Cement and Concrete Composites 74 (2016) 88–99

Contents lists available at ScienceDirect

Cement and Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Pseudo-coating model for predicting chloride diffusion into surface-coated concrete in tidal zone: Time-dependent approach

Aruz Petcherdchoo

Department of Civil Engineering, Faculty of Engineering, King Mongkut's University of Technology, North Bangkok, Bangkok, 10800, Thailand

ARTICLE INFO

Article history:
Received 4 December 2015
Received in revised form
11 July 2016
Accepted 24 August 2016
Available online 26 August 2016

Keywords:
Pseudo-coating model
Chloride diffusion
Surface-coated concrete
Tidal zone
Time-dependent performance

ABSTRACT

There are three fundamental physical types for repairs by surface treatment on concrete, i.e., coating, penetrant, and sealer. Due to the inconsistency in using the penetrant-based model in a previous study, three limitations occur. To avoid the limitations, this paper proposes a simple pseudo-coating model embedded in a Fick-based time-dependent approach for modeling the performance of surface-coated concrete in the tidal zone subjected to chloride attack. In addition, the time-dependent regression equation is also developed and combined in computation. To validate the approach, the chloride diffusion predicted by the developed approach is compared to that measured in the previous study. From the study, it is found that the nonlinear and linear surface chloride functions are suitable for uncoated and coated concrete, respectively. The sensitivity analysis shows that the chloride content in concrete is most sensitive to the time-dependent parameter in the surface chloride functions. The surface coating can either decrease or increase initial surface chloride, and the deterioration rate of the surface coating depends on coating materials. By considering the change of the surface chloride after surface treatment, two criteria are proposed to assess the lifetime of coating materials, i.e., equivalent amount of surface chloride, and equivalent instantaneous slope of surface chloride. And, the lifetime is calculated and compared to other literatures. The service life extension of concrete structures with different surface coatings is also compared. The benefit of combining the repair by surface coating with the durability design by increasing concrete cover is also shown.

1. Introduction

The attack of chloride ions has been known as one of the main causes accounting for steel corrosion which shortens the service life of concrete structures under marine environment. However, there are two principal methods to extend the service life, i.e., making concrete durable [1–5] and applying proper repairs [6–11]. Nowadays, the repair by surface treatment on concrete is known as one of the popular repair methods among other methods in the market, e.g., sacrificial anodes, cathodic protection, replacement of affected concrete, etc. According to some studies [12–14], there are three types for surface treatment, i.e., (a) coatings, (b) penetrants, and (c) sealers, as shown in Fig. 1. A coating could be seen as an additional physical layer on the original concrete surface. A penetrant penetrated through the concrete surface for lining or blocking pores. A sealer acted as both a coating and a penetrant. For penetrants or sealers, the concrete layer impregnated by treating materials could be regarded as equivalent to a coating on the underlying substrate concrete which therefore had a reduced thickness.

For years, the test results on the surface treatment have been reported by researchers as follows. By considering water absorption, a group of researchers [15] concluded that surface impregnation of un-cracked concrete and RC structures with silane was a highly efficient measure to reduce water absorption. Later, it was indicated that there was 97% confidence that silanes provided a residual protective effect against water even after 20 years of service [16]. Using the chloride migration test [17], a study [18] indicated that two different types of concrete (w/c 0.45 and 0.65) showed a dramatic decrease in chloride diffusion after surface treatment. In the study of Zhu et al. [19], different dosages of silane-based water repellent agents were either coated on the surface of the concrete or integrally added into the concrete mixture. It was found that the impregnation depth of silane is about 6.8–9.1 mm and 2.4–4.1 mm, for air-dried and oven-dried samples, respectively. Franzoni et al. [20] performed a chloride resistance test to

E-mail addresses: aruzp@kmutnb.ac.th, aruz.p@eng.kmutnb.ac.th.

http://dx.doi.org/10.1016/j.cemconcomp.2016.08.009

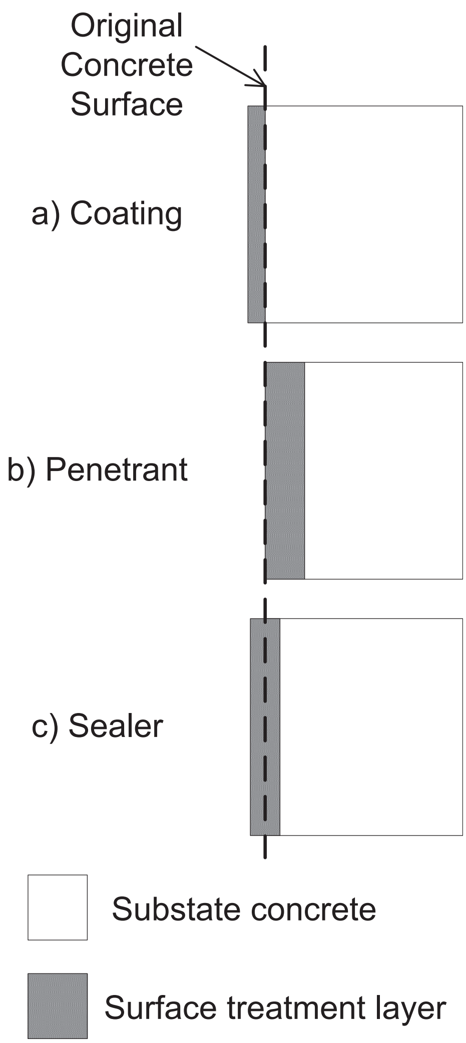

Fig. 1. Physical model for chloride diffusion through surface-treated concrete.

