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# Time-dependent chloride penetration in concrete in marine environments

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## HIGHLIGHTS

- A field investigation is conducted in the Beibu Gulf, Guangxi province, China.
- Distribution of age factor is theoretical studied and experimental verified.
- There commonly used corrosion models are comparatively analyzed.

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ABSTRACT

In order to study the effects of exposure conditions (atmospheric, tidal and splash zones) on chloride ingress into concrete and time-dependent chloride diffusivity of concrete, the chloride concentration of existing concrete in the Beibu Gulf was tested by field investigation. In addition, a reasonable calculation model was chosen by comparative analysis to achieve an accurate corrosion initiation time of the tested concrete. The results indicate that splash zone affects the durability of concrete structures more harshly than tidal and atmospheric zones. The age factor, which represents the time-dependent properties of chloride diffusion coefficient, is a normally distributed random parameter. In atmospheric, tidal and splash zones, the mean value of the age factor equated to 0.19, 0.35 and 0.43, respectively. Compared with the Life 365 model and the LNEC E465 model, the DuraCrete 2000 model can better characterize the chloride transport in the tested concrete. Based on this model, given the target reliability index $\beta_d$ = 1.3–1.5, the corresponding corrosion initiation time is 42–47.5a.



## 1. Introduction

Reinforced concrete (RC) is one of the most widely used man-made building materials in the world, and chloride ingress is the most deteriorating factor for RC structures exposed to marine environments [1]. Due to the extensive use of reinforced concrete and high maintenance costs, the prediction of chloride transport in concrete has attracted more and more attention from scholars and engineers [2,3]. Fick's second law is widely used nowadays to describe chloride penetration in concrete, it is given as follows:

$$C(x,t) = C_s\left[1 - erf\left(\frac{x}{2\sqrt{D \cdot t}}\right)\right] \quad (1)$$

where $C_s$ is surface chloride concentration, $D$ is apparent chloride diffusion coefficient, $x$ is corrosion depth, $C(x,t)$ is the chloride concentration at the corrosion depth $x$ with exposure time $t$, and $erf(.)$ is the error function.

Numerous studies have reported that $D$ and $C_s$ are the key parameters that influence the transport of chloride in concrete [4–7]. And these two parameters were mainly affected by the concrete mix ratio and exposure condition (i.e. atmospheric, splash and tidal zones). Moreover, early studies usually assumed that $D$ and $C_s$ were constant, while the time-dependent properties of $D$ and $C_s$ have become better understood in recent years. Song et al. [4] systematically described the influence of the water-cement ratio, mineral admixture, and curing conditions on chloride diffusion coefficient and surface chloride concentration, and pointed out that $D$ and $C_s$ are time-varying parameters. Valipour et al. [6] also discussed the influence of the concrete mix ratio, curing conditions and exposure conditions on chloride penetration behavior. However, compared to the water-cement ratio and mineral admixture, the influence of curing conditions on chloride transport in concrete is not so obvious [3,7].

When referring to the time dependency of chloride transport, based on the data collected from 11 coastal concrete bridges, Pack

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et al. [8] built up a prediction model to describe the time-dependent properties $D$ and $C_s$; the model was also compared with the well-known model, Life 365. Similarly works have also been presented by Petcherdchoo [9] and Muthulingam [10], in which the object was fly ash concrete instead of ordinary Portland cement (OPC) concrete. Besides, laboratory investigations were carried out by Wang et al. [11], in which the impact of sustained compressive loading on time-dependent chloride diffusivity of concrete was studied.

For chloride caused reinforcement corrosion of RC structures, scholars and engineers have done a lot of work. However, most of these studies focus on indoor accelerated corrosion tests or field exposure tests. Relatively few studies have been devoted to existing RC structures. Besides, the effect of time-dependent properties of $D$ on service life prediction and the random properties of the age factor still need to be further studied. Moreover, investigation of existing RC structures usually involves a durability assessment of the structure, so choosing a reasonable prediction model is also very important. Therefore, this paper mainly focuses on existing coastal RC structures located in the Beibu Gulf. Based on the test results, the distribution of chloride concentration under different exposure conditions (atmospheric, tidal and splash zones) is discussed, and the time-dependent properties of $D$ are also studied. Furthermore, a reasonable model was obtained through comparative analysis of three calculation models to predict the initial time of reinforcement corrosion.

