

Multi-Factor Coupling Model of Concrete Chloride-Ion Diffusion Coefficient in a Salt Lake

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Abstract: Immersion in salt-lake solution was adopted to periodically test the concrete chloride-ion diffusion coefficient. The regression analysis was also completed. Also investigated was the time-dependent law of concrete chloride-ion diffusion coefficient with time. The influence of chloride-ion concentration in solution, water-to-cement ratio, and corrosion time on the largeness and accumulation rate of the concrete chloride-ion diffusion coefficient was also analyzed. Test results show that the concrete chloride-ion diffusion coefficient gradually decreased with increasing time and increased with increasing chloride-ion concentration in a salt lake . Taking into account the influence of factors such as water–binder ratio, chloride-ion concentration, and time-varying characteristics, a multi-factor calculation model for the concrete chloride-ion diffusion coefficient was established. Combining the prediction results and the measured data reported in this paper, the effectiveness and applicability of the established concrete chloride-ion diffusion coefficient calculation model were compared and verified, and the durability design and service life of a concrete structure under cool chlorine were compared. The results of analysis provide important boundary conditions.

Keywords: salt-lake environment, concrete, concrete chloride-ion diffusion coefficient, multi-factor coupling model, chloride-ion concentration

1.introduction

The chloride-ion concentration of salt solutions ^[1] is more than 10 times that of the marine environment, with the dry climate and the difference in the morning and evening temperatures being large. Therefore, in salt-lake environments, the problem of insufficient durability of concrete structure generally ^[2,3] leads to the lack of durability of concrete structure, which is the main factor causing the difference between the internal and external chloride-ion concentration caused by chloride-ion diffusion ^[4,5] and steel corrosion in concrete structures ^[6]. Thus, there is an urgent need to adopt the corresponding technical means to achieve more than 50 years of service life for concrete structures. The current method of estimating the service life of concrete structures in salt-lake environments is mainly based on Fick's second law of diffusion ^[7]; therefore, the concrete

chloride-ion diffusion coefficient is an important parameter in predicting the service life of concrete structures.



Fig. 1. Chaerhan Salt Lake, Qinghai, China.

Many scholars ^[7–11] have established the concrete chloride-ion diffusion coefficient of the prediction model for marine environments, the model parameters are mainly sometimes become model ^[7,8], water-to-binder ratio ^[9–11], the time-varying model, etc. However, neither the concentration of chloride ions in an environment influencing the chloride-ion diffusion coefficient of concrete has been reported nor has a model been set up to determine the concrete chloride-ion diffusion coefficient of chloride-ion concentration in a salt environment.

Furthermore, a multi-factor model of determining the chloride-ion diffusion coefficient of concrete in a salt-lake environment has not been published, to the best of our knowledge, in the literature. In view of this, analyses of actual salt-lake brine immersion test data from the Qinghai, Inner Mongolia, Xinjiang, and Tibet regions have been carried out, and the concentration of chloride-ion solution, water-to-cement ratio, and the influence of the exposure time of surface chloride-ion concentration discussed. A salt-lake environment was built using experimental data from a concrete chloride-ion diffusion coefficient calculation model using multiple factors. An experiment comparing empirical model calculation values with measured data was conducted and the results compared with the corrected values, thus verifying the effectiveness and applicability of the model.

2 Test design

2.1 Test plan

A simulated salt-lake-brine immersion test was carried out to study the concentration of chlorine-ion solution, water-to-cement ratio of surface chloride-ion concentration, and the influence of exposure time. The concrete test was divided into two test groups as shown in Table 1. The tests used a mix of conch cement, p.o. 42.5 cement, medium-grade natural river sand, stone produced in Nanchang Anyi with a (5–16)-mm continuous gradation of gravel, tap water, and carboxylic acid as a superplasticizer, with a water-reduction rate of >20%. The differences in proportion between the concrete in the two test groups are shown in Table 1. The chemical compositions of the salt solution are shown in Table 2.

Table 1. Concrete test groups and mix ratios

Group	Factors	Sample no.	Cl ⁻ concentr ation (%)	Water- to- cement ratio	Material content / (kg.m ⁻³)				
					Cement	Stone	Sand	Water	Superpla sticizer
1	Salt- lake solution	XZ	9.2						
		NMG	10.8						
		XJ	13.3	0.55	369	1103	735	203	0
		QH	20.4						
		S50		0.50	398	1362	690	196	0
2	W/C	S45		0.45	407	1328	715	183	0
		S40		0.40	435	1085	665	174	0
		S35	20.4	0.35	452	1131	679	158	0
		S30		0.30	500	1116	657	150	4.07
		S25		0.25	544	1062	708	136	5.85

Table 2. Chemical compositions of various salt-lake brines

Salt lake	Na ⁺	Mg ²⁺	K ⁺	Ca ²⁺	Cl ⁻	SO ₄ ²⁻	CO ₃ ²⁻	HCO ₃ ⁻
Xin jiang	84.23	9.85	1.87	0.72	133.43	33.36	2.04	3.87
Qin hai	68.36	35.13	5.98	4.24	204.21	22.29	0.17	0.13
Nei meng gu	97.17	3.96	2.64	0.13	108.64	36.44	25.38	4.59
Xi zang	61.61	4.66	6.65	0.16	92.29	27.95	1.192	0.95

2.2 Test steps

The test steps are as follows:

1) The sizes of all concrete block specimens were 100 mm×100 mm×100 mm and were cured, on average, for 28 d. After removing the specimens from molds, specimens designated Group 1 were soaked in Xinjiang, Inner Mongolia, Qinghai, and Tibet experimental salt solutions, while designated Group 2 specimens were soaked in a Qinghai salt-lake experimental solution. The exposure times were t=28, 56, 90, 270, and 520 d.

As described in the literature [12,13], the three-dimensional was derived based on Fick's second law applied to the chloride-ion-diffusion theory model:

$$C_f = C_s + \sum_{m=1,3,5}^{\infty} \sum_{n=1,3,5}^{\infty} \sum_{p=1,3,5}^{\infty} \frac{64}{mnp\pi^3} (C_0 - C_s) \sin\left(\frac{m\pi}{L_1}x\right) \sin\left(\frac{n\pi}{L_2}y\right) \sin\left(\frac{p\pi}{L_3}z\right) \exp\left[-Dt\left(\frac{m^2\pi^2}{L_1^2} + \frac{n^2\pi^2}{L_2^2} + \frac{p^2\pi^2}{L_3^2}\right)\right]$$

2) The specimens were removed after different exposure times and powder was collected from the two sides of the specimen by drilling. The drilling equipment comprised a small drill with a drill diameter of 6 mm; the drilling position is shown in Fig. 2. In the figure, labels I–IV show the four powder collection points. The distances from a collection point to the two sides of the specimen are $d_1=20$ mm and $d_2=20$ mm. Eight holes were drilled on each test piece. The sampling depths were selected as 0–5, 5–10, 10–15, 15–20, and 20–25 mm, and the powder collected from each concrete sample weighed approximately 5 g. A sieve with a pore size of 0.15 mm was used to remove coarse particles.

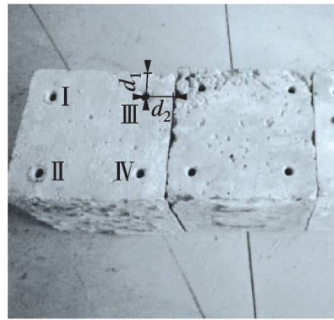


Fig. 2. Sample drilling position.

3) The concrete chloride-ion content determination method used for different exposure times can be found in [14].

3 Test results analysis

3.1 Relationship between chloride-ion diffusion coefficient and solution concentration

As shown in Fig. 3(a), the chloride-ion diffusion coefficient of concrete in each group increases with increasing chloride-ion concentration in the salt-lake solution. In addition, the growth rate is faster when the chloride-ion concentration is less than 10.8%, and then gradually slows down and gradually increases until it reaches a stable state. In the same salt-lake solution, the longer the corrosion time, the smaller the chloride ion diffusion coefficient of the concrete. The linear function, power function, exponential function, polynomials, and other functions of MatLab software (MathWorks, USA) were used to perform regression analysis on the data plotted in Fig. 2. Considering the boundary value (i.e., the chloride-ion diffusion coefficient when the corrosion time is zero is also zero), the results show that the chloride-ion diffusion coefficient on the concrete surface has a significant power-function relationship with the chloride-ion concentration in the salt-lake solution for exposure times of 28 and 56 d. The correlation coefficients R for exposure times of 28, 56, 90, 270 and 520 d are 0.953, 0.951, 0.942, 0.958, and 0.961, respectively. Therefore, the relationship between the chloride diffusion coefficient of the concrete surface and the chloride-ion concentration in the solution can be expressed by an exponential equation:

$$D_t = \alpha C_{Cl}^{\beta} \quad (2)$$

where α and β are the fitting parameters as shown in Table 3. D_t is the chloride-ion diffusion coefficient and C_{Cl} is the chloride-ion concentration in salt-lake solution in percent.

3.2 Relationship between chloride-ion diffusion coefficient and water-to-cement ratio

As shown in Fig. 3(b), the chloride-ion diffusion coefficient of the concrete surface increases with increasing water-to-cement ratio. When the water-to-cement ratio is the same, the longer the corrosion time, the smaller is the chloride-ion concentration on the concrete surface. The same regression analysis described above was performed on the data plotted in Fig. 3 in MatLab. Considering the boundary value (i.e., the chloride-ion diffusion coefficient when the water-to-cement ratio is zero is also zero), the results show that the chloride-ion diffusion coefficient on the concrete surface has a significant exponential function relationship with the water-cement ratio. For exposure times of 28, 56, 90, 270, and 520 d, the correlation coefficients R^2 are 0.973, 0.970, 0.965, 0.967, and 0.936, respectively. Therefore, the relationship between the chloride-ion concentration on the concrete surface and the water-to-cement ratio can be expressed by the following power-function equation that follows the law in [16]:

$$D_t = 10^{n+bR_{W/B}} \quad (3)$$

where n and B are fitting parameters with values shown in Table 3, D_t , the concrete chloride-ion diffusion coefficient, and $R_{W/B}$, the concrete water-to-binder ratio.

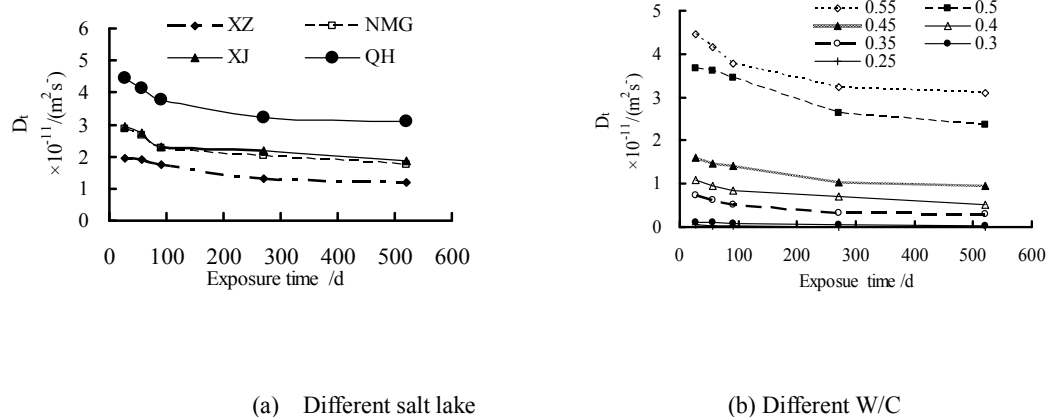


Fig. 3. Relationship between concentration, W/C and D_t .

Many studies [14–17] have shown that the time-varying model of the concrete chloride-ion diffusion time-varying model can more reasonably describe the time-varying characteristics of the chloride-ion diffusion coefficient of concrete. Values for concrete chloride-ion diffusion time dependence coefficient m are shown in Table 3. As shown in the table, the time-varying coefficient

m decreases as the chloride-ion concentration and water-to-binder ratio in the salt-lake solution increases. The m values in Table 3 were fitted using a spreadsheet m was exponentially related to the chloride-ion concentration and water-to-binder ratio in the salt-lake solution. The correlation coefficients were both higher than 0.90, namely, 0.957 and 0.989. The functional relationship is established, as is the relationship between m and the solution's chloride-ion concentration and water-to-binder ratio:

$$D_t = D_{28} \left(\frac{28}{t} \right)^m \quad (4)$$

where D_{28} is the chloride-ion diffusion coefficient of the concrete exposed for 28 d, D_t , the chloride-ion diffusion coefficient of concrete, t, the exposure time (in d), and m, the time-varying coefficient:

$$m = \frac{0.133}{R_{W/B} C_{Cl}^{0.2}} \quad (5)$$

where C_{Cl} is the chloride ion concentration (in %) in the salt-lake solution and $R_{W/B}$ is the concrete water-to-binder ratio.