compare the performance and effectiveness of ethyl silicate to some inorganic products based on sodium silicate and nanosilica. It was found that the protection of ethyl silicate on reinforced concrete structural elements was more effective in reducing the chloride penetration depth. From a literature [21], it was found that the effective diffusion coefficient of silane-treated concrete with assuming 30-mm depth was reduced to 30% of that of untreated concrete. Medeiros and Helene [14] compared the effectiveness of silane/siloxane dispersed in water and solvent. They concluded that the effective diffusion coefficient of silane-treated concrete was reduced to 91% and 83% of that of substrate concrete for silane/siloxane dispersed in water and solvent, respectively. According to these results, it is found that these studies rely on assuming the time independency of surface chloride and diffusion coefficient. However, both of them are known as time-dependent. An example of the time-dependent behavior was shown in the study of Nanukuttan et al. [22] that conducted a 7-year full scale tests on treated and untreated concrete under marine exposure. They found that the surface chloride increased steadily and then achieved a constant level, and the magnitude of constant surface chloride was dependant on the exposure regime. And also, the diffusion coefficient followed a decreasing trend with duration of exposure, and the rate of decrease varied according to the exposure conditions. As an example for the reason of the time dependency, the study of Zhou [23] stated that the square-root buildups of surface chloride occurred in concrete exposed to wet-and-dry cyles. And, Song et al. [24] stated that the diffusion coefficient was time-dependent, because the process of cement hydration results in connection and condensation of concrete pore structures. In 2012, Moradllo et al. [25] studied the time-dependent performance of concrete surface treatments in tidal zone of marine environment, and reported both the effectiveness and the lifetime of several kinds of surface treatments. They found that epoxy polyurethane and aliphatic acrylic were the most efficient coatings, which caused a reduction the chloride penetration and enhanced the service life of concrete structures. And, the performance of surface coatings was time-dependent. However, the assumption in their approach causes some limitations as explained in the next section. To avoid the limitations, this study proposes a time-dependent approach to bridge the gap.

2. Statement of problems

In 2002, Moradllo et al. [25] (in this study called as “the previous study”) proposed an approach to evaluate the time-dependent performance of several kinds of surface treatment (see Table 1) on concrete exposed to the tidal zone of Persian Gulf region, and also verified their model with their experimental data. In their model, they employed the simple closed-form solution for the one-dimensional partial differential equation (1-D PDE) of the Fick's second law as

$$C(x,t) = C_S\left[1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)\right] \quad (1)$$

where C_S is the surface chloride, D is the diffusion coefficient, and $erf(\cdot)$ is an error function. In their experiment, they measured the chloride content in the test materials at different exposure times, for example, concrete and CPE at 3- and 60-month exposures, as shown in Fig. 2. By the regression analysis on their experimental data, they used Eq. (1) to compute the values of surface chloride and diffusion coefficient for the two test materials at various exposure times as shown in Fig. 3a and b, respectively. By curve-fitting for C_S and D in Fig. 3, they calculated parameters to represent the time-dependent surface chloride $C_S(t)$, and also the lifetime of treating materials. Then, they repeated the same process for PU, AA, CE, and SA. Table 2 represents the parameters for four types of time-dependent surface chloride functions $C_S(t)$. To represent the deterioration of treating materials, they evaluated both the effectiveness and the lifetime of surface treatments by considering the ratio of the time-dependent diffusion coefficients as well as the exponential function as follows

$$\frac{D_{treat}(t)}{D_{conc}(t)} = a \cdot e^{-bt} \quad (2)$$

where $D_{treat}(t)$ and $D_{conc}(t)$ were defined as the diffusion coefficient of treated and untreated concrete, respectively, at time t. And, “a” and “b” were defined as the coefficients varying with the type of surface treatments, and calculated as shown in Table 3. Furthermore, they defined the time which $D_{treat}(t)$ is equal to $D_{conc}(t)$ as the lifetime of treating materials, t_{lif}. Hence, Eq. (2) was rewritten as

$$a \cdot e^{-bt} = 1 \quad \rightarrow \quad t_{lif} = \frac{1}{b}\ln\left(\frac{1}{a}\right) \quad (3)$$

where the lifetime of treating materials, t_{lif}, is shown in Table 3.

Although their approach can be used to estimate the lifetime of treating materials, there are three limitations as follows: