Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2021.26870

219 (2021) 258–263
April

Study on the behavior of chloride ion migration in concrete under cross sea pressure

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Received 15 August 2020; Accepted 23 November 2020

ABSTRACT

Based on the theory of durability degradation of marine concrete, thorough investigation and analysis and field measurement of solid engineering components, the coupling test scheme of environment and load is formulated, and the pressure effect under different load levels and loading frequencies are studied. It is found that the chloride ion diffusion coefficient of concrete increases significantly with the increase of load level and the frequency of cyclic fatigue load increases. The results show that the chloride diffusion coefficient of structural concrete also increases significantly. The chloride diffusion coefficient of structural concrete with 2 and 5 Hz loading frequency conforms to the exponential relationship with the load level and the structural concrete with 10 Hz frequency conforms to the power relationship. Significantly reduce the service life of the concrete structure.

Keywords: Chloride diffusion; Load frequency; Load level; Concrete durability degradation

1. Introduction

The ocean is a rich but undeveloped treasure house of resources. It provides mankind with rich products, energy, and broad space for production and living. With the progress of science and technology, marine development has entered a new stage, and large-scale marine development is forming a blue wave. China, as a coastal power, has entered a new stage. The development and utilization of marine resources and space are of great strategic significance for the sustainable development of the economy [1]. Among them, the construction of cross-sea bridges closely related to people's production and life can shorten the distance between coastal areas (islands and reefs) more efficiently, and promote the further vigorous development of the economy. In addition to the direct damage of waves, storm surges and typhoons, the erosion of concrete by seawater is one of the severe tests that cross-sea bridges need to face.

The concrete structure is one of the most widely used structural forms in construction engineering. The damage to the concrete structure is generally caused by the lack of durability. However, the service environment of the marine concrete structure is bad, which not only suffers from marine environmental factors such as temperature, humidity changes, chlorine ion erosion. The coupling effects of environment and load lead to the problems of concrete structure such as peeling off of protective layer and corrosion of steel bars, premature deterioration of materials and loss of durability of the structure. There are many factors that affect the durability of reinforced concrete, which can be divided into internal and external factors according to their action modes. The internal factors are closely related to the characteristics of materials, while the external factors are mainly related to the environmental conditions and service load of the structure. The corrosion of steel bars caused by chloride ions is particularly prominent in the

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marine environment [2]. In this paper, the behavior of concrete members under different loading frequencies and sea environments are investigated.

2. Literature review

Based on the unsteady chlorine ion migration (NSSCM) test, Cheng et al. [3] established a two-dimensional finite element model of concrete with different crack widths and crack quantities and determined the control parameters. In addition, based on the finite element model of concrete, the influences of the crack width, the number of cracks and the erosion time on the behavior and characteristics of chloride ion transport were studied. On this basis, a prediction model was established to simulate the influence of different crack states on the surface chloride ion concentration of reinforcement in concrete. This model is used to deduce the corrosion current density and corrosion depth prediction model of reinforcement, which can be used by engineers to estimate the migration behavior of chlorine and corrosion degree of reinforcement in the reinforced concrete structure in a short time and evaluation time after the reinforced concrete structure crack status and chlorine diffusion source. Yang et al. [4] proposed a new theoretical model to describe the chloride ion transport in saturated concrete under fatigue load. The model divides concrete into two parts, the matrix and the microcrack, and the chloride diffusion coefficient of concrete is characterized according to the crack area. The influence of fatigue damage on the concrete microcrack area is analyzed quantitatively and the relationship between fatigue load and chloride diffusion coefficient is established. Then, according to Fick's second law, the model is proposed and solved analytically. The correctness of the model is verified by experiments, and the simulation results are in good agreement with the measured results. Finally, the transport characteristics of chloride ions under different influencing factors are analyzed by using this model. Xue et al. [5] studied the corrosion behavior of low carbon steel in 0.1 M $NaHCO_3$ + 0.1 M NaCl solution with different dissolved oxygen concentrations by weight test and electrochemical measurement. The results show that the corrosion mass loss of steel increases significantly with the addition of chloride ions. In the initial stage, carbon steel has the tendency of active dissolution due to the dissolution of chlorine ion on the oxide film, and the corrosion potential is maintained at a low level. With the extension of soaking time, the accumulation of corrosion products increased the corrosion potential of steel. However, due to the metamorphism of chloride ions, the rust layer is loose and porous, reducing the reduction of oxygen. At the same time, the porous rust layer can be repaired by oxygen depolarization. Under the synergistic action of chlorine ion and oxygen, the corrosion of steel is accelerated in the process of repeated dissolution and repair of the oxide film.

