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Non-uniform time-to-corrosion initiation in steel reinforced concrete under chloride environment

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ABSTRACT

Chloride-induced corrosion in reinforced concrete (RC) leads to non-uniform distribution of corrosion products around the rebar perimeter. The present study focuses on corrosion caused by sea-salt particles floating in the air, by considering diffusion as the dominant mode of chloride intrusion into concrete. Detailed parametric study is carried out involving critical chloride content, structural configuration, distance from the coastline, concrete cover thickness and rebar diameter, to understand their effects on chloride ingress into concrete. Qualitative comparison of damage induced on concrete cover as a result of non-uniform corrosion layer formation around rebars is presented through time-to-corrosion initiation (TCI) profiles.

1. Introduction

In coastal (atmospheric marine) zone, salinity is the main source of built infrastructure deterioration, particularly important to the corrosion process of rebar in concrete structures due to chloride attack. Past studies [1–4] on the effect of distance from the coastline on the marine salt presence inland reported rapid decay of sea-salt concentrations in the first hundred meters inland. Nevertheless, winds can carry airborne chlorides over long distances inland, as much as 3 km or further [5]. Structural configuration (orientation of the concrete surface) also affects the movement of airborne salts: when eddies occur in the air, salts can reach the landward faces of structures. In addition, the concentration of airborne chlorides on the surface of a concrete member is very much dependent on environmental conditions, topography, and distance from the coastline [6]. It has been proposed that surface chloride concentration in atmospheric marine zone is constant with time (e.g. [7,8]).

In reinforced concrete (RC) structures, generally at the end of construction period, concrete protects embedded reinforcing steel against corrosion by providing a highly alkaline environment ($pH > 13.0$) that maintains the steel in a passive state. The concrete cover also serves as a physical barrier against the ingress of aggressive substances that are necessary to initiate and sustain the process of corrosion. However, chloride-induced corrosion begins when the concentration of chloride at the steel bars reaches critical chloride content or chloride threshold value thereby destroying the protective layer. Critical chloride content or chloride threshold value of rebar in concrete, can be defined as the concentration of chloride at the depth of the rebar that is necessary to sustain localized breakdown of its passive film and hence initiate its active corrosion [9]. The time taken by chloride ions from external sources (such as marine environments) to reach threshold at the rebar depth is defined as time-to-corrosion initiation (TCI). Critical chloride or chloride threshold data in published literature scatter over a wide range of values [10,11].

In the atmospheric marine zone, concrete is never directly in contact with sea water, rather exposed to the effects of airborne chlorides carried by sea winds. Chloride ingress into concrete, essential for corrosion initiation is a complex interaction between many physical and chemical processes. Several studies have focused on understanding and modeling the phenomenon of chloride ingress. The main transport process in case of airborne chlorides ingress into concrete is by diffusion [12]. The airborne chloride diffusion is generally represented by Fick's second law for which the solution is sought either analytically or numerically. The analytical solution of the diffusion equation based on the error function is valid only when: (1) RC structures are saturated; (2) subjected to a constant concentration of chlorides on their exposed surfaces; (3) material is homogeneous; and (4) diffusion coefficient is constant in time and space. Nevertheless, saturated conditions are only valid for submerged zones where the low concentration of dissolved oxygen reduces considerably corrosion risks in comparison to unsaturated zones. Moreover, concrete is a heterogeneous material that is often exposed to time-variant chloride diffusion coefficient

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and surface chloride concentration. Saetta et al. [13] and Martin-Perez et al. [14] presented an alternative solution to Fick's second law of diffusion to enhance chloride ingress prediction.

Vast majority of existing works in the literature assume a uniform corrosion pattern around the rebar circumference, e.g. [15–21]. This is rarely the case in practice as chloride ions generally take a long time to transport to the steel–concrete interface that is facing the interior of concrete because of the impermeability of steel bars. Therefore, steel surface facing the outside environment is usually subjected to a higher-level concentration of chloride ions, and so gets depassivated and starts to corrode earlier than the other side of steel surface does. While on the surface facing the interior of concrete, the amount of chloride ions is maintained at a very low-level because of the impermeable nature of steel bars. Hence, breakdown of surface passive film and corrosion of steel could hardly happen in this area before the cracking of concrete cover. Variation in the onset of corrosion reaction over the entire rebar surface, results in non-uniform distribution of steel corrosion. Hence, the morphology of steel corrosion in concrete is quite different from the widely employed assumption of uniform corrosion, and it will undoubtedly propel the evolution of corrosion-induced damage in a different way than uniform corrosion does [22,23]. In addition, it was reported [23] that the chloride accumulates in front of a rebar, which is much more pronounced for larger-size bars. The higher accumulation of chlorides at bar location causes faster corrosion of rebars. Hence the real state of corrosion is not uniform around a rebar. The importance of considering the real state of corrosion in rebar is also supported by the fact that the effect of non-uniform corrosion induced stresses in RC are more conducive to cover cracking than uniform corrosion [24].

