Relationship between chloride diffusion coefficient and ASTM C1202 electric flux under different environments and durability evaluation

Wenxiu Dong, Ming Zhou

School of Architecture and Civil Engineering, West Anhui University, Lu’an, 237012, China

*Corresponding author’s e-mail: wxxyzm123@163.com

Abstract: The relationship of the diffusion coefficient and charge passed is developed employing the analysis of the traditional model and 244 groups of experimental data. The differences in the types of concrete were considered to determine the variation coefficient of the diffusion coefficient in the models. Results revealed that the different environmental conditions of the concrete chloride diffusion coefficient cannot be described solely by the existing maturity method. Reasonably good agreement is observed between the experimental and computational model of this paper, thus indicating that the proposed prediction model can be successfully used to estimate the chloride diffusion coefficient. An example of a durability assessment is performed to verify the applicability of the concrete durability assessment method. The concrete durability assessment method can control the durability quality and direction of the production of concrete.

1. Introduction

Because the electric flux method has the advantages of simplicity, rapidity, and stability in testing the diffusion properties of concrete, the method of the electric flux of concrete is adopted to evaluate the chloride ion permeability of concrete in technical code for corrosion prevention of concrete structures in harbor engineering JTJ275-2000 in China, the design code for the durability of railway concrete (TB10005-2010, J1167-2011) of China also stipulates the 6-hour electric flux limits for 56-day-old concrete under different design service life and strength grades. Analysis of chloride ion service life prediction, durability design, and maintenance reinforcement of engineering structures requires the use of a diffusion coefficient for durability quantitative analysis, however, the quantitative relationship between diffusion coefficient and electric flux is not given in the current code, and the electric flux measured by the experimental method can’t meet the requirement of calculation. On the other hand, the durability of concrete can’t be evaluated by the measured electric flux after the limit value of the diffusion coefficient is determined by durability design, it is necessary to establish the quantitative relationship model between diffusion coefficient and electric flux in a different environment, and put forward the corresponding evaluation method of concrete durability based on electric flux method. At present, many groups of experimental data on chloride ion resistance of concrete have been tested by scholars, among which there are references on testing chloride ion resistance of concrete by the RCM method and electric flux method.

In this paper, the experimental data of six-hour electric flux of ASTM C1202 method and the results of the chloride diffusion coefficient of the RCM method are collected and compared with the
traditional model, the relation model between chloride diffusion Coefficient and electric flux of concrete under different environment is established, and the evaluation method of concrete durability under chloride erosion is put forward, which provides a basis for quality control of concrete durability.

2. Calculation model of electric flux and diffusion coefficient and durability evaluation method

2.1 Stochastic characteristics of the diffusion coefficient

The chloride diffusion coefficient is a quantitative description of the resistance of concrete to chloride attack, which is mainly related to the composition, porosity, pore size, and hydration degree of concrete. Due to the uncertainty of concrete during preparation, pouring, construction, and later curing, therefore, the physical properties of concrete, such as the actual composition, pore type, and pore size distribution, the type and number of cracks, aggregate size, and distribution, sand rate, etc. Therefore, the diffusion coefficient of concrete should be a random variable with a larger coefficient of variation.

The results of Louis et al. [1] and Karimi et al. [2] show that the variation coefficient of the chloride diffusion coefficient of some reinforced concrete is 0.300, which is very random, this is the main reason that the relationship between the diffusion coefficient and the electric flux is not uniform.

The Coefficient of variation (CV) of the diffusion coefficient is a parameter that describes the random dispersion of the diffusion coefficient:

\[ \delta_D = \frac{\sigma_D}{\mu_D} \]  

(1)

In the formula, \( \sigma_D \) is the standard deviation of the concrete chloride diffusion coefficient, \( \mu_D \) is the mean value of the concrete chloride diffusion coefficient.

Many scholars have shown that the diffusion coefficient has a linear relationship with the electric flux. The linear relationship between the diffusion coefficient (the mean value of the diffusion coefficient) and the electric flux is:

\[ D = \alpha + \beta Q \]  

(2)

In the formula, \( \alpha, \beta \) is the coefficient constant, \( D \) is the chloride diffusion coefficient and \( Q \) is the six-hour electric flux of concrete measured by ASTM C 1202.

The measured diffusion coefficients were normalized and the Coefficient of variation (\( \delta \)) was calculated to be:

\[ \delta = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} \frac{(D_i - \mu_D)^2}{\mu_D}} \]  

(3)

In the formula, \( n \) is the experimental group number of concrete with the same mixture ratio, \( D_i \) is the diffusion Coefficient of the RCM experiment measured by group \( i (1=1,2,3... N) \).

