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Investigation of chloride transportation mechanism in reinforced concrete subjected to eccentric compression

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ABSTRACT

In order to figure out the chloride ion transportation mechanism in eccentric compressive concrete column in marine environment, a theoretical model was developed, from which, the result was compared with that from experiment. As the detailed work for this study, stress distribution in the cross section of eccentric compressive concrete was analyzed firstly. Then the relationship between chloride diffusion coefficient and stress level was investigated according to the porosity variation under different load levels. Finally, the equation that expresses the relationship between chloride diffusion coefficient and different stress levels was developed. Further, a three-dimensional model was built by COMSOL Multiphysics, in which, the above-mentioned equation was used to analyze the chloride ion diffusion process. Three beams were cast and then eccentrically loaded to different stress levels. After that, all the specimens were exposed to chloride solution for 180d and 540d and chloride concentrations at different depth of concrete were detected. The simulated results were found agreed well with the test results, which demonstrated that the developed model and simulation process of chloride ion transportation process in eccentric compressive concrete were reliable.

1.INTRODUCTION

Chloride ions in seawater will continuously invade the coastal bridges, wharf and other concrete structures through the pore liquid. When the chloride ion concentration on the surface of the steel in the concrete accumulates to a certain value, The bluntness of the steel will be stripped and the steel bars will begin to rust, resulting in the occurrence of rust cracks in the components and the decline of bearing capacity eventually lead to a shortened service life.[1,2,3]The study of the penetration law of chloride ions in concrete can get the initial corrosion time of the steel bars, so that the durability life of the concrete structure can be predicted in advance[4,5,6]. Relevant scholars at home and abroad have conducted a lot of research in this regard.

Because the actual serviced concrete members are generally in a state of being bent or stressed, domestic and foreign scholars have studied the durability of concrete structures under the coupling of these two types of loads and chloride salts. Among them, more research is on the bent members such as main beams and bridge decks. Based on the similarity between the chloride ion diffusion equation and the heat transfer equation, Deng Da [7] uses the thermal analysis module of ANSYS to simulate the chloride corrosion of a prestressed concrete railway bridge in the coastal atmosphere. The durability of the axial compression members has also been studied to some extent. However, the actual compression concrete members in service are mostly in a state of small eccentric compression, such as abutments, unequal span bridge piers, pier wall, etc, and the stress distribution of different internal sections and the bent members and axial members are different, from this causes that the chloride ion transport process is not completely similar. The research in this aspect can provide a more accurate method for the durability analysis of actual eccentric compression concrete members.

In this paper, a model of the diffusion coefficient of chloride ion related to water-cement ratio and stress level is established. The finite element software is used to analyze the transmission of chloride ions in small eccentrically compressed concrete members. The effectiveness of the chloride ion transport model established in this paper was tested by comparing the results of the chloride salt attack test with the eccentric compression member of the artificial climate simulation accelerated test.

2.STRESS DISTRIBUTION IN SLIGHTLY ECCENTRIC COMPRESSION CONCRETE

The eccentrically pressed concrete section shown in Figure 1 below is used to analyze the stress distribution of concrete at different positions under normal use limit states (assuming one side is pressed while being pulled). At this time, the concrete is basically in the elastic non-cracking stage, and its strain distribution is shown in Figure 1 below.

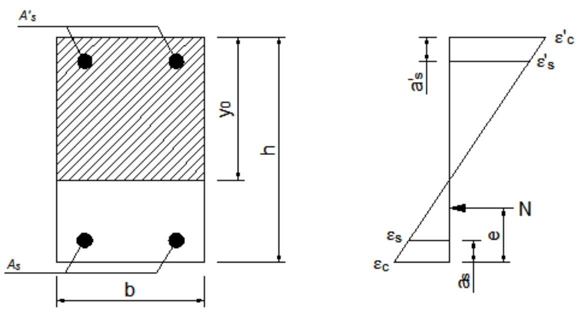


Figure 1. Schematic diagram of reinforced concrete section stress under eccentric compression

Assuming that the neutral wheelbase is under the external load y_0, the equilibrium equation based on the axial force of the section can be obtained:

$$\frac{1}{2}E_c\varepsilon_c' b y_0 + E_s'\varepsilon_s' A_s' = \frac{1}{2}E_c\varepsilon_c b(h-y_0) + E_s\varepsilon_s A_s + N \qquad (1)$$

