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Quantifying maximum phenomenon in chloride ion profiles and its influence on service-life prediction of concrete structures exposed to seawater tidal zone – A field oriented study

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HIGHLIGHTS

- The maximum phenomenon is examined in samples were exposed to tidal zone for 5 years.
- The results show that the occurrence of maximum phenomenon is time-dependent.
- Both the skin layer thickness and the maximum Cl content are evolving with time.
- The modifications in mixture design affect the formation of the maximum phenomenon.
- Neglecting the maximum phenomenon causes an overestimation in predicted service-life.

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ABSTRACT

Only limited work has been completed to characterize and quantify the chloride ion (Cl) maximum phenomenon and its impact on service-life prediction. In addition, there is limited long-term experiment to examine the evolution of the maximum phenomenon. The present study investigates the maximum phenomenon in concrete samples with sixteen varying combinations of water-to-binder ratios (w/b) and silica fume (SF) contents which have been exposed to tidal zone of marine environment for five years. Results show that the presence of maximum phenomenon is time-dependent, and both the maximum phenomenon thickness and the maximum Cl concentration are evolving with time. In addition, concrete matrix plays an important role in occurrence of the maximum phenomenon. Neglecting the maximum phenomenon results in a large discrepancy between the simulated and measured Cl profiles and can cause a significant overestimation in predicted service-life of concrete structures.

1. Introduction

The chloride-induced corrosion of the embedded steel has become the most common cause of loss of integrity and failure in concrete structures placed in the marine environment [1,2], which can impose considerable repair costs every year [1,3,4]. Accordingly, special precautions, including modification of existing service-life prediction models need to be established, under these extreme ambient conditions, in order to enhance the design life and durability of concrete infrastructures in harsh environments.

The mechanisms of chloride ion (Cl) penetration into concrete mainly depend on internal moisture state of the concrete pores and the exposure condition [5–7]. These mechanisms consist of absorption, diffusion, permeation, wicking, and dispersion [8–10]. Absorption due to the capillary action and diffusion under influence of concentration gradient are the main combined transport mechanisms in the splash and tidal zones, where wetting and drying cycles take place [5,11–14]. In addition, carbonation can influence the chloride distribution in these exposure conditions [15]. This complicated penetration mechanism can lead to a non-Fickian Cl distribution profile, resulting in formation of a local peak in Cl concentration profile. In such cases, the maximum Cl concentration occurs in the interior of concrete rather than its surface, resulting in higher risk of corrosion due to elevated Cl concentra-

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tions in the vicinity of the reinforcing bars [5,11]. This phenomenon has been referred to as the “maximum phenomenon” in the literature [5,11]. The presence of maximum phenomenon indicates that there are two different layers with different predominant ionic transport mechanism within the concrete surface, the “skin” layer where the Cl concentration increases over the sample depth and the internal or concrete bulk zone where the Cl profile shows a Fickian trend (Fig. 1) [11,16].

The absorption–desorption/evaporation process (convection), skin effect, carbonation, and leaching are the main reasons that have been stated as a cause for the formation of maximum phenomenon in concrete skin layer [5,9,11,12,14,16–21]. However, given the cyclic drying and wetting conditions, the absorption–desorption/evaporation and carbonation processes are the crucial factors in occurrence of maximum phenomenon in tidal zone [5,9,12]. It worth to mention that concrete mixture properties can also influence the presence and extent of maximum phenomenon.

Cl diffusion coefficient (D_c) and surface concentration (C_s) are crucial input parameters in service-life prediction of concrete structures. The most common method to determine D_c and C_s is to conduct a nonlinear regression on Cl profiles obtained from field or laboratory samples using the simplified solution of Fick’s second law of diffusion, i.e. the error function equation [16,22–24]. The presence of maximum phenomenon influences the accuracy of the calculated D_c and C_s based on this simplified procedure, and consequently leads to the unreliable service-life prediction [5,11].

Several methods have been suggested to account for the maximum phenomenon in calculating D_c and C_s and service-life prediction. Andrade et al. [16] demonstrated occurrence of the skin layer in Cl profiles by defining two separate values of diffusion coefficient for diffusivity in the concrete skin layer and concrete bulk zone in the solution of Fick’s second law. RILEM TC 178-TMC [11,25] suggested neglecting the skin layer and using the maximum Cl concentration as an apparent surface concentration (C_{max}), and fitting the error function equation into the decreasing concentration profile towards the interior. Recently, Andarde et al. [11] presented a practical procedure to implement RILEM TC 178-TMC method to take the maximum phenomenon into consideration. Liu et al. [12] developed a numerical model to predict the depth of maximum phenomenon with assumption of a linear change of Cl concentration and water influential depth in skin layer.

