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Probability distribution of convection zone depth of chloride in concrete in a marine tidal environment

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HIGHLIGHTS

- Convection depth of chloride with different W/C ratios, admixtures and exposure time was researched.
- Convection depths of chloride were appeared in all tested concretes.
- Mean value of convection zone depth of chloride is in a range from 4 mm to 6 mm.
- Convection zone depth of chloride follows a Gumbel distribution.

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ABSTRACT

Based on a field experiment of concrete exposed to a marine tidal environment and according to measured chloride ingress data, diffusion coefficients of chloride ion in concrete after different exposure time are fitted by Fick-second law. Concrete with different types of admixture are tested in this paper, with water-cement ratios of 0.40, 0.45, 0.50, 0.55 and 0.60, respectively. Based on 270 group chloride ingress curves of test concrete, the convection zone depth of chloride and peak value of chloride concentration in concrete are acquired. According to chloride ingress curves of concrete with different water-cement ratio under the same exposure time, the probability distribution forms of convection zone depth of chloride are investigated by statistical test using the log-normal distribution, the normal distribution and the maximum value distribution, respectively. The statistical results show that the mean value of convection zone depths of chloride is in a range from 4 mm to 6 mmin this paper, disregarding the difference in exposure time, water-cement ratio and with or without the admixture in the specimens. The majority of convection zone depths of chloride in different exposure time and water-cement ratios, as well as the admixture, follow a Gumbel distribution, and the convection zone depth of chloride in total 270 specimens follows a Gumbel distribution with the mean value of 3.99 mm and the standard deviation of 1.05 mm. The exposure time, water-cement ratio and different admixture have negligible effect on the mean value and the probabilistic characteristic of convection zone depth of chloride, however, different admixture and lower water-cement ratio can significantly reduce the diffusion coefficients and peak values of chloride concentration in concrete.

1. Introduction

The penetration of chloride ions through concrete cover to steel reinforcement resulting in the corrosion of reinforcing steel is a major problem of structures, particularly those exposed to marine environments [1,2]. The existing studies on chloride-induced reinforcing steel corrosion have showed that the penetration of chloride ions in concrete is a complex process, depending on many factors, including not only the concrete material itself but also the environmental condition where the concrete is exposed to and the loading condition where the concrete structure is subjected to [3–5]. Most of these factors are the random variables. For instance, in some studies, the chloride diffusion coefficient, the chloride concentration calculated on the surface of reinforcing steel bar, the thickness of concrete cover, the threshold chloride concentration, and the convection zone depth of chloride ions in concrete cover were all modeled as the random variables [6–8].

Many concrete structures exposed to marine environment may be subjected to dry-wet cycles, in which moisture transport can also take place in part of the concrete cover. In this case, the transport of chloride ions involves not only the diffusion but also the

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convection. The region which involves both diffusion and convection of chloride ions is often called the convection zone. The convection zone is normally a thin layer from the exposure surface to the location where the chloride concentration has a peak value. The thickness of the convection zone is usually defined to be the convection zone depth [9]. Under wet-dry cycles in natural tidal environment, the convection zone depth is considered as a key variable, which can affect the prediction of chloride concentration in concrete cover, particularly when Fick's second law is used to calculate the chloride concentration [10,11]. In order to determine the convection zone depth in concrete cover, different artificial simulation environments and field tests have been carried out. It was reported that the depth of washout or convection zone is approximately 7 mm for Portland cement mixture, 14–15 mm for fly ash mixture [12], and 14 mm for marine concretes [13]. Other ranges from 20 mm to 30 mm [14], and from 5 mm to 15 mm were also suggested in literature [15]. In addition, it was found that the depth of convection zone increases with the cracking width [8,16], and thus it is likely that the depth of convection zone will increase with the concrete service life.