The strain in the tensile stress zone and the compressive stress zone changes linearly, according to similar triangles:

$$\frac{\varepsilon_c'}{\varepsilon_s'} = \frac{y_0}{y_0 - a_s'} \qquad (2)$$

$$\frac{\varepsilon_c}{\varepsilon_s} = \frac{h-y_0}{h-y_0-a_s} \qquad (3)$$

There are similarities in the strains of the tension zone and the compression zone:

$$\frac{\varepsilon_c'}{\varepsilon_c} = \frac{y_0}{h-y_0} \qquad (4)$$

According to the section moment balance equation $\sum M_N = 0$, we can get:

$$\frac{1}{2}E_c\varepsilon_c' b y_0\left(h-e-\frac{1}{3}y_0\right) + E_s'\varepsilon_s' A_s'\left(h-e-\frac{1}{3}y_0-a_s'\right) = \frac{1}{2}E_c\varepsilon_c b(h-y_0)\left(e-\frac{1}{3}(h-y_0)\right) + E_s\varepsilon_s A_s\left(e-\frac{1}{3}(h-y_0)-a_s\right) \qquad (5)$$

In the above formulas (1) to (5),

ε_c' and ε_c are the strain of concrete at the edge of the tension zone and the edge of the compression zone, respectively; ε_s' and ε_s are the strains of the steel bars in the tension zone and the compression zone, respectively; E_s is the elastic modulus of longitudinally tensioned steel bars; E'_s is the elastic modulus of the tensile reinforcement; E_c is the elastic modulus of the concrete; y_0 is the distance of the edge of the tension zone of the neutral wheelbase; h is the beam height; a'_s is the distance from the joint point of the upper tensile bar to the top edge of the section; a_s is the distance from the resultant point of the pressed bar to the bottom edge of the section. Using the above formula, the linear distribution of the tensile strain and compressive strain of the concrete section under a certain eccentric pressure with the height of the section can be obtained.

3. Analysis of chloride ion diffusion coefficient of loaded concrete

Concrete can be regarded as a non-uniform mixed material composed of three parts: aggregate, interface transition zone and cement mortar. Pores is the main channel for the transport of chloride ions in concrete, and the effect of stress on the transport of chloride ions is mainly through changing the size of the pores, so that the diffusion coefficient of chloride ions changes. Research has shown that [8], the initial porosity of stress-free concrete p_0 is related to the water-cement ratio *w/c* and degree of hydration α:

$$p = \frac{w/c - 0.17\alpha}{w/c + 0.32} \quad (6)$$

The degree of hydration α can be determined by the curing time and the water-cement ratio, and The hydration degree of concrete after being cured for 28 days is [9]:

$$\alpha = 0.967\exp[-0.131/(w/c)] \quad (7)$$

From a micro perspective, cement mortar consists of unhydrated cement particles, hydration products, mortar and pores. According to the generalized effective medium theory, Zheng[10] assumes that the cement mortar is composed of two parts: pore and impermeable solid, and the relationship between the chloride diffusion coefficient D_s and the porosity p in the cement mortar is obtained, as shown in the following formula（8）:

$$D_s = \frac{2p^{2.75}D_w}{p^{1.75}(3-p)+14.44(1-p)^{2.75}} \quad (8)$$

Where: D_w is the diffusion coefficient of chloride ion in the pore solution. Considering the size effect of the pore and the hydration reaction, It is about 0.4 times of the diffusion coefficient of chloride ion in pure water at 25 °C, taking D_w=8×10^{-10}m^2/s [11]. Considering the existence of aggregate and interfacial transition zone, Sun Guowen [12] established a four-phase composite ball model of concrete material, and studied the relationship between the chloride ion diffusion coefficient D_0 in concrete and the chloride ion diffusion coefficient D_s in cement mortar. as shown in the following formula（9）:

$$D_0 = D_s \frac{6D_s(1-V_a)(V_a+V_{ITZ})+2V_{ITZ}(13.26D_s-D_s)(1+2V_a+2V_{ITZ})}{3D_s(2+V_a)(V_a+V_{ITZ})+2V_{ITZ}(13.26D_s-D_s)(1-V_a-V_{ITZ})} \quad (9)$$

Where: V_a is the volume fraction of the aggregate (the ratio of the mass of the aggregate contained in the concrete of 1m^3 to the density of the concrete), which is directly determined by the mixing ratio of the concrete. V_{ITZ} is the volume fraction of the interface transition zone, and the ratio of the thickness of the interface transition zone to the corresponding aggregate particle size can be taken as 0.006 approximately (such as light aggregate) [13], therefore, V_{ITZ}=0.0181V_a. Simultaneously, the chloride ion diffusion coefficient considering the time decay characteristic of the chloride ion diffusion coefficient can be expressed as:

$$D_t = D_0\left(\frac{t_0}{t}\right)^n \quad (10)$$

Where: D_0 is the apparent chloride ion diffusion coefficient of concrete corresponding to reference time t_0 that is generally taken 28d; n is the time attenuation coefficient, according to the experience of ordinary concrete, n=2.5*w/c*-0.6 [14].