Although numerous studies [5,8,9,11–14,18,26] have observed the maximum phenomenon in field and laboratory experiments, limited long-term experiment has been completed to quantify the impact of this phenomenon on ionic transport properties and service-life prediction. In addition, there is a need for long-term experimentation to examine the evolution of the maximum phenomenon depth and C_{max}, as well as the influence of concrete mixture design parameters on these variables [5,11]. Therefore, the present study explores the maximum phenomenon in concrete samples exposed to tidal zone of a natural marine environment. Data obtained from testing 16 different concrete mixtures with varying combinations of water-to-binder ratios (w/b) and silica fume (SF) contents was investigated. The specimens were monitored for up to 60 months of exposure to a highly saline natural environment. The influence of concrete matrix (w/b and SF content) on maximum phenomenon was examined. Moreover, the evolution of the maximum phenomenon with time was quantified and its influence on service-life prediction was investigated using field data.

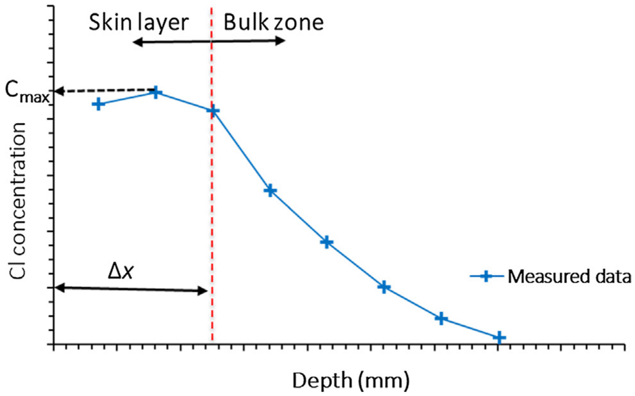

Fig. 1. Schematic of maximum phenomenon.

2. Service-life prediction with consideration of maximum phenomenon

The Cl penetration rate as a function of depth from the concrete surface and time can be represented by Fick’s second law for diffusion as formulated in Eq. (1) [22].

$$\frac{\partial C}{\partial t} = D_c \frac{\partial^2 C}{\partial x^2} \tag{1}$$

where x is distance from sample surface; t denotes time; D_c is diffusion coefficient; C_s is surface Cl concentration; and $C_{(x,t)}$ represents Cl concentration at the depth of x from the surface after time t.

A general solution (error function equation) to the equation is given in Eq. (2) [11,16,22].

$$C_{(x,t)} = C_s\left(1 - erf\left(\frac{x}{2\sqrt{D_c t}}\right)\right) \tag{2}$$

$$C_{(x,0)} = 0 \quad x > 0, \quad C_{(0,t)} = C_s \quad t \geqslant 0$$

where $C_{(x,t)}$ represents total Cl concentration at the depth of x from the surface after time t; and erf is the error function and D_c is the apparent diffusion coefficient.

Eq. (2) assumes that the porous material is fully saturated; the ion concentration at the exposure surface is constant; and there is no impact of co-existing ions. In addition, this equation does not take into account the effect of other ion penetration mechanisms such as capillary absorption. Although these assumptions do not apply to all of the conditions, this equation may still be useful where diffusion plays a significant role in the penetration of outside ions.

Andrade et al. [5,11,25] suggested a modified version of Eq. (2) as shown in Eq. (3) in order to account for the maximum phenomenon.

$$C_{(x,t)} = C_{max}\left(1 - erf\left(\frac{x - \Delta x}{2\sqrt{D_c t}}\right)\right) \tag{3}$$

where C_{max} is the maximum Cl concentration and Δx is the thickness of maximum phenomenon. The apparent diffusion coefficient (D_c) is determined by fitting the error function equation (Eq. (2)) into the decreasing part of Cl profile.

Eq. (3) assumes that the D_c and C_{max} remain constant with time. However, previous studies [3,8,10,17,23,27,28] have shown that the D_c and C_{max} are time dependent. Therefore, the time dependency of the D_c and C_{max} was expressed mathematically as demonstrated in Eqs. (4) [28] and (5) [23,29], respectively. These equations were drawn based on long-term experimental work in marine environment with varying concrete mixtures and exposure conditions.

$$D_{c,t} = D_{ref}\left(\frac{t}{t_{ref}}\right)^{-m} \tag{4}$$