2.2 Relationship between diffusion coefficient and electric flux of concrete in a dry environment

In the traditional model [3], the relation between the conductivity and the diffusion coefficient is established by using the transport principle of ions in the Fast ion conductor, namely, the Nernst-Einstein equation, with the concrete as a Fast ion conductor:

\[ D_i = \frac{RT \sigma_i t_i}{z_i^2 F^2 c_i} \]  

(4)

In the formula, \( D_i (cm^2/s) \) is the diffusion Coefficient of the particle, here is the diffusion coefficient of the Chloride Ion, \( R \) is the gas constant 8.314 J/mol, \( T \) is the absolute temperature of the diffuser when diffusing, the unit is \( K \), \( \sigma_i (s/cm) \) is the electrical conductivity of the concrete; \( z_i \) is the charge or Valence number of the particle, \( F \) is the Faraday constant, 96500c/mol, \( c_i (mol/cm^3) \) is the concentration of the particle, and \( t_i \) is the migration number of the ion. The traditional model considers that there is a good linear relationship between the diffusion coefficient and the electric flux,
and the relationship between the electric flux and the electric conductivity is measured through experiments:\(^3\):

\[ D = 0.257765 + 0.000492Q \]  \hspace{1cm} (5)

In this equation, \( D \) (10\(^{-8}\) cm\(^2\)/s) is the diffusion coefficient, \( Q \) (C) is the electrical flux.

For concrete structures that do not come into direct contact with chloride-containing solutions such as seawater in a dry environment (such as structures in the marine atmosphere), the assumptions of the model are met, therefore, the traditional model can be used to predict the chloride diffusion coefficient of concrete in dry environment. This model is used to calculate the chloride diffusion coefficient and electric flux in dry environment. On the other hand, in the environment of Ocean, deicing salt and other chloride ion erosion, most of the building is usually in a humid environment or dry-wet alternate environment, concrete pores contain a large number of solutions or water, and the chloride ion diffuses very quickly in the pore solution, which is one of the main decisive factors of the chloride ion diffusion rate, the use of concrete as a fast ion conductor does not conform to the actual situation, and a reasonable calculation model needs to be established.

2.3 Relationship model between diffusion coefficient and electric flux of concrete in dry-wet alternate environment

RCM and ASTM C1202 are more suitable to simulate the chloride resistance of concrete under dry-wet alternate environment, so in this paper, 244 sets of experimental data on 6-hour electric flux and RCM diffusion coefficient are summarized to establish the calculation model of the diffusion coefficient and electric flux of concrete in the dry-wet alternate environment such as splash zone or water level changing zone\(^3\)-\(^6\), according to the formula (2), the linear fit between 6-hour electric flux and diffusion coefficient is made, and the linear relationship between diffusion coefficient and 6-hour electric flux is obtained as follows:\(^7\):

\[ D = 0.0027Q + 0.6918 \]  \hspace{1cm} (6)

In this equation, \( D \) (10\(^{-8}\) cm\(^2\)/s) is the diffusion coefficient, \( Q \) (C) is the electrical flux.

The fitted linear correlation model is in good agreement with the experimental data, and the Correlation Coefficient reaches 0.8266, which meets the precision requirement of correlation. The correlation can be used to predict the diffusion coefficient of concrete in the wet-dry alternate environment and can be used to calculate the diffusion coefficient of different kinds of concrete. Formula (3) is used to calculate the Coefficient of variation of the diffusion coefficient of concrete with different admixtures. The results are shown in Table 1.

| Type of concrete          | OPC         | Fly ash concrete | Slag concrete | Silica fume concrete | Compound fly ash and silica fume concrete | Concrete mixed with slag and silica fume |
|--------------------------|-------------|------------------|---------------|----------------------|------------------------------------------|----------------------------------------|
| Coefficient of variation | 0.234       | 0.392            | 0.343         | 0.310                | 0.300                                    | 0.396                                  |

From Table 1, it can be seen that the diffusion coefficient of ordinary concrete is the closest to the fitting formula, and the coefficient of variation is 0.234, while the coefficient of variation is close to 0.4 for the concrete mixed with fly ash, slag and mixed with slag and Silica fume. The relationship between the diffusion coefficient of concrete in different diffusion environment and the 6-hour electric flux can be determined by using the traditional model, namely the diffusion coefficient model of the dry zone:

\[
D = \begin{cases} 
0.000492Q + 0.257765 \times 10^{-8} \text{cm}^2/\text{s} & \text{Dry Environment} \\
0.0027Q + 0.6918 \times 10^{-8} \text{cm}^2/\text{s} & \text{Wet-dry environment}
\end{cases}
\]  \hspace{1cm} (7)