Through the simultaneous (1) to (5), it can predict the chloride ion diffusion coefficient of a concrete with a water-cement ratio under normal maintenance without stress.

Under normal service conditions, concrete bears a certain load and there is a certain stress inside.Many scholars have studied the influence of stress on chloride ion diffusion through experimental methods, and established a transport model of chloride ion in concrete under stress state. In this paper, the calculation formula of chloride ion diffusion coefficient at different stress levels obtained by Wang [15] et al.

Under compressive stress:

$$D = D_t(1-0.28\sigma / f_c) \quad (11)$$

Under tensile stress:

$$D = D_t(1+0.35\sigma / f_t) \quad (12)$$

Where: f_c and f_t are the measured values of axial compressive strength and tensile strength of concrete, respectively; σ/f_c and σ/f_t characterize the compressive and tensile stress levels of concrete, respectively.

Based on the above formula (6) to (12), through the mixing ratio parameters such as concrete water-cement ratio and aggregate volume fraction, the chloride ion diffusion coefficient of eccentrically pressed concrete members changing with time under different stress states can be obtained.

4.Calculation and verification of chloride ion corrosion in eccentric compression concrete

Due to the uneven distribution of stress in the eccentric concrete, the concentration of chloride ions inside may be different after exposure for a certain period of time [16,17]. In order to more intuitively reflect the distribution of chloride ion concentration in concrete, it is necessary to establish a three-dimensional model for numerical analysis.

4.1 Transmission test of chloride ion in eccentric compression concrete

The test was carried out with a reinforced concrete beam of 150 mm × 200 mm × 1500 mm. The concrete mix ratio was as shown in Table 1. The measured compressive strength of the cube for 28 days was 49.8 MPa. The specimen size and section reinforcement are shown in the figure. The upper frame rib adopts HPB235, the lower longitudinal rib adopts HRB335, and both diameters are 10mm. The eccentric load is realized by the post tension tension rib. The prestressing rib adopts the stress relief wire 2φ^p7, and considering different water-cement ratios and The test pieces of the pressure level are shown in Table 2. The specimen was placed in an artificial climate simulation test chamber after applying eccentric pressure, and long-term chloride ion erosion was achieved by continuously spraying a salt spray of 5% concentration, and then taken out and dried after 180d and 540d, respectively.

Sampling near the mid-span section, the sampling position at different times is shown in Figure 4. Each time is taken three times on the same section, and the sampling position is shown in Figure 4. The sampling interval was 5 mm along the depth, and it was taken out and placed in a sealed bag for storage, then the free chloride ion concentration in each sample was measured by RCT [18].

Table 1. The mixing proportion of concrete (kg/m^{-3})

W/C	water	cement	sand	stone	Water reducing agent
0.412	164	398	745	1189	1.59

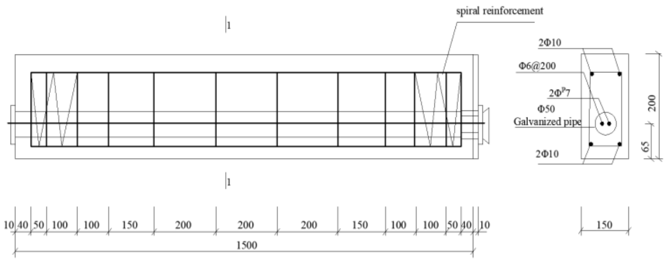


Figure 2. Size and reinforcements in specimen（mm）

Table 2. Series of specimens

Test piece number	Water cement ratio	Eccentric pressure (kN)
A-0	0.412	0
A-1	0.412	71.5
A-2	0.412	100

