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Time dependence and similarity analysis of peak value of chloride concentration of concrete under the simulated chloride environment

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HIGHLIGHTS

- Experiments to measure C_{max} of concrete under the field and simulated environment were conducted.
- Quadratic fitting is used to analyze the value of C_{max} as a function of exposure time.
- We proposed two indicators to obtain the correlation of C_{max} under the field and simulated environment.

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ABSTRACT

The appearance of peak value of chloride concentration and convection zone is a typical characteristic of concrete exposed to a dry-wet environment. It is necessary that the combined process of diffusion and convection should be taken into account in analyzing chloride ingress into non-saturated concrete. Since the significant effect of ambient chloride concentrations on the accumulated process of the peak value of chloride concentration, field environment test and accelerated simulated experiment have been employed to investigating the time dependent characteristic and similarity of the peak value of chloride concentration of concrete. In addition, two indicators (ratio of concentration difference, $K_{c\Delta}$ and ratio of concentration, $\lambda_{c_{max}}$) were proposed to obtain their correlation of peak value of chloride concentration. Results indicate that under the field and simulated environment, the peak value of chloride concentration C_{max} increases with the exposure time generally within one year, regardless of the W/C ratio. Besides, there is an obvious acceleration effect of the simulated experiment, by using the peak value of chloride concentration with exposure time of 120 d under the simulated environment, we can obtain the peak value of chloride concentration of concrete with different W/C ratios with an average exposure time of approximate 360 d.

1. Introduction

Chloride ingress into concrete is a complex interaction between physical and chemical processes. Previous researches often simplified this phenomenon to be a diffusion problem under different assumptions [1,2]. However, it only made sense of water-saturated concrete [3]. Actually, in a real environment, concrete is often subjected to a dry-wet environment, which is a non-saturated state, thus both diffusion and capillary suction will occur in concrete [4]. As a consequence, a "concrete skin" layer which not follow a diffusion process and an internal bulk zone that follows a diffusion process will appear [5]. In other words, in a dry-wet environment, the chloride profiles show an increasing trend from the exposure surface to reach a maximum value and then decrease [6], the maximum value is often defined as the peak value of chloride concentration, and the depth of this "concrete skin" layer is usually defined as the convection zone depth [7,8]. The convection action has a significant influence on the transportation of chloride ion in the "concrete skin" layer. Only knowing the relevant information about the shape and meaning of chloride profiles, the prediction of chloride diffusivity may be reliable [9,10]. Irrespective of the appearance of peak value of chloride concentration and convection zone may lead to an unreliable result of chloride diffusion coefficient *D* by directly fitting the error function solution to Fick's second law of diffusion, and finally decrease the accuracy of the service life prediction of concrete [11,12]. Therefore, it is evident that the combined process of diffusion and convection should be

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taken into account in analyzing chloride ingress into non-saturated concrete.

Andrade et al. [13] proposed two calculation methods of chloride diffusion parameters, one is re-scaling the "zero" of the penetration axis placing it at the point of the maximum and using the value of the maximum chloride concentration C_{max} as value of surface concentration C_s (method 1), the other is the extrapolation of internal chloride profile to the concrete surface (method 2), as shown in Fig. 1. Test results indicated that method 1 is more suitable to obtain diffusion coefficient of chloride profile in a dry-wet environment [12].

According to method 1 proposed by Andrade et al., Fick's second law of diffusion should be calibrated by considering the peak value of chloride concentration and convection zone, as shown in Eq. (1) [14]:

$$C(x,t) = C_0 + (C_{s,\Delta x} - C_0) \times \left[1 - erf\frac{x - \Delta x}{2\sqrt{D(t)t}}\right] \quad (1)$$

With *C(x,t)*: the chloride content at the depth *x* and at the exposure time *t*, C_0: the initial chloride content, $C_{s,\Delta x}$: chloride content at the depth of the convection zone Δx, $erf(\cdot)$: error function and $D(t)$: chloride diffusion coefficient. Currently, some scholars [15–17] have adopted Eq. (1) to conduct service life prediction of concrete structures exposed to the dry-wet cycling environment.