3. Determination of diffusion coefficient of chloride ion

At present, the natural immersion test (natural diffusion test) is the most widely recognized and the most practical method to determine the chloride ion diffusion coefficient in concrete. Other commonly used test methods for chloride ion diffusion coefficient include electric quantity method, RCM method and NEL method. In the natural diffusion test, the specimens were immersed in a salt solution for a long time, and then the relationship between chloride diffusion depth and concentration was obtained by chemical analysis. Finally, the diffusion coefficient of chloride ions in concrete is calculated by Fick's law [6–8]. The diffusion coefficient of chloride ions in concrete is also measured and calculated by the natural diffusion test.

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \tag{1}$$

where C is the chloride ion concentration (%), expressed as the percentage of chloride ion in the weight of concrete or cement; X is the location (m); t is the time (s); D_c is the diffusion coefficient (m^2/s). Therefore, the analytical solution of the simple chloride diffusion theory of concrete is:

$$C(x,t) = 1 - \frac{2}{\sqrt{\pi}}\int_0^{\frac{x}{2\sqrt{D_c \cdot t}}} e^{-\eta^2} d\eta \tag{2}$$

where $x = 0$, the initial condition is 0, $C = C_0$; where the boundary condition is $x = 0$ and $T > 0$, $C = C_s$.

$$C(x,t) = C_0 + (C_s - C_0)\left[1 - \frac{2}{\sqrt{\pi}}\int_0^{\frac{x}{2\sqrt{D_c \cdot t}}} e^{-\eta^2} d\eta\right] \tag{3}$$

where $C(x,t)$ is the chloride concentration (%) at depth x at time t; C_s is the surface concentration (%); C_0 is the initial concentration (%); D_c is the effective diffusion coefficient of concrete (mm^2/s). The error function erf is expressed as $\mathrm{erf}(u) = \frac{2}{\sqrt{\pi}}\int_0^u e^{-\eta^2} d\eta$. It can be rewritten as follows:

$$C(x,t) = C_0 + (C_s - C_0)\left[1 - \mathrm{erf}\left(\frac{x}{2\sqrt{D_c \cdot t}}\right)\right] \tag{4}$$

In order to obtain the chloride diffusion coefficient of the specimen D_c. In the case that $C(x,t)$, x, t are known D_c. The construction of the identification equation can be summarized as follows:

$$\mathrm{erf}\left(\frac{x}{2\sqrt{D_c \cdot t}}\right) = 1 - \frac{C(x,t) - C_0}{C_s - C_0} \tag{5}$$

Use error function $\mathrm{erf}(u) = \frac{2}{\sqrt{\pi}}\int_0^u e^{-\eta^2} d\eta$ inverse function of erfinv. The above formula is converted into an inverse function:

$$\frac{x}{\sqrt{D_c \cdot t}} = 2\mathrm{erfinv}\left[1 - \frac{C(x,t) - C_0}{C_s - C_0}\right] \tag{6}$$

The diffusion coefficient of chloride ion can be obtained D_c. The identification equation is as follows:

$$D_c = \frac{1}{4 \cdot t} \cdot \frac{x^2}{\text{erfinv}^2\left[1 - \frac{C(x,t) - C_0}{C_s - C_0}\right]} \tag{7}$$

According to the obtained diffusion coefficient of chloride ion D_c. Based on the test data, the chloride diffusion coefficient of the specimen can be obtained by using the least square method D_c.

4. Experimental results and analysis

The formation of microcracks in concrete will change the transmission characteristics of chloride ions in the marine environment, and the spraying time of chloride ions in the environment box will also affect the concentration of chloride ions in concrete [9–11]. However, the effect of chloride penetration on the fatigue behavior of concrete is not clear.