By using formula (7), the actual diffusion coefficient of the concrete structure can be predicted according to the environment and electric flux of the concrete structure.
3. Application example of model validation and durability evaluation

3.1 An example of verifying the relation model between diffusion Coefficient and electric flux

A harbor-wharf in Zhoushan City, Zhejiang Province, has been operating for 15 years. One of the structures in the water level fluctuation area, wave splash area, and atmosphere area was selected, and its corrosion by chloride ion is shown in Table 2. The concentration of chloride ion in the table is expressed as the mass percentage of chloride ion to concrete. Because the panel is located in the atmosphere, the diffusion coefficient is small, the depth of chloride ion invasion is shallow, but the concentration of acid-soluble chloride ion is about 0.0200% at the depths of 4 ~ 5 cm, 5 ~ 6 cm, 6 ~ 7 cm, it can be considered that the initial chloride ion concentration C₀ = 0.0200% in the process of concrete configuration.

| Type of structural component | Component area       | Chloride ion content at different depth (%) |
|------------------------------|----------------------|---------------------------------------------|
| Pier abutment                | Fluctuation area     | 0.3180 0.2826 0.2342 0.2074 0.1586 0.1549 0.1313 ACID soluble |
| Square pile                  | Splash area          | 0.2117 0.1618 0.1159 0.0893 0.0489 0.0319 0.0101 ACID soluble |
| Faceplate                    | Atmospheric region   | 0.0418 0.0364 0.0276 0.0217 0.0201 0.0203 0.0199 ACID soluble |

Table 2 Measured values of chloride ion concentration

Based on the analytical solution of chloride ion diffusion equation in concrete, the measured values of chloride ion concentration at different depths are fitted, and the surface chloride ion concentration and Effective diffusion coefficient of each region are obtained as shown in table 3, the measured values of chloride ion concentration in concrete under different environmental conditions are compared with the fitting values as shown in figures 1 and 2.

Figures 1 and 2 show that the fitting values are in good agreement with the measured values, and the surface chloride ion concentration and concrete diffusion coefficient obtained by the fitting are the reflections of the actual conditions of the members.
Using the correlation model of diffusion coefficient and electric flux (7), the electric flux in different environmental regions is calculated according to the fitted Effective diffusion coefficient $D$, and the results are shown in Table 3.

### Table 3 Fitted diffusion parameters

| Diffusion parameter | Component name       | Pier abutment | Square pile | Faceplate |
|---------------------|----------------------|---------------|-------------|-----------|
| $C_s$ (%)           |                      | 0.346         | 0.236       | 0.048     |
| $D \times 10^{-8}$ cm$^2$/s |                      | 4.750         | 1.58        | 0.523212  |
| Inverse flux (C)    |                      | 1503.037      | 328.963     | 539.0955  |

As can be seen from Table 3, the electric flux of concrete calculated by correlation model is in the normal range (the electric flux of concrete is generally between 200C and 4000C), if the 6-hour electric flux of pier and abutment concrete calculated by the traditional model is $q = 9130.6$ c, it is too large and does not accord with the actual situation. Therefore, the correlation model between the diffusion Coefficient and the electric flux should be used to fit the model (7) for the components in the wet and dry environments such as the splash zone and the fluctuating water level zone. The chloride diffusion coefficient of the concrete panel in the dry atmosphere is $0.5232 \times 10^{-8}$ cm$^2$/s. If the electric flux is calculated by using the fitting formula (7) of the wet environment or other scholars fitting formula, it is difficult to get the reasonable value of the electric flux, it even appears that the calculated electric flux is negative, and the traditional model (that is, the diffusion coefficient formula of the concrete member in the dry area) is used to calculate the 6-hour electric flux of the concrete slab in the dry area (the air area), a reasonable electric flux value of 539.0955C can be obtained. Therefore, according to the actual structure or the environment of the component, we should choose the relation model of electric flux and diffusion coefficient to calculate the conversion between the chloride diffusion coefficient and 6-hour electric flux.