Since the significant effect of ambient chloride concentrations on the accumulated process of the peak value of chloride concentration [18,19], two methods, namely field environment test and accelerated simulated experiment have been often employed to investigate the chloride diffusivity. Thomas and Matthews [20] conducted a field test to investigate the chloride diffusivity of concrete exposed to a marine environment. Yu et al. [21] designed the field test and artificial simulated environment experiments to model the chloride diffusion coefficient coupled with environmental factors. However, even under the artificial simulated environment, the obtained results on the diffusivity of concrete are still questionable [22]. By investigating the similarity of the chloride ingress in concrete under the field and simulated environments, we can build a relation of chloride diffusivity between artificial simulated and field environment and make the short-term forecast of the service life of reinforced concrete structures possible. It is worth noting that chloride concentrations of the test environments have a significant effect on the accumulated process of the peak value of chloride concentration [18]. Therefore, it is necessary to conduct similarity analysis of peak value of chloride concentration under field and simulated environments, because there is obvious difference of ambient chloride concentration between the two above-mentioned environments.

Moreover, a clear understanding of the change of peak value of chloride concentration with exposure time is of importance for service life prediction of concrete structures when exposed to the chloride environment. Therefore, in this paper, we aim to analyze the time dependent characteristic of peak value of chloride concentration firstly. Thus, two experimental studies to determine the peak value of chloride concentration were carried out for concretes with different water to cement ratios, exposed to an accelerated simulated environment up to 200 d and a field marine environment up to 600 d, respectively. The relationship of the peak value of chloride concentration with time is fitted with a quadratic function. Secondly, in consideration that there is a significant difference of peak value of chloride concentration between the accelerated simulated experiment and field environment test, two indicators (ratio of concentration difference, $K_{c\Delta}$ and ratio of concentration, $\lambda_{c_{max}}$) are proposed to obtain the correlation of peak value of chloride concentration under field and accelerated simulated environments.

2. Mix proportion of concrete and test environments

2.1. Mix proportion of concrete

In total, five concrete mixtures were manufactured (Table 1), with W/C ratio of 0.40, 0.45, 0.50, 0.55 and 0.60, respectively. The maximum size of coarse aggregates is 40 mm with apparent density of 2700 kg/m^3. Common river sand is used as fine aggregates with fineness modulus of 2.4 and apparent density of 2600 kg/m^3. The ratio of fine aggregates to coarse aggregates was purposely kept at 32% for reducing the influence of raw material randomness on the experimental results.

The cylindrical specimens of size Φ 100 $\times$ 50 mm were used for test. There were 55 specimens for each mix type, in which 25 (5 $\times$ 5) specimens were used in the accelerated simulated experiment, and 30 (5 $\times$ 6) specimens were used in the field test. The first 5 represents the repeated tests in the same exposure time, and the second 5 (6) represents five (six) different exposure times. Under the simulated environment, five exposure times are designed with 40, 80, 120, 160 and 200 days respectively, under the field marine environment, six exposure times are designed with 60, 120, 240, 360, 480 and 600 days.

2.2. Test environments

The chloride ingress test under the field environment was carried out in a natural tidal zone in Zhoushan city, Zhejiang province, China. Table 2 shows the basic temperature information of

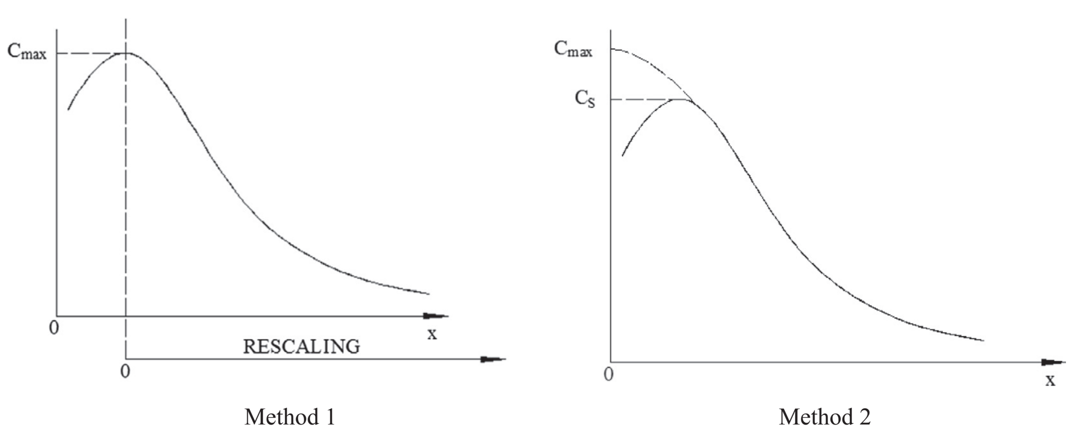

Fig. 1. Calculation methods of diffusion parameters by considering the peak value of chloride concentration.