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Investigation of computational model for surface chloride concentration of concrete in marine atmosphere zone

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ABSTRACT

Current computational models for the surface chloride concentration of concrete exposed to marine atmosphere zone cannot comprehensively take into account the influence of marine environmental conditions and material parameters of concrete. To overcome this limitation, the transportation process of chloride ions from the marine atmosphere into bulk concrete were explored. Then an improved computational model for the surface chloride concentration of concrete exposed to the marine atmosphere zone was developed on the basis of a large amount of field data. Both environmental conditions and material parameters were considered in the proposed model, including the distance from the sea, wind speed, water-to-binder ratio, binder type and exposure time. The accuracy and applicability of the proposed model were validated by comparing with current computational models and field investigation data. Results show that the proposed model is consistent with the process of transportation and accumulation of chloride ions from sea air into bulk concrete, which overcomes the aforementioned limitation in current models.

1. Introduction

Due to the aggressive effect of the marine environment, reinforced concrete (RC) structures such as buildings and bridges constructed in the marine atmosphere zone usually exhibit significant degradation with increased exposure time in terms of rebar corrosion as well as the cracking or spalling of concrete. Reinforcing steel in concrete is generally well protected against corrosion by a passive film, which is quite stable in the highly alkaline environment provided by the concrete. However, in the marine atmosphere zone, chloride ions from the sea are often transported inland by wind and deposited on the surface layer of unsaturated concrete. As chloride ions penetrate into concrete and accumulate near an embedded steel rebar, it may result in the destruction of the passive film and the initiation of active corrosion or even cracking and spalling of concrete. The transportation of chloride ions from the marine atmosphere zone into concrete is largely related to the surface chloride concentration of concrete. Therefore, the model of surface chloride concentration for concrete not only represents the intensity of aggressive action of marine atmosphere on the concrete structure, but also provides an important boundary condition for the service life prediction and quantitative durability design of RC structures in the marine atmosphere zone (Yang et al., 2014).

Owing to many environmental and material factors, the transportation of chloride ions within concrete in the marine atmosphere zone is more complicated than that in the submerged, tidal or splash zone. The transportation of chloride ions from sea air into concrete usually involves two stages. During the first stage, airborne chloride salt is brought inland by wind from the sea and it deposited on the surface layer of the concrete. During the second stage, chloride ions on the concrete surface penetrate into bulk concrete. When chloride ions from the sea are transported inland by wind, airborne chloride salt may deposit on the surface layer of the concrete due to the action of gravitational settling (Cole et al., 2003a, 2003b). Although chloride deposition is closely related to the surface chloride concentration or chloride concentration of the surface layer of concrete, it does not accurately reflect the chloride concentration within the concrete. Chen et al. (2013) presented the relationship between the chloride deposition amount and the average level of chloride concentration within a 5 mm depth of concrete surface layer in terms of wind speed, precipitation and seasonal variation. Based on long-term field data for concrete in the marine atmosphere zone, Meira et al. (2010, 2007, 2006) provided an alternative way to describe the relationship between chloride

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deposition and the average total amount of chloride ions within a 30 mm depth in terms of the distance from the shore, water-to-binder ratio, binder type and exposure time. It has been observed that the chloride concentration within concrete first increases and then decreases with the distance from the concrete surface. This is due to the effects of rainfall and wetting and drying cycles. As a result, the average chloride concentration on the concrete surface layer does not reflect the distribution profile of chloride ions and hence cannot provide an appropriate boundary condition for chloride diffusion analysis within the concrete. Therefore, it is necessary to develop a more reasonable computational model for the surface chloride concentration of concrete in the marine atmosphere zone. This model should be consistent with the two stages of the transportation process of chloride ion from the marine atmosphere into bulk concrete.

Based on three years of field data from the Japanese coastline, Akiyama et al. (2012) developed a model in terms of a power function to describe the relationship between the surface chloride concentration of concrete and chloride deposition; meanwhile, an empirical model for the surface chloride concentration of concrete was proposed in terms of wind speed, wind direction and the distance from the coast. Furthermore, McGee (1999) proposed an empirical model for the surface chloride concentration of concrete as a function of the distance from the coast, based on the field data from 1158 bridges located in the Australian state of Tasmania. Note that the above models for the surface chloride concentration of concrete focus on the first stage of chloride ion transportation from the marine atmosphere into concrete. They take into account the influence of environmental conditions but ignore the influence of material parameters such as the water-to-binder ratio and binder type. These models can be categorized as environmental models since they are consistent with the transport characteristics of airborne chloride salt.