4.1. Analysis of the influence of loading level on chloride ion permeation and migration

The same frequency of chloride ion erosion is shown in Fig. 1.

It can be seen from Fig. 1 that the influence of fatigue load on the chloride corrosion process of the concrete structure is significant. Under the fatigue cyclic load, the chloride ion in concrete can be eroded to the interior in a short time [12–14]. It can be seen that the chloride ion distribution curve has an obvious protrusion in the near-surface area. This phenomenon is mainly due to the fact that in the surface area of concrete. The moisture content in concrete changes with the surrounding environment. In the deeper area of concrete, the moisture content is relatively stable or changes slowly. Therefore, in the concrete interior, the chloride ion transport behavior is closer to diffusion, and the chloride ion transport in the surface layer area

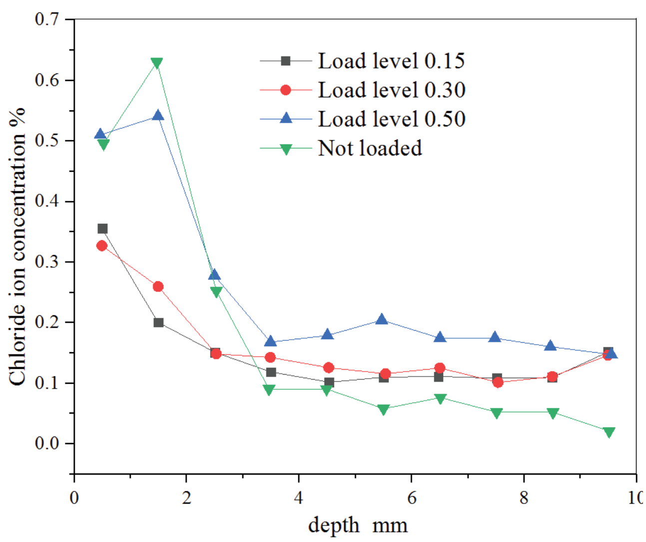

Fig. 1. Chloride ion erosion law of concrete structure under different load levels.

deviates from the diffusion model. The erosion law of chloride ions is related to the thickness, climate, environment, salt solution contact period and concrete quality.

The number of tests is controlled to 2 million times, and the test period is 2 d 7 h. For the structural concrete without load, chloride ion only has a certain content in the surface layer (within 5 mm from the surface layer), but it is basically the same as the initial chloride ion concentration in the structure concrete (5~12 mm), that is, the chloride ion does not invade into the concrete. However, for the structural concrete with fatigue load, the chloride ion content is basically greater than 0.10% at the depth of 8~10 mm, which has a high chloride penetration. The main reason is that under the fatigue load, the micro-cracks and pores in the structural concrete continuously evolve, expand and penetrate, and eventually form irreversible damage and deformation in the concrete. According to the relevant research, the residual ultimate tensile strain corresponding to fatigue failure is about 0 (300–360) × 10^{-6}. Within the range, these irrecoverable damages become a fast channel for chloride ion invasion.

With the increase of the load level, the chloride ion concentration at the same depth in the structural concrete increases continuously. In addition, compared with the traditional plain concrete or small reinforced concrete specimens, the large-scale structural concrete is used in this test, and the specimen size and reinforcement refer to the actual engineering structure, so the test process is closer to the actual situation.

4.2. Effect of loading frequency on chloride ion migration

The influence of different alternating frequencies on the chloride corrosion process of the concrete structure is shown in Figs. 2–4.

Due to the spray salt spray in the test process, the test period has a certain impact on the chloride ion concentration distribution in concrete. Therefore, when comparing the chloride ion corrosion law of concrete with different alternating frequency, it is not easy to compare the chloride ion content at different depths of structural concrete, but also consider the influence of test age. The chloride ion erosion law of concrete structure is greatly affected by the loading frequency. With the increase of the loading frequency, the chloride ion content in the structural concrete at the same depth increases. By comparing the chloride ion distribution in the structural concrete with different load levels and loading frequencies of 10 and 5 Hz, it can be found that the test period of the structural concrete with 10 Hz loading frequency is only 2 d 7 h. The main reason is that the effective frequency of crack is far less than 5 Hz when the chloride content is applied to the concrete structure. Under the action of the next cyclic load, the chloride ion content in the structural concrete with the loading frequency of 2 Hz is much higher than that of other loading frequencies. The main reason for the effect of 2 Hz loading on concrete is the long test period.