The mean value of the convection zone depth was found quite different in various concretes exposed to different environments, varying from 5 mm to 20 mm [10,13,17–19]. According to the analysis of 127 chloride ingress curves obtained from concrete under a marine environment, the convection zone depth was found to follow a Beta distribution with μ = 8.9 mm, σ = 63%, a = 0 and b = 50, in regard of the chloride source and water-cement ratio [20]. Note that, the results described above on the chloride convection zone depth are mostly based on the measured data obtained by using the deterministic model. Even if there was probabilistic research on convection zone depth of chloride, they were all based on the mean value. And the research on the randomness of convection zone depth of chloride is few. In reality, however, there is strong randomness in the process of the chloride ingress into concrete, and the relevant influence parameters on RC structures' service life such as the chloride diffusion coefficient and the initial corrosion time of the steel bars in concrete are random variables. Therefore, from the durability point of view, the lifetime assessment of a deteriorating RC structure should be carried out by using the probabilistic method and considering the uncertainties of materials, structures, and environmental conditions [21–23].

In a dry-wet cycling environment, chloride ingress into concrete can be divided into two typical zones, namely the convection and diffusion zones. Let the convection zone depth X_c, then the typical distribution profile of free chloride ions in the convection and diffusion zones can be plotted as what is shown in Fig. 1.

Note that the Fick's second law is commonly used to represent the chloride concentration profile in concrete [24]. However, when a convection zone is involved [4,5,25,26], the Fick's second law can only be applied in the diffusion zone and thus it needs to know the convection zone depth and the corresponding chloride concentration at that point in order to determine the chloride distribution in the diffusion zone. In this paper an experimental study to determine the convection zone depth and the corresponding chloride concentration at that depth was carried out for concretes with different water to cement ratios, exposed to a marine tidal environment up to 600 d. The experimental work was performed at different stages and the influences of exposed time, water to cement ratio, and concrete admixture on the convection zone depth and corresponding chloride concentration at that depth are examined. The statistical distributions of convection zone depth and corresponding chloride concentration at that depth are also discussed.

2. Mix proportion of concrete and test environment

2.1. Raw material and mix proportion of tested concrete

All tested concretes presented in this study were prepared using coarse aggregates of the maximum size 40 mm, fine aggregates (sand) of the fineness modulus 2.4, and Qian-Chao complex Portland cement (PC32.5). The water used in the mix as well as for curing is the laboratory tap water. The admixtures used in tested concretes include chopped basalt fiber (BF) with filament diameter 17 ~ 20 μm and tensile strength 390 ~ 450 MPa, silica fume (SF) with Bertrand specific area 21,000 m^2/kg, and stair fly ash (FA) with fineness 4.6% and apparent density of 2240 kg/m^3. Table 1 gives the details of the mix proportion of the tested concretes, in which the percentage of admixture represents the weight percentage of the admixture in the binder.

2.2. Specimen casting

The preparation of specimens of the tested concrete is in accordance with the Chinese standards of SL352-2006. Two types of specimens were cast. One is the cubic specimens of size 150 × 150 × 150 mm, which were used for the compressive strength test. The other is the cylindrical specimens of size ϕ

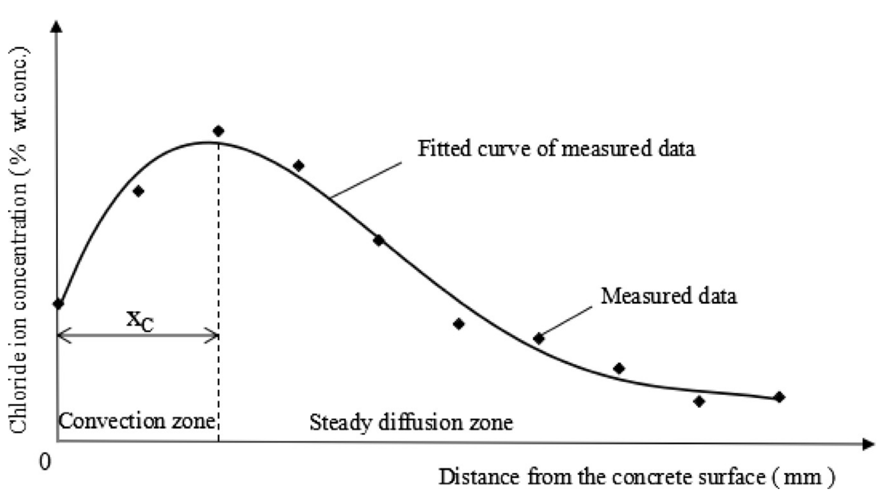

Fig. 1. Typical distribution of free chlorides in convection and diffusion zones.