Figure 3. Accelerated test conditions

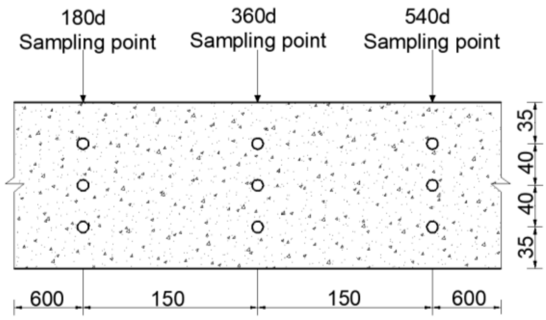


Figure 4. Sampling locations of specimen

4.2 Finite element analysis of test beam

The analysis software uses COMSOL Multiphysics. The convection-diffusion module is mainly used to simulate the material transfer process with convection-diffusion as the transmission mode, which can be used to obtain the concentration of substances dissolved in gases, liquids and even solids,and it's governing equations are compatible with the transport mechanism of chloride ions in concrete. Therefore, this paper uses this module to numerically analyze the chloride ion transport process of eccentrically pressed concrete members. The calculation process includes: building a model, selecting materials, determining physical fields and parameters, setting boundary conditions, dividing the mesh, and solving.

To facilitate comparison of the results, the finite element analysis determines the model parameters based on the test beams described above.

(1) Building a model: the model geometry is 150*200*1500mm. The reinforcement along the length is only considered. And the position and diameter of the longitudinal reinforcement are consistent with the test beam. Regardless of the transport of chloride ions in the longitudinal reinforcement, the cuboid representing the test piece and the cylinder representing the reinforcement are separately established, and then the cylinder is subtracted by the difference of the Boolean operation.

(2) Select materials: select concrete according to actual conditions.

(3) Determining the physics field and parameters: using the convection-diffusion equation and according to the actual test conditions (complete immersion), the diffusion process is only considered, and the simplified transmission control equation of chloride ion in the concrete is:

$$\frac{\partial C}{\partial t} = \nabla(D\nabla C)$$

Where, C is the mass fraction of chloride ions in concrete pore fluid. The chloride ion diffusion coefficient is determined based on the above calculation results. According to the actual applied eccentric pressure and the equations (1) to (4), the stress σ in each test beam is varied with the beam height y can be calculated. The results are shown in Table 3 below.

Table.3 The variation of stress along the height of the beams

Test beam Numbering	Internal stress
A-1	$\sigma = 0.022(y-94.627)-2.149$
A-2	$\sigma = 0.031(y-94.627)-3.01$

The chloride ion diffusion coefficient of the mid-span section is obtained by this calculation is distributed along the beam height as shown in the following figure. The distribution of chloride ion diffusion coefficient along the beam length at a position 50 mm from the surface of the tension zone and the compression zone is shown in the figure.

The initial chloride ion concentration inside the concrete mixture was measured to be 0.01%.

(4) Setting boundary conditions: the surface chloride ion concentration adopts the exponential model, and the chloride ion detection data of the reference beam A-0 is used to return the relevant parameters. The equation for the resulting surface chloride ion concentration $C_S(t_{ref})$ as a function of erosion time t_{ref}(s) is:

$$C_s\left(t_{ref}\right) = 0.4474\cdot\left[\exp\left(1.0301\times10^{-8}\cdot t_{ref}\right)\right] \quad (9)$$

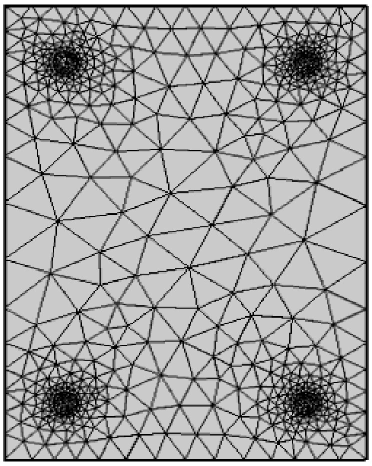
The chloride ion concentration of the concrete surface calculated according to the actual erosion time of this test is shown in Table 4 below.

Table 4. surface chloride ion concentration of immersed specimens

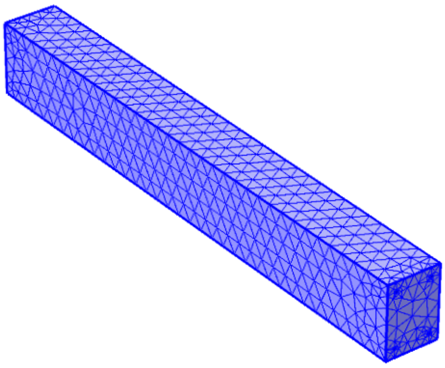
parameter	180d	540d
C_s (%)	0.5250	0.7230
D_t ($10^{-12}m^2/s$)	7.4	4.6

From this, the diffusion coefficient of chloride ion at different depths of the concrete section can be obtained (since the calculation formula of the diffusion coefficient under the tensile stress and the compressive stress is different, it is represented by a piecewise function).

