Similarity study on chloride corrosion of prestressed concrete in marine atmosphere

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1. Introduction
There are many influencing factors on the mechanism of concrete erosion in the marine environment. For different research objectives, its corresponding durability evaluation index, test methods are different. The concrete exposure test shows the real degradation process and regularity of the research object, but it usually takes 2 to 3 years or longer to obtain meaningful test data. At the same time, there are many unpredictable factors that interfere with the test. For the corrosion degradation mechanism and regularity of concrete structures in marine environment, most of the research is based on the method of indoor rapid erosion test, which can simulate a single indoor erosion factor or multi-factor interaction to make the research object closer to its real working state. Although the indoor experiment has many merits such as strong pertinence and short test period, the accelerated test time is short. And the relationship between them is fuzzy and complex compared with the degeneration law of the object in the actual erosive environment. Therefore, the correlation between artificial simulation environment and corrosion law of concrete structure in real marine environment has aroused the concern of relevant scholars. Zhejiang University[1] proposed the "Multi-Environmental Time Similarity Theory" (METS) based on the similarity theory of the traditional theory by introducing a third-party reference with similar environmental conditions and a certain service life. Under natural and artificial simulated environments, the differences of chloride ingress into concrete are in terms of surface chloride content, convective zone depth, and diffusion coefficient[2]. Clearing the similarity between the indoor rapid test and the long-term natural exposure test and the intrinsic quantitative link between the two test results is the prerequisite for the effective application of the research results of the indoor acceleration test to the durability design of the new concrete structure and the durability evaluation of
the in-service concrete structure. Therefore, the study of experimental methods based on indoor accelerated simulation of durability degradation similar to that of long-term exposure test is a long-term concern for researchers.

In this paper, we take the port environment of east coast of China as the background, and the material and component stress state of site prestressed concrete port structure as reference. The free chloride ion content at different depths of prestressed concrete structures under the environment of marine atmospheric environment and artificial climate simulation is measured by experiment. This paper also analyzes the influence of the ratio of water-cement ratio, prestressed tendon tension and fly ash content on the chloride ion transport mechanism in concrete. It establishes the time similarity between the field test and the indoor chloride ion transport in the indoor accelerated test concrete, which is of great significance to the actual life prediction.

2. Time-Similarity Relation of Chloride Transport in Prestressed Concrete

2.1 Simulating Process and Similarity Analysis Based on Similarity Theory

Artificial simulation system and the actual system should have some form and a certain degree of similarity, so the establishment of artificial simulation system, the similar principles and similar methods should be throughout the entire artificial simulation process, so as to make artificial simulation system more accurate, efficient and credible[3].

The study of chloride ion transport similarity in prestressed concrete structures is based on the similarity theory. Based on the similarity between the laboratory accelerated test and the on-site environmental erosion effect, the service life prediction and the durability design of the proposed structure are realized. For the service structure, based on similar environmental effects, similar load history, the same material composition, the establishment of artificial climate simulation accelerated erosion system, to carry out artificial climate simulation acceleration test. The apparent chloride ion diffusion coefficient is calculated by measuring, comparing and analyzing the chloride ion content in the field service structure and the artificial climate simulation acceleration test. The influence of water-cement ratio, prestressing tension and fly ash content on the diffusion of chloride ions is analyzed with the time attenuation coefficient. The similarity relation between concrete parameters and durability parameters is established by using the time similarity constants as the link, and the life prediction of the objects is carried out.

2.2 Time Similarity Constant

Chloride ion diffusion coefficient is an important indicator of the durability of concrete. Generally, the diffusion coefficient is often called the apparent diffusion coefficient of chloride ions, which is used to describe the diffusion rate of chloride ions under unsteady conditions. Its value in addition to the material properties of concrete itself, but also with the erosion medium solution chloride ion concentration, binding effect, age, etc. are also closely linked. The apparent chloride ion diffusion coefficient was adopted as equation (1). Where, $D_{RCM,0}$ is the effective chlorine ion diffusion coefficient ($m^2/s$) measured by RCM at time $t_0$; $k_e$ is the temperature influence coefficient; $k_w$ is the influence coefficient of concrete water saturation $w$; $n$ is the time decay coefficient.

$$D_a(t) = \frac{\int_0^t D_{RCM,0}(r)k_e k_w (t_0/r)^n \, dr}{t-t_0}$$  (1)

From Eq. (1), the apparent diffusion coefficient of the concrete structure decreases with the increase of the exposure time, and even decreases in the order of magnitude. The relationship can be described by Eq. (2). Where, $D_{a,i}$ ($i=1,2$) is the apparent diffusion coefficient ($m^2/s$) for the corresponding exposure time $t_i$ (s), and $n$ is the time decay coefficient.
\[ D_{a,2} = D_{a,1} \left( \frac{t_1}{t_2} \right)^n \]  

When the apparent chloride diffusivities of the concrete and the artificial climate simulation environment are all \( D_{a,0} \), the erosion time is \( t' \), \( t \), the time similar constants is:

\[ \lambda_t = \frac{t'}{t} \]  