4.3. Load level frequency coupling effect

According to the measured chloride concentration values at different depths of concrete, the chloride diffusion

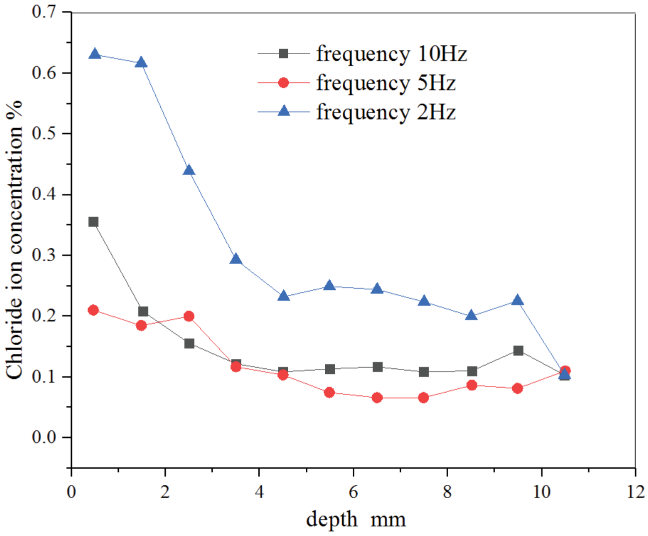

Fig. 2. When the horizontal loading frequency of concrete is 15.0.

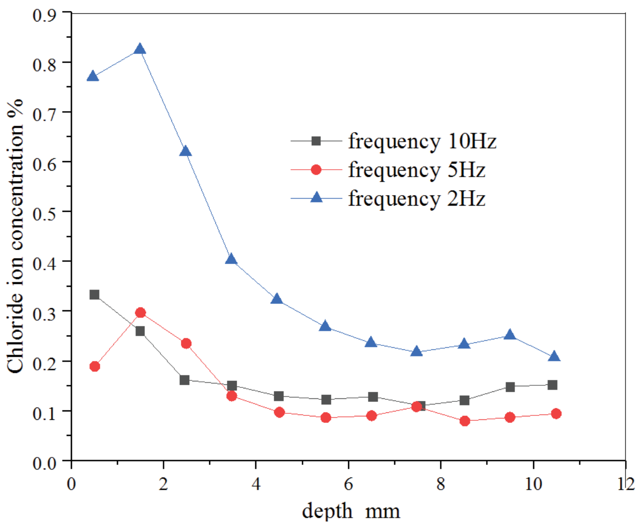

Fig. 3. Chloride corrosion of concrete under different loading frequencies at 0.3 load level.

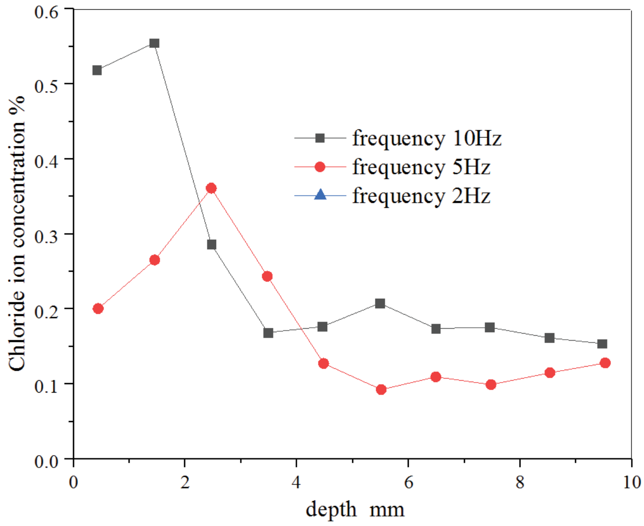

Fig. 4. Chloride corrosion of concrete under different loading frequencies at 0.5 load level.