### 3.2 Application example of concrete durability evaluation

The strength grade of the main concrete is $C_{40}$, and the limit value of chloride diffusion coefficient of concrete in water level changing area is $D_{con} = 3.21 \times 10^{-12}$ mm$^2$/a. The 6-hour electric flux of 28-day-old concrete specimens with single fly ash was tested by ASTM C1202 during the concrete durability test and trial-mixing stage, as shown in table 4. Using the relation model of the electric flux and diffusion coefficient proposed in this paper, and according to the durability evaluation method in this paper, whether the batch concrete meets the durability design requirements or not is evaluated.

### Table 4 electrical flux measurements

| Serial number | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Electrical Flux (C) | 876.4 | 854.3 | 886.3 | 668.8 | 786.1 | 743.7 | 621.9 | 648.5 | 625.1 | 768  |

Using the calculation model of water level variation region in the relationship model of electric flux and diffusion coefficient (7) presented in this paper, the electric flux control limit value can be calculated, and the measured average value of electric flux can be calculated according to table 4:

$$
\overline{Q_{con}} = \frac{D - 0.6918}{0.0027} \approx 932.7C, \quad \overline{Q}_c \approx 747.9C
$$

(8)

According to the evaluation method(9):\\n
$$
\sigma = \sqrt{\frac{1}{m-1} \left( \sum_{i=1}^{m} Q_{i}^2 - m \overline{Q}_{con}^2 \right)} = 103.3C
$$

(9)

The acceptance rates of 95% for mean and maximum tests are calculated:
confinement materials used in the structures to be built, and the durability can be evaluated by sampling the 6-hour electric flux of concrete produced in this stage, it can provide a suitable evaluation method for the durability quality control of engineering construction.

4. Conclusion

Based on the analysis of the traditional diffusion coefficient model and the experimental results of the diffusion coefficient measured by RCM method and ASTM C1202 method and the statistical analysis of their discreteness, the variation coefficients of diffusivity of different types of concrete are determined, and the calculation models of diffusivity and 6-hour electric flux of concrete in the dry zone and dry-wet alternate zone are determined respectively, the diffusion coefficient fitting and electric flux calculation are carried out based on the measured data. The correctness and applicability of the model are verified by the analysis of the calculated results. Based on the calculation model of diffusion coefficient and 6-hour electric flux of concrete in the dry zone and dry-wet zone, the applicability of this method is verified by an example. The evaluation method can be used to evaluate the durability of the concrete materials used in the structures to be built, and the durability can be evaluated by sampling the 6-hour electric flux of the concrete materials under construction, it can provide a suitable evaluation method for the durability quality control of engineering construction.

Acknowledgments

The authors are grateful to the financial support from Scientific Research Project of the Anhui Provincial Education Department (KJ2018A0415, KJ2020A0627), and high-level talents start-up funds of West Anhui University (WGKQ201702009) and school-level youth funds (WXZR201908).

References:

[1] Lounis Z, Amleh L. (2004) Reliability-based prediction of chloride ingress and reinforcement corrosion of aging concrete bridge decks. J. Life Cycle Performance of Deteriorating Structures, 2004; 113-122.
[2] A.R. Karimi, K.Ramachandran, N.Buenfeld. (2005) Probabilistic analysis of reinforcement corrosion with spatial variability. J. Safety and reliability of Engineering Systems and Structures, 2005; 679-685.
[3] Zhao Shangchuan. (2001) Reliability-based durability evaluation and experimental study of reinforced concrete structures. Dissertation at the Dalian University of Technology, 2001.
[4] Chao Ming, Gao Meirong, Xu Jian, et al. (2011) Influence of test method and carbonation on chloride diffusion Coefficient of concrete. J. Journal of the Southeast University, 2011(6):1313-1318.
[5] Wang Fuhong, Lei Yufang, Xu Changsheng, et al. (2005) Discussion on the relationship between the electric flux of concrete and diffusion coefficient of chloride ion. J. Transport Engineering, 3:27-30.

[6] Liu Bingjing. (2007) Durability design of concrete structures. People's communications press, Beijing.

[7] Yang Lufeng, Zhou Ming, Chen Zheng. (2014) Quantitative analysis and design for durability of marine concrete structures. J. China Civil Engineering Journal, 47(10):70-79.

[8] Wang Chengqi, Gu Kunpeng. (2010) Chloride corrosion characteristics of a port in the East China Sea after 15 years of operation. J. Concrete, 2010, 10: 11-13.

[9] Zhou Ming, Tu Jinsong, Zhao Hong, et al. (2019) Evaluation Method for the durability of concrete against chloride ion. J. Journal of Henan Urban Construction University, 28(01): 18-23.