If erosion under the artificial climate simulation environment is known as 28d, the apparent chloride diffusion coefficient of the concrete is \( D_{a,28} \). Then according to Eq. (2), we have:

\[ t = 28 \cdot \sqrt{\frac{D_{a,28}}{D_{a,0}}} \]  

So, the time constant of chloride ion transport \( \lambda_t \) can be expressed by Eq. (5):

\[ \lambda_t = \frac{t'}{28 \cdot \sqrt{\frac{D_{a,28}}{D_{a,0}}}} \]  

### 2.3 Time Decay Coefficient \( n \)

As shown in equation (1), \( n \) is the time decay coefficient. Professor Mangat\(^4\) proposed the following empirical formula for the relationship of ordinary concrete between the time attenuation coefficient and water-cement ratio \( W/C \):

\[ n = 2.5(W/C) - 0.6 \]  

Equation (7) was recommended as the empirical formula for the time attenuation coefficient by the American Society of Concrete Life-365, where, \%FA is the percentage of fly ash in the cementitious material.

\[ n = 0.2 + 0.4 \cdot \%FA / 50 \]  

Considering the effect of prestressed tension on the prestressed concrete members under the erosion of chloride salt, the influence function \( f \) and the fitting coefficient \( P \) are introduced to correct the time attenuation coefficient:

\[ n = f(\eta) \cdot (2.5W/B - 0.6 + P \cdot \%FA) \]  

Where \( \eta \) is the ratio of the effective tensile stress to the tensile strength of the prestressing tendon; \( f(\eta) \) is the influence function of the prestressing level on the time decay coefficient; \( W/B \) is the water cement ratio; \( P \) is the fitting coefficient, dimensionless.

### 3. Test Scheme

#### 3.1 Determination of Chloride Contentin for Service Structures

The concrete structure of a port in the east coast of China is selected in the field service structure. The port was built in 1974, for the prestressed reinforced concrete high-piled wharf. The part of the service structure in Marine atmospheric zone was selected as the research object. The depth and content of chloride intrusion in structural concrete are detected by using the method of drilling and taking powder. Take the powder point distribution diagram in the beams, in a random manner, in the region are taken ten points are recorded as A0-A9. In this paper, the RCT method is used to detect the chloride ion content in the concrete powder.

#### 3.2 Artificial Climate Simulation Accelerated Test

Prestressed concrete specimen size is 150 × 200 × 1500mm; specimen uses prestressed steel side of the configuration, using post-tensioning method. The material composition and structural features of
the specimen are basically the same as those of the on-site service structural members. The specimen number is shown in Table 1.

The experiments are conducted in an artificial climate simulation laboratory. The concentration of salt solution used in the salt fog is 5% according to the environmental conditions of the port. The temperature is based on the monthly average temperature of the port environment. The time scale of the salt spray test procedure is 1:1 for the spray time and drying time. Every 24 hours for a cycle process. After the samples are put into the artificial climate simulation laboratory, the samples are collected at the top of the specimen after 30 days, 90 days, 180 days, 270 days, and 360 days after several times of salt spray - drying and wetting cycles. The method of powder sampling is consistent with the field test method.

4. Test Results and Analysis

4.1 Result and Analysis of Chloride Ion Content in Service Structure Concrete

The results of the chloride ion content of marine concrete structures in the marine atmosphere are shown in Fig. 1, in which the thick solid lines are multi-curve averages. The test results show that, at the depth of 50 mm from the concrete surface, the chloride ion content in the range of 0.13%−0.30%. It is assumed that the concrete material is an isotropic homogeneous material, regardless of the chemical bonding and physical adsorption between the chloride ion and the concrete material, and the pore of the concrete is always saturated and non-flowing. The chloride diffusion behavior can be expressed in Fick's second law. Fick's Second Law The analytical solution of a constant boundary condition can be expressed as:

$$C(x,t) = C_0 + (C_i - C_0) \left[1 - \text{erf} \left( \frac{x}{2\sqrt{D}t} \right) \right]$$

(9)

Where, \(t\) is the exposure time (s); \(x\) is the distance from the concrete surface (mm); \(C\) is the content of chloride ion in concrete (%); \(C_i\) is the chloride ion mass fraction (%) of the surface concrete in contact with the environment (%); \(C_0\) is the initial chloride ion content in concrete (%); \(D\) is the apparent diffusion coefficient of chloride ion (mm²/s).