In contrast, DuraCrete (2000) proposed a model of the surface chloride concentration as a linear function of the water-to-binder ratio and a correction coefficient for the binder type. However, it does not take into account the influence of environmental conditions (such as wind speed, wind direction and the distance from the coast) explicitly; therefore, it can be categorized as the material model. Evidently, environmental models of the surface chloride concentration focus on the transportation of chloride ions from atmospheric marine air and the deposition of airborne chloride salt on the surface layer of concrete, but they ignore the transport process of chloride ions within bulk concrete. As a result, material models of the surface chloride concentration only take into account material factors but ignore the environmental factors. Therefore, neither the environmental nor material models are consistent with the overall process of transportation and accumulation of chloride ions from sea air into bulk concrete. LNEC E465 (2007) developed an empirical model for the surface chloride concentration of concrete by taking into account some environmental conditions and material factors; however, this model ignores several important factors such as wind speed and binder type (IPQ, 2007; LNEC, 2007).

The main objective of this paper is to develop an improved computational model for the surface chloride concentration of concrete exposed to the marine atmosphere zone by considering both environmental conditions and material parameters. The transportation and accumulation process of chloride ions from the marine atmosphere into bulk concrete was explored first. Then influence of environmental conditions and material parameters (e.g. the distance from the sea, wind speed, water-to-binder ratio, binder type and exposure time) on the surface chloride concentration was investigated. Finally, an improved computational model taking into account both environmental conditions and material parameters was developed to determine the surface chloride concentration of concrete exposed to the marine atmosphere zone. The accuracy and applicability of the proposed model were validated by comparisons with current computational models and a large quantity of field investigation data.

2. Transportation and accumulation process of chloride ions and major influential factors

The transportation process of chloride ions from the marine atmosphere into bulk concrete can be divided into two stages: first, chloride ions in sea air are transported inland by wind to the concrete surface; then, chloride ions permeate, diffuse and accumulate within bulk concrete due to the concentration gradient and capillary sorption. The following sections will investigate the transport mechanism, accumulation rules and influential factors for chloride ions within concrete in the marine atmosphere zone.

2.1. Transportation process of chloride ions in marine atmosphere zone

Due to the action of the sea wind, both seawater agitation and waves hitting each other often cause marine whitecaps, whereas waves crashing on the seashore usually cause a breaking surf (Chen et al., 2013; Cole et al., 2003a, 2003b; Meira et al., 2010, 2006). Biological, physical and chemical reactions in the seabed often generate air bubbles that explode and rise to the sea surface, which causes the marine whitecaps and breaking surf to form a marine aerosol. In fact, the sea wind, which stirs up and entrains seawater, is the force responsible for the marine whitecaps and breaking surf in the marine atmosphere zone. With ascending air currents, marine aerosols can reach thousands of meters into the upper air and can be transported several kilometres inland by the prevailing winds. These aerosols naturally generate a chloride environment (i.e. a sea spray environment) due to the action of wind on the seawater surface. The marine aerosol formed by the breaking surf has a high chloride concentration and heavy particles, whereas the marine aerosol formed by whitecaps has a low chloride concentration and small particles. An investigation (Xu, 1994) showed that the marine aerosol concentration formed by the breaking surf is about 40 times larger than that formed by the whitecap. Therefore, the sea spray formed by the breaking surf plays a major role in the chloride-induced corrosion of marine RC structures. However, marine aerosols with large particles formed by the breaking surf travels less distance in the air, and its concentration will reduce sharply with the distance from the coast. Therefore, the distance from the coast has a dramatic influence on both chloride salt deposition and the surface chloride concentration of concrete (Cole et al., 2003b; Morcillo et al., 2000; Mustafa and Yusof, 1994). Field data reported in the literature (Alizadeh et al., 2008; Castro et al., 2001; Costa and Appleton, 1999; Meira et al., 2007; Mustafa and Yusof, 1994; Nanukuttan et al., 2008; Safehian and Ramezanianpour, 2013; Tang, 2003; Valipour et al., 2013) were collected to investigate the relationship between the surface chloride concentration of concrete and the distance from the coast (see Fig. 1). Based on a nonlinear regression analysis, an exponential function was adopted to describe the relationship between the surface chloride concentration and the distance from the coast:

$$C_{s,\mathrm{air}}^{1}(d) = 1.16\mathrm{e}^{-0.01d} \tag{1}$$

where $C_{s,\mathrm{air}}^{1}(d)$ is the apparent surface chloride concentration (% by mass of the binder) of concrete in terms of the distance from the coast, and d is the distance from the coast (m).

Note that the surface chloride concentration of concrete discussed in this study is obtained by fitting analysis in terms of the error function solution to the Fick's second law of diffusion and the chloride concentration within diffusion zone of concrete by field measurement. This is actually the apparent surface chloride concentration and referred as the surface chloride concentration for short in this study, which is quite different from the chloride concentration measured in the surface layer of concrete.