Table 3. Test data-fitting parameters.

Exposure time (d)	Fitting parameter		R	Fitting parameter		R	Cl^- (%)	m	R	$R_{W/B}$	m	R
	α	β		n	B							
										0.5	0.164	0.934
28	3E-12	0.937	0.953	-13.8	6.763	0.973	9.2	0.183	0.987	0.45	0.195	0.969
56	2E-12	0.894	0.951	-14.5	8.175	0.970	10.8	0.166	0.948	0.4	0.235	0.967
90	1E-12	0.865	0.942	-14.8	8.475	0.965	13.3	0.149	0.969	0.35	0.334	0.983
270	8E-13	0.801	0.958	-15.3	8.838	0.967	20.4	0.132	0.945	0.3	0.501	0.914
520	6E-13	0.757	0.961	-15.6	9.115	0.969	-	-	-	0.25	0.596	0.952

4. Establishment and verification of the multi-factor model for chloride-ion diffusion coefficient

The Life365 model^[17] was applied to calculate the chloride-ion diffusion coefficient and water-to-binder ratio using the following formula:

$$D_t = 10^{(-12.06 + 2.40 R_{W/B})} \left(\frac{28}{t} \right)^{0.2} \quad (6)$$

where t is the exposure time (in d) and $R_{W/B}$ is the water-to-binder ratio.

4.1 Establishment of the multi-factor model for chloride-ion diffusion coefficient

It is found through the analysis of test results that there is a significant power-function relationship between the chloride-ion diffusion coefficient of the concrete and the chloride-ion concentration and corrosion time of the solution [18,19]. In addition an exponential function relationship with the concrete water-to-binder ratio was found. Based on the comprehensive analysis of experimental data, in this paper we propose the following calculation model to reflect the effects of solution chloride-ion concentration, water-to-binder ratio, and time-varying factors on the diffusion of chloride ions in concrete. Inserting Eqs. (4) and (5) into Eq. (6), we obtain the model proposed:

$$D_t = 1.732 C_{Cl}^{0.468} 10^{(-12.93 + 2.682 R_{W/B})} \left(\frac{28}{t} \right)^{\frac{0.133}{R_{W/B} C_{Cl}^{0.2}}} \quad (7)$$

where t is the exposure time (in d), $R_{W/B}$, the water-to-binder ratio, and C_{Cl} , the chloride-ion concentration (in %) in the solution.

4.2 Verification of the multi-factor model of chloride-ion diffusion coefficient

Using the test data in this paper, the results of various calculation models for verifying the chloride-ion diffusion coefficient of concrete, including the Life365 model and a multi-factor chloride-ion diffusion coefficient model are shown in Fig. 4. It can be seen from the figure that the a fore-mentioned two models both reflect that the chloride-ion coefficient of concrete decreases with increasing exposure time. In general, the results obtained by multi-factor chloride-ion diffusion coefficient model are closest to the measured values, while the Life365 prediction results deviate significantly from the measured values.

Through further comparison and analysis of the difference between the value predicted by the Life365 model and the model proposed in this paper and the field-measured values, it can be seen from Fig. 4 that the value predicted by the Life365 model increases rapidly with decreasing water-to-binder ratio, while the increase of the value predicted by the proposed model is relatively flat. It can also be seen that when the water-to-binder ratio is greater than 0.35, the values predicted by both the Life365 model and the proposed model are smaller than the measured values. Moreover, the values predicted by the model proposed in this paper are closer to the measured values. When the water-to-binder ratio is 0.35, the values predicted by the Life365 model and the proposed model are consistent with the measured values; when the water-to-binder ratio is less than 0.35, the values predicted by the Life365 model and the proposed model are larger than the measured values, but the values predicted by the model proposed in this paper are closer to the measured values. The reason for these results is that the Life365 model does not consider the effect of solution chloride-ion concentration on the chloride-ion diffusion coefficient of concrete. It can be seen that, when compared with the Life365 model, the proposed model is better adapted to include the effects of the chloride-ion diffusion coefficient of concrete in salt-lake environments.