Within this context, the present study focuses on corrosion caused by sea-salt particles floating in the air and assumes that the dominant mode of chloride intrusion is by diffusion. Based on the works by Saetta et al. [13] and Martin-Perez et al. [14], the adopted methodology solves the governing equations of airborne chloride ingress into concrete using a numerical scheme which combines finite element (FE) method with finite difference scheme. The adopted methodology accounts mainly for: (1) chloride binding capacity of the cementitious system; (2) time-variant nature and the effects of temperature, humidity and chloride concentration in the surrounding environment; (3) decrease in chloride diffusivity with concrete age; and (4) two-dimensional airborne chloride ingress into concrete. The originality of the present work comprises detailed parametric study involving: (1) critical chloride content or chloride threshold value; (2) structural configuration (orientation of the concrete surface to airborne chloride exposure); (3) distance from the coastline; and (4) concrete cover thickness and rebar diameter. These parameters are considered to understand rebar effects on chloride ingress and to present qualitative indication of non-uniform corrosion in RC structures under chloride-laden environment. Nevertheless, this study does not consider the effect of concrete cracking that can increase concrete diffusivity [2,11]. Section 2 presents the governing equations of the model of airborne chloride ingress and boundary conditions. Their numerical implementation and experimental validation are presented in Sections 3 and 4 respectively. Section 5 details different parameters considered in this study followed by results and discussion in Section 6.

2. Transport process in concrete

Transport process in concrete is very complex due to the interaction between many physical and chemical phenomena. It also depends on many internal parameters (level of hydration in concrete, porosity, cement type, etc.) and external environmental stressors (temperature, relative humidity, chloride, etc.). The problem of airborne chloride ingress into concrete can effectively be studied as the interaction between three phenomena, namely: heat transport; moisture transport; and chloride transport. Each of these phenomena is represented by a partial differential equation (PDE) and their interaction is considered by solving them simultaneously. The most important principle in modeling chloride ingress into concrete are diffusion process and nature of chloride binding [13]. Chloride diffusion is highly nonlinear and strongly coupled with other diffusive parameters like temperature and relative humidity. Because this study involves corrosion initiation due to airborne chlorides, diffusion is assumed to be the predominant mechanism in all three phenomena. Subsequent subsections present each phenomenon separately and Section 3 summarizes the numerical procedure to solve the whole PDE system.

2.1. Heat transport in concrete

By combining thermal equilibrium and Fourier heat law, the PDE for heat transport is given as [25]:

$$\rho c_p \dot{T} - \vec{\nabla} \cdot (\mathrm{D}_T \vec{\nabla} T) - Q = 0 \tag{1}$$

where ρ is the density of concrete/rebar (kg/m^3), c_p is the specific heat capacity of concrete/rebar (J/kg K), D_T is the thermal conductivity of concrete/rebar (W/m K), and Q is the rate of heat generation per unit volume (W/m^3). Because transport process in concrete is studied after hydration period, Q is negligible. It is worth to note here that the heat flux from concrete surface to surrounding environment and vice versa reaches quasi-balanced state within short time.

2.2. Moisture transport in concrete

The mass conservation equation corresponding to moisture flow in concrete can be expressed in two different ways [26], namely in terms of the free water content gradient, i.e.,

$$\dot{w}_e - \vec{\nabla} \cdot (D_w \vec{\nabla} w_e) = 0 \tag{2}$$

or in terms of the pore relative humidity gradient, i.e.,

$$\frac{\partial w_e}{\partial h} \dot{h} - \vec{\nabla} \cdot (D_h \vec{\nabla} h) = 0 \tag{3}$$

where w_e is the evaporable water content (m^3 of water/m^3 of concrete), D_w is the moisture diffusion coefficient (m^2/s), h is relative humidity (a ratio between water vapor pressure and saturated vapor pressure) and D_h is the relative humidity diffusion coefficient (m^2/s).

The moisture transport equation in terms of pore relative humidity (Eq. (3), valid under isothermal conditions) is practical and preferred over expressing the same in terms of free water content, because: (1) for common water/cement ratio (a ratio by mass) the drop in h due to self-dessiccation caused by the corresponding changes of evaporable water content due to hydration of cement is small; (2) $\vec{\nabla} h$ can be considered as a driving force but not $\vec{\nabla} w_e$, when generalization to variable temperature is considered; (3) usually boundary conditions are specified in terms of h [25,26].

Alternatively, pore water saturation is also used to substitute for moisture content of concrete by some researchers in related studies. Moisture content in terms of degree of pore water saturation was adopted in a prediction model of corrosion rate of reinforced bars in concrete [27]. An improved liquid conductivity model in concrete was proposed [28] by considering a hypothetical existence of a time lag phenomenon between a pore water and microstructure, bringing about the change in the pore water state, roughly to depend on the history of pore humidity. Generally, it is