## 2. Experimental investigations

### 2.1. Structure descriptions

A field investigation was conducted in the Beibu Gulf, Guangxi province, China. The test objects including Fangcheng, Qinzhou and Tieshan ports, are shown in Fig. 1. 13# dock of Fangcheng port is a gravity type thin-walled cylindrical caisson structure, built in November 2005 and put into operation in 2007. 10# dock of Qinzhou port is 50,000 t docks and belongs to the category of large cylinder gravity structure. 1# dock of Tieshan port, built in August 2009, is 150,000 t bulk cargo docks, and belongs to the category of gravity caisson structure. The concrete mix ratio of these three docks is all the same, with a water-cement ratio of 0.40 and a concrete strength grade of C40. Additionally, the tested concrete docks are located in a tropical area; the average relative temperature is 22.4 °C and the average relative humidity is 80%. By the time of the field investigation, these three concrete docks had been exposed to the chloride environment for 80, 62 and 35 months, respectively.

### 2.2. Sampling and testing

In the in-situ test, the concrete powders were taken from the external wall of the structures. In Fangcheng and Qinzhou ports, 36 concrete samples were taken from the atmospheric, tidal and splash zones. However, since the Tieshan port had the shortest service time, only 12 concrete samples were collected. Therefore, a total of 48 concrete samples were obtained for in-situ tests. Since the concrete cover depth is 60 mm, the drilling depth was set at 56 mm, divided into eight sections, with each section of 7 mm. Collected concrete powders were sieved with a 0.16 mm square hole sieve to remove the coarse aggregates. Then, the concrete powders were placed into the aluminium specimen boxes, and put into 105 ± 5 °C ovens for drying for two hours. After that, the aluminium specimen boxes went into the dryer to cool to room temperature, as shown in Fig. 2. Eventually, the chloride concentration was determined by RCT (Rapid Chloride Concentration Tester).

## 3. Results and discussion

### 3.1. Chloride distribution

For coastal RC structures, the exposure conditions can generally be divided into four zones (i.e. submerge, tidal, splash and atmospheric zones) [6,12]. The tidal and splash zones are subjected to long-term chloride corrosion with drying-wetting cycles. Due to the coupling effect of convection and diffusion [13,14], the exposure conditions in these two zones are particularly harsh. Therefore, the tidal and splash zones have been a busy area of research for the durability assessment of coastal RC structures.

Fig. 3 shows the mean chloride concentration of the tested concrete. It can be observed in Fig. 3 that the splash zone has the highest chloride concentration, followed by the tidal zone and the lowest concentration is present in the atmospheric zone. Taking Fangcheng dock as an example, the mean chloride concentration at a depth of 3.5 mm in the splash, tidal and atmospheric zones is 0.60%, 0.27% and 0.10% by the weight of concrete, respectively. If the mean chloride concentration in the atmospheric zone was set as a reference, then the tidal and splash zones are 2.7 and 6.0 times higher, respectively. It can clearly be seen that, at a depth of 50 mm, the mean chloride concentrations in the splash and tidal zones are 0.02% and 0.07% by the weight of concrete, respectively.

**Fig. 1.** Field condition (Qinzhou port).

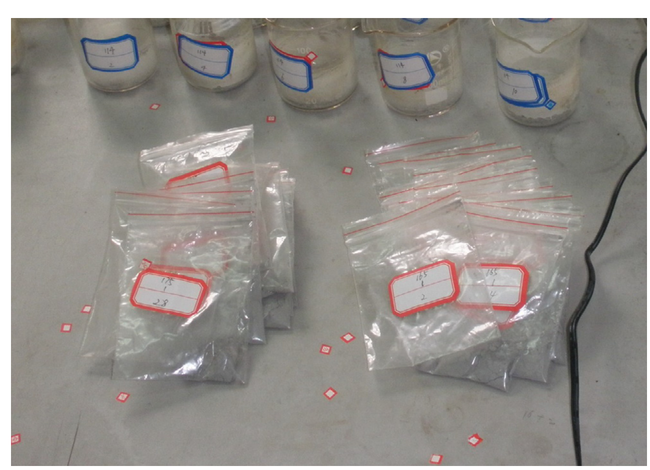

**Fig. 2.** Concrete powders.