherdchoo [14] combined this linear form with constant surface chloride to predict the service life of a supplementary cementitious material (SCM) in form of matakaolin concrete structures exposed to chloride environment. Metakaolin was of interest because the availability and the production of commonly used SCMs (e.g., fly ash, blast-furnace slags) were much less than the worldwide production of cement [15]. The closed-form solution for the linear form of surface chloride for metakaolin concrete systems was expressed as

$$C(xt) = kt\left[\left(1 + \frac{x^2}{2Dt}\right) erfc\,\frac{x}{2\sqrt{Dt}} - \frac{x}{\sqrt{\pi Dt}}\,exp\left(-\frac{x^2}{4Dt}\right)\right] \tag{4}$$

where k is a constant related to the linear function of exposure time t. It is noted that Eqs. (2) to (4) are applicable to constant diffusion coefficient D. If the time-dependent diffusion coefficient is taken into account, further modifications are required. This will be explained later in this study.

The closed-form solution in Eqs. (2) to (4) was applied by considering only a single form of surface chloride function, e.g., constant, exponential, or linear. However, in many cases, the use of a single form of surface chloride function is not sufficient. The linear form of surface chloride function can be considered as an example. In the infinite time, the surface chloride may approach the infinity. However, this is inapplicable in the real practice. Hence, Thomas and Bentz [16] proposed the time that the surface chloride started to be constant as equal to 10 years for marine splashing zone, and 15 years or more for the atmosphere in coastal area. If this is the case, a mixed form of surface chloride functions, i.e., a mixture of linearly increasing and constant surface chloride function, must be taken into account.

To treat the mixed form of surface chloride functions, there are two optional parameters, i.e., the boundary condition in form of the surface chloride C_S, and the material property in form of the diffusion coefficient D. In 2014, Zhou [17] selected to treat D, and proposed a set of closed-form solutions to predict the diffusion of chloride ions in concrete. In the solutions, two correction factors related to exposure time were assumed and optimally searched for enforcing the continuity of the solutions. Due to this treatment, there are two limitations in the solutions. First, the solutions may not be suitable in the real practice. For example, if we want to develop a chloride transport model to predict the diffusion of chloride ions in a material, we need to do curve fitting between the chloride profiles predicted by the chloride transport model and those measured in an experiment. For this purpose, there are two basic regression parameters to be necessarily determined, i.e., C_S and D. However, if the solutions by Zhou [17] are used, the two correction factors will be redundant. These factors may disturb the regression analysis. Second, the solutions are just approximate, because they were developed by treating the diffusion coefficient. The inconsistency due to this approximation will be shown in Section 2.

To avoid the two limitations, this study proposes a set of new closed-form solutions for the mixed form of linearly increasing and constant surface chloride. The idea of the proposed solutions is to treat the surface chloride function C_S by including a superposition term in the solutions. To show the applicability of the proposed solutions, three examples are studied as shown in Section 4.

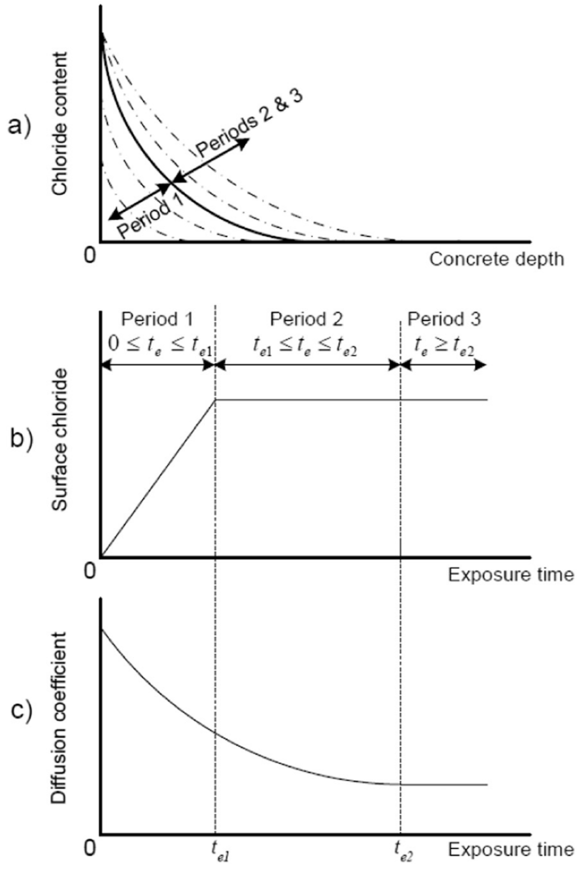

Fig. 1. Three periods for chloride diffusion and corresponding C_S and D.

2. Review of the previous study

This section is devoted to reviewing the reference solutions in the previous study by Zhou [17]. To deal with the mixed form of surface chloride functions, there are two parameters, i.e., the surface chloride C_S and the diffusion coefficient D. By selecting to treat the diffusion coefficient, three periods corresponding to the time dependency of C_S and D were defined as shown in Fig. 1. Fig. 1a represents the diffusion of chloride ions with respect to concrete depth for the three periods, and Figs. 1b and c show the time dependency of C_S and D, respectively. In the Period 1, C_S linearly increases with the time, while D decays with the time. At the starting time of the Period 2, C_S starts to be constant, while the D still decays with time. At the starting time of the Period 3, C_S remains constant, while the D starts to be constant. According to the three periods in Fig. 1, the reference solutions in the previous study [17] were shown as follows.

2.1. Period 1: increasing C_S and decreasing D

The previous study [17] reviewed some literatures [18–21], and indicated two observations. First, in some situation, a specific amount of chloride ions was initially available in the whole concrete. This situation was considered by including a parameter called the initial chloride content C_0 in closed-form solutions. Second, the chloride profile in the outmost surface zone was not necessary to follow Eq. (2), but had a lower chloride content than expected. Moreover, its peak appeared away from concrete surface. Beyond the peak, the chloride profile followed Eq. (2). The zone between the outmost concrete surface and the peak of chloride content was called the convection zone. To deal with this zone, the prediction of chloride diffusion was assumed to