(5) Dividing the mesh: In order to ensure the accuracy and speed of the calculation, the model uses a thinner tetrahedral mesh. The maximum unit size is 0.0825m, the minimum unit size is 0.006m, the maximum unit growth rate is 1.4, the curvature factor is 0.4, the narrow area resolution is 0.7, and the mesh of the steel and concrete contact surface is finer, as shown in Figure 5 a). The meshed model is shown in Figure 5 b).

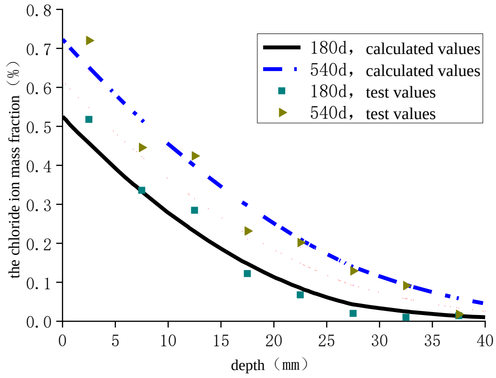


a) Model cross-section grid diagram

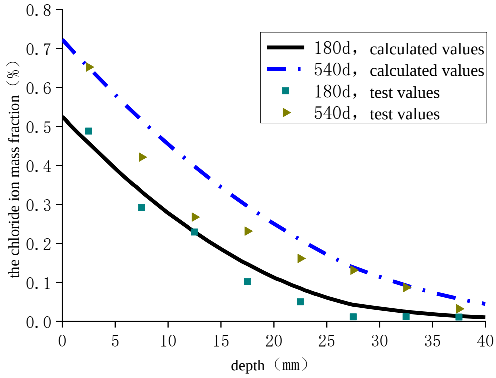


b) 3D model grid diagram

Figure 5. Mesh diagram of FEM testing beam model



(a) beam A-1



(b) beam A-2

Figure 6. Comparison of calculated values with test values of beam

(6) Solving: Using the transient solution method, the analysis step length is 10d, and the calculation time is 540d.

4.3 Comparison of simulation and test results

The comparison between the chloride ion mass fraction at different depths near the cross section of the concrete span and the corresponding position obtained by the finite element simulation of the test beam detected after 540d of chloride salt erosion is shown in Figure. 6.

It can be found from the above figure 6 that: (1) The distribution of chloride ion concentration in the concrete member obtained by the test is consistent with the theoretical calculation results, and the chloride ion concentration decreases along the depth of the section; The test value of the A-1 beam with lower stress level is closer to the analog value, which indicates that the model is more suitable for low stress levels, and it is consistent with the theoretical assumptions. (2) As the immersion time is prolonged, the mass fraction of chloride ions at the same depth in the eccentrically compressed and unstressed concrete is gradually increased, which shows that chloride ions have a cumulative effect in concrete. (3) The mass fraction of chloride ion obtained by numerical simulation is closer to the experimental value in the deep layer of concrete, because the mechanism of chloride ion transmission in the deep layer of concrete is relatively simple, mainly for diffusion. However in the shallow layer of concrete, due to the influence of pore water flow, there is convection in addition to diffusion. (4) According to Fig.6, it can be concluded that: with the increase of eccentric pressure level, the mass fraction of chloride ion in the pressure-reinforcing area steel surface (at a depth of 22.5mm from the pressure surface) gradually decreases, and the chloride ion mass fraction of the steel surface of the tension area (at a depth of 22.5mm from the tension surface) gradually increase. This is related to the increase of the chloride ion diffusion coefficient in the tension area and the decrease of the chloride ion diffusion coefficient in the compression area.

5. CONCLUSIONS

(1) The uneven distribution of stress in the eccentric compression concrete results in a non-uniform distribution of the internal chloride ion diffusion coefficient along the longitudinal cross section, wherein the chloride ion diffusion coefficient of the compression area is reduced, and the chloride ion diffusion coefficient of the tension area is increased.

(2) As the axial pressure increases, the distribution of chloride ion diffusion coefficient in the concrete becomes more uneven, and the chloride ion concentration on the surface of the tensioned steel bar gradually increases.

(3) With the increase of the axial pressure eccentricity, the increased area of chloride ion diffusion coefficient in concrete is expanding continuously, and the chloride ion concentration on the surface of the tensioned steel surface also increases.

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