Based on Eq. (9), according to the measured values of chloride ion content in each point, the apparent point of diffusion coefficient of chloride ion in concrete can be calculated as shown in Table 2, where \(R^2\) is the coefficient of determination. The average chloride ion diffusion coefficient in the region \(D_0 = 2.3720 \times 10^{-4}\) mm²/s.

| number | \(D\) (×10⁻⁴ mm²/s) | \(R^2\) | number | \(D\) (×10⁻⁴ mm²/s) | \(R^2\) |
|--------|---------------------|--------|--------|---------------------|--------|
| A0     | 0.7468              | 0.9260 | A5     | 3.5950              | 0.9307 |
| A1     | 2.5880              | 0.9199 | A6     | 1.7110              | 0.9470 |

Table 1. Concrete member number for artificial climate simulation test

| number | water cement ratio (W/B) | prestress level | amount of fly ash (%) | number | water cement ratio (W/B) | prestress level | amount of fly ash (%) |
|--------|-------------------------|----------------|-----------------------|--------|-------------------------|----------------|-----------------------|
| A-a- I | 0.349                   | 0.5f_{p_k}     | 0                     | B-a- I | 0.412                   | 0.5f_{p_k}     | 0                     |
| A-a- II| 0.349                   | 0.5f_{p_k}     | 15                    | B-a- II| 0.412                   | 0.5f_{p_k}     | 15                    |
| A-b- I | 0.349                   | 0.7f_{p_k}     | 0                     | B-b- I | 0.412                   | 0.7f_{p_k}     | 0                     |
| A-b- II| 0.349                   | 0.7f_{p_k}     | 15                    | B-b- II| 0.412                   | 0.7f_{p_k}     | 15                    |

Fig. 1 Chloride ion content in the marine atmosphere
4.2 Experimental Result and Analysis of Accelerated Test Component by Artificial Simulation

The results of chloride ion content in the accelerated test component show that: (1) The erosion of chloride ion is more serious with time; (2) For the same erosion time, the chloride content at the same depth of the prestressing tendon is 0.7$f_{pk}$ higher than that of the beam with tension of 0.5$f_{pk}$; (3) When the size of prestressing tendon is the same, the incorporation of fly ash can effectively improve the resistance of concrete to chloride ion erosion. The apparent chloride diffusion coefficients $D(t)$ of 12 prestressed concrete beams are calculated as shown in Fig. 2, according to the measured chloride ion content.

![Fig. 2 Apparent chloride diffusion coefficients D (t) of 12 prestressed concrete beams](image)

According to the formula (2), $D_{28}$ and time attenuation coefficient $n$ of concrete samples with different mix proportions and prestressing levels are curve fitted. The results show that the time attenuation coefficient $n$ should be related to three parts: (1) the decay coefficient increases with the increase of water-binder ratio; (2) the addition of fly ash has physical water-reducing effect; (3) the level of prestress increases, the chloride ion diffusion slows down, and the decay cycle increase. By fitting the test data multiple times, the error is minimized when the time attenuation coefficient is linearly related to the square root of the prestress level. After the simplified treatment, the time attenuation coefficient of the prestressed concrete member in the atmosphere area can be expressed as:

$$n = 3\sqrt{\eta} \cdot \left(2.5W/B - 0.6 + 0.45 \cdot \% FA\right)$$

(10)

According to Eq.(5)、(10), we can have chloride ion transport time similarity:

$$\lambda' = \frac{t'}{28,3\sqrt{\eta} \cdot 2.5W/B - 0.6 + 0.45 \cdot \% FA\sqrt{D_{0,28}/D_{0,0}}}$$

(11)

4.3 Time Similarity Relation Verification

In order to verify the similarity of chloride ion transport time, three trabeculae,B-a-II (1), (2), (3), which are similar to the material and stress conditions, are taken as the members of the artificial climate simulation accelerated test.

From the test results of the chloride content of the field components, we have $D_0=2.3720\times10^{-6}\text{mm}^2/\text{s}$, $T=14400d$. According to Eq. (2), when the apparent chloride diffusion coefficient is $D_0$, the erosion time is 559d, 414d and 532d respectively. Using the formula (3) and formula (11) we have the experimental value $\lambda_{t,1}$, the theoretical value $\lambda_{t,2}$ and the error shown in Table 3.
5. Conclusions
In this paper, a pre-stressed concrete structure in the oceanic atmosphere is taken as a reference, and the artificial climate simulation acceleration test is carried out on the basis of its environment, material and prestress level. The chloride ion content of the concrete specimen in two environments is tested, the influence of prestressing level on the diffusion of chloride ions in concrete is studied. The influence of prestressing level on the chloride diffusion in concrete is also discussed. The experimental results show that the time similarity coefficient is less when the time attenuation coefficient is linear with the square root of the prestressing force. The time similarity relation of the chloride ion transport of the prestressed concrete in the marine atmosphere is analyzed by the measured value of the service structure. The results are in good agreement with the experimental results, indicating that the expression is of practical significance for the life prediction of the existing marine prestressed concrete structures.

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Acknowledgements
The authors appreciate the support of the National Science Foundation of China (51778272), Research and innovation plan of postgraduate research of ordinary university in jiangsu province (CXZZ12-0655), and science and technology project of Jiangsu province construction system (2015ZD47).

Table 3. Chloride ion transport time similarity

| number | experimental value $\lambda_{t,1}$ | Theoretical value $\lambda_{t,2}$ | error (%) |
|--------|-----------------------------------|---------------------------------|-----------|
| B-a-Ⅱ(1) | 25.76 | 28.93 | 12.31 |
| B-a-Ⅱ(2) | 34.78 | 34.60 | -0.52 |
| B-a-Ⅱ(3) | 27.07 | 28.48 | 5.21 |