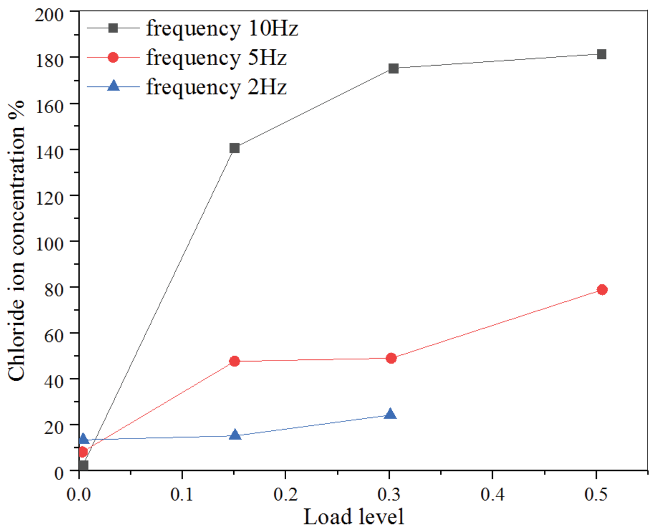

Fig. 5. Influence of horizontal loading frequency on the chloride diffusion coefficient of concrete at different load levels.

coefficient of structural concrete with different loading frequencies and load levels can be calculated by fitting the chloride ion diffusion coefficient identification equation, as shown in Fig. 5.

It can be seen from the figure that the influence of alternating frequency of loading on chloride diffusion coefficient in structural concrete is very significant. With the increase of alternating frequency, the chloride diffusion coefficient in concrete presents an order of magnitude growth trend. Under fatigue load, the load level also affects the chloride diffusion coefficient in structural concrete, which generally increases with the increase of load level. According to the corresponding relationship between chloride diffusion coefficient in concrete and different load levels under different loading frequencies (Table 1), the relationship formula between chloride diffusion coefficient in concrete and fatigue load level can be established, as shown in Figs. 6 and 7.

The results show that the frequency of 2 Hz and the frequency of concrete load are 2 Hz, which is in accordance with the structure table.

4.4. Comparison of dynamic and static load test results

In order to further verify the influence of dynamic load on chloride penetration in concrete, the chloride penetration law obtained from dynamic and static load tests is compared and studied in this paper. Other conditions of the static load test are the same as those of the dynamic load test. The chloride diffusion coefficients of the static load test specimens exposed to the splash zone for 56 and 90 d are shown in Table 2.

It can be seen from Table 2 that under the same load level, the chloride diffusion coefficient of concrete specimens

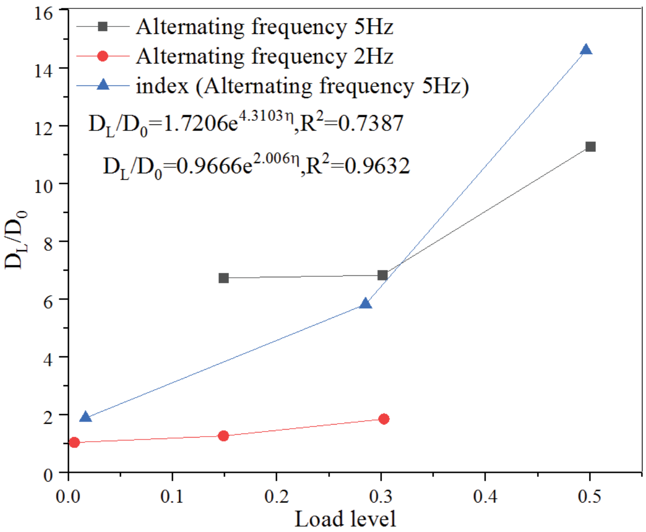

Fig. 6. Relation curve between the chloride diffusion coefficient of concrete and load level under the alternate frequency of 2 and 5 Hz.