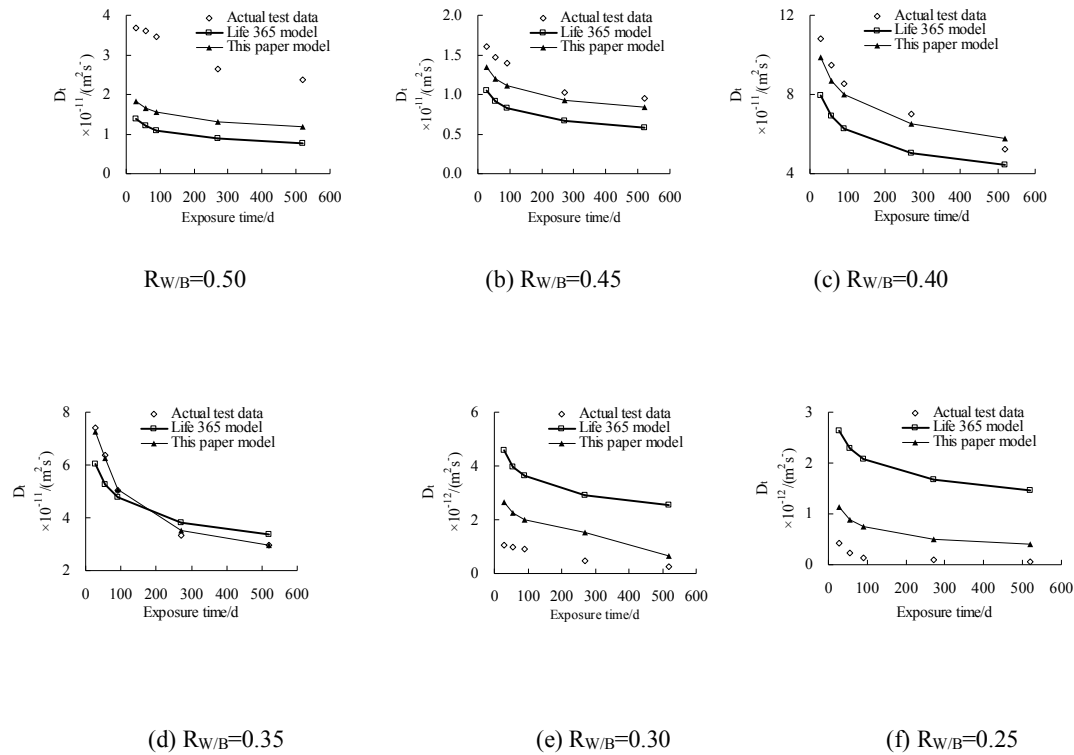


Fig. 4. Comparison between different prediction models and measured values of concrete chloride-ion diffusion coefficient.

5 Conclusions

We draw the following conclusions:

1) When concrete is immersed in salt-lake solution, the chloride-ion diffusion coefficient of the concrete increases with increasing chloride-ion concentration and water-to-cement ratio in the salt-lake solution, and decreases with the delay in the corrosion time. The chloride-ion diffusion coefficient of concrete has a power-function relationship with solution chloride-ion concentration, water-to-binder ratio, and exposure time. The time-dependence coefficient m decreases with increasing chloride-ion solution concentration and water-to-binder ratio.

2) Based on the measured data reported in this paper, a multi-factor coupling calculation model for the chloride-ion diffusion coefficient of concrete is proposed by considering factors like water-to-binder ratio, chloride-ion content, and time-varying characteristics in the solution.

3) Under different water-to-binder ratios and corrosion time conditions, the proposed multi-factor coupling calculation model of the concrete chloride-ion diffusion coefficient is more suitable for salt-lake environments than the Life365 model, which is critical to informing the durability design and service life of concrete structures under salt-lake environments. The results of the analysis also provide important boundary condition.

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