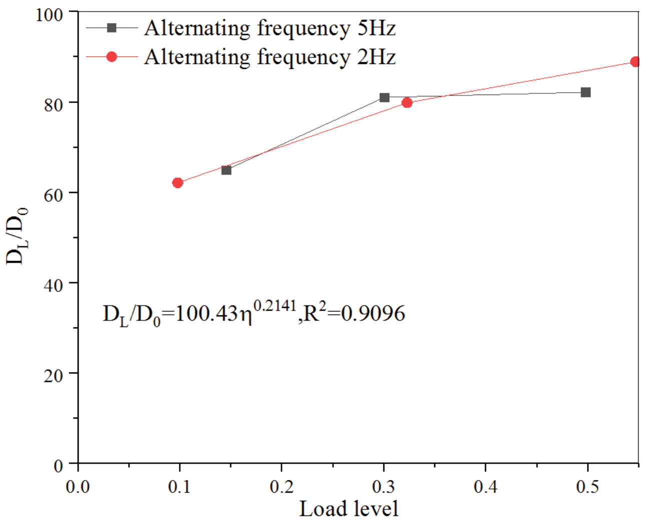

Fig. 7. Relation curve between chloride diffusion coefficient of concrete and load level under 10 Hz alternating frequency.

with exposure age of 56 and 90 d increases with the increase of bending load level. When the load level reaches 0.5, the chloride ion diffusion coefficient of concrete specimens is about 2 times of that of unloaded specimens. By comparing the chloride diffusion coefficient of concrete specimens with different exposure ages, it can be found that the chloride diffusion coefficient of 90 d exposure age is slightly lower than that of 50 d exposure age specimen.

It can be seen from the variation law of load level that the chloride diffusion coefficient in structural concrete can be expressed by the formula $y = A{\cdot}e^{Bx}$. The relationship between chloride diffusion coefficient and bending load level of concrete specimens is the exponential function, where a and B are parameters related to the composition of cementitious materials $y = 0.732{\cdot}e^{1.2342x}$.

Table 1
Relationship among loading frequency, chloride diffusion coefficient and load level

Loading frequency (Hz)	D_L	R^2
2	$0.96D_0 \times e^{2.005}\eta$	0.9633
5	$1.72D_0 \times e^{1.3103}\eta$	0.7382
10	$100.42D_0 \times \eta^{0.2143}$	0.9067

Chinese style D_L, D_0 is the chloride diffusion coefficient of loaded and unloaded concrete under the same conditions; η load level is the ratio of applied load to the ultimate bearing capacity of the concrete structure.

Table 2
Diffusion coefficients of concrete specimens exposed to splash zone for 56 and 90 d under different bending load levels

Exposure time	Chloride diffusion coefficient (10^{-12} m²/s)			
	0%	15%	30%	50%
56	0.69	0.87	1.16	1.26
90	0.76	1.12	1.20	1.25

Compared with the static load, the diffusion coefficient of chloride ions is increased from 30.2 Hz to 83.1 times under static load. Under the fatigue load with frequency of 5 Hz, the diffusion coefficient increases to 6.8 times, which is obviously larger than that of static load. The conclusion that the chloride diffusion coefficient increases with the increase of loading frequency are further verified.

5. Summary

In this paper, based on the durability degradation theory of marine concrete, through the investigation and analysis and field measurement of solid engineering components, the environmental and load coupling test scheme is formulated to study the chloride ion migration behavior characteristics in the cross-sea bridge concrete under different load levels and loading frequencies. The main results and conclusions are as follows:

- Chloride ion diffusion coefficient of concrete increases with the increase of load level, and with the increase of fatigue load alternating frequency, the chloride ion diffusion coefficient of structural concrete also increases greatly.
- Relationship between chloride diffusion coefficient and stress level of structural concrete under different bending load frequencies is established. The relationship between chloride diffusion coefficient and stress level of structural concrete with loading frequency of 2 and 5 Hz is exponential, and that of structural concrete with the frequency of 10 Hz conforms to the power relationship.
- Compared with the static load test, the alternating bending load will aggravate the internal damage of the concrete structure. The greater the loading frequency is, the more serious the damage will be, which will significantly

reduce the service life of the concrete structure. Enough attention should be paid to the durability design, construction and maintenance of the concrete structure.

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