DURABILITY OF REINFORCED CONCRETE MEMBERS CONSIDERING THE DYNAMIC INTERACTION OF STRESS-CORROSION EXPANSION AND CRACKING

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Abstract - In order to study the whole process of corrosion expansion and cracking of protective coatings of reinforced concrete columns under the coupling condition of load and chloride corrosion environment, the transmission characteristics of chloride salts in loaded concrete columns and the deterioration mechanism of cracking and spalling of protective coatings caused by steel corrosion are studied. The transport characteristics of chloride salts in concrete under the coupling condition of load and erosion environment are studied by means of creep tester. The load-bearing levels of specimens are divided into four groups according to the design values of ultimate load: 0%, 20%, 40% and 60%. The transport of chloride ions in concrete in marine environment is simulated by dry-wet cycling method. The results show that the existence of compressive stress accelerates the chloride ion transport in concrete at the initial stage of loading, and the higher the stress level, the faster the chloride ion transport. With the increase of loading time, the stress hinders the transport process of chloride ion. In the same period, the transmission efficiency in concrete without stress is the highest. In the same period, the chloride ion concentration on the surface gradually decreases with the compressive stress level. The longer the time, the more obvious the downward trend. The peak chloride ion content has little change with the increase of the compressive stress level; at the same compressive stress level, the chloride ion diffusion coefficient is basically unchanged with the increase of the dry-wet cycle; in the same cycle, the chloride ion diffusion coefficient increases with the increase of the stress level, but does not show a linear relationship. Using large-scale finite element DIANA (High-end Nonlinear Finite Element Analysis Software), the whole process of rust expansion and cracking of protective layer of loaded concrete column is numerically analyzed.

Keywords: Reinforced Concrete Column; Durability; Corrosion Protective Coating.

1. Introduction

Reinforced concrete has been widely used in various fields of civil engineering, but steel corrosion is common in the use process, which seriously threatens the safety and durability of concrete structures. The corrosion of steel bars not only reduces the area under stress, but also causes local rust pits, which can cause stress concentration and promote early structural damage.

Especially under the condition of repeated loading, corrosion fatigue will occur, which will greatly reduce the fatigue strength and bring about brittle failure. In reinforced concrete, the reinforced concrete protective layer will cause cracking, serious concrete protective coating, and steel strip, the bond between steel and concrete stress loses or completely loses, endangering the safety of the structure.

Therefore, steel corrosion has great influence on the service life of reinforced concrete structures.
Concrete cracking is an important field of the research of concrete durability, which has been widely concerned.

Many scholars have done a lot of research work in theory, experiment and numerical simulation.

The theoretical model of corrosion cracking and the finite element method are applied to study the influencing factors and failure mechanism of corroded concrete shadow, which have made a lot of achievements.

However, in general, compared with other fields of reinforced concrete theory, there is not yet a set of relatively complete cracking theory with full argument, so it still needs further research.

2. Literature Review

Taffese [1] make a list of the macro factors of concrete carbonation impact on EU bilateral norms, such as environmental action grade, concrete material limits, and the maximum water cement ratio.

On this basis, Wang [2] and Von [3] analyzed the structure service life of the atmospheric environment, and compared with the actually measured data, which focuses on the analysis of effects of concrete strength grade and thickness of the protective layer on the carbonation life of reinforced concrete structure. It is considered that the stipulated values of concrete strength and protective layer thickness in China's codes are too small, so that the calculated residual service life of the structure is quite different from that of Europe, and the difference is nearly three times.

Van-Loc et al. [4] made a comparison between the relevant provisions of the Chinese and European codes on durability design of concrete bridges, such as environmental action grade, minimum strength and minimum protective layer thickness, and predicted the durability design life of bridges under carbonation and chloride environment by numerical calculation method. It was considered that the provisions of the two codes could meet the durability of bridges under carbonation environment. But it cannot meet the durability requirements in the environment of ocean wave splashing area.

Enhancing the drainage capacity of bridges and reducing the frequency of deicing salts have a greater impact on the durability.

Jamshaid et al. [5] compared the provisions of the minimum thickness of protection among Chinese, the United States, Japan, Europe and the UK.

Xu et al. [6] made a more specific elaboration of the definition, requirement, durability, the responsibility of the parties in the life period in Britain, Japan and Canada, and gave some advice on the formulation of China's durability specification.

Godycki et al. [7] made a comparative analysis of the durability, material and crack provisions in the design codes of concrete structures in China and Europe.

Cai and Zhao [8] compared the protective layer thickness stipulated in the general atmospheric environment of the Chinese and European code for durability of concrete, and concluded that the value stipulated in the European code was 10mm larger than that in China, thus prolonging the carbonization life of the structure for at least 40 years.

Tadeusz et al. [9] analysed the influencing factors of the crack width, maximum crack limit factors, and the specific value of crack width under environmental conditions in specifications of China, Japan, Europe, New Zealand and the United States.

They also pointed out the characteristics and connotation of the standard limit, and put forward the factors that should be considered in the limit value of durability crack width of bridge structures.

Wang et al. [10] believed that concrete attacked by sulfate is not common, which only occurs in some local places so that it does not conform to what is concerned in the laboratory research. However, in the actual situation of the project, there are a large number of engineering examples by sulfate erosion. Therefore, a large number of scientific and technical personnel in scientific and technical level are needed to solve the problem of durability of concrete.

Lu et al. [11] also pointed out that the laboratory study of sulfate corrosion of concrete enlarged the sulfate erosion in practical engineering of concrete.

Rashid and Balouch [12] confirmed by the experiment that the erosion products generated in the cement matrix and aggregate interface zone is formed after the samples are obviously swelled. Based on the experimental results, combined with the pressure of crystallization theory, it can be conjectured as follows: when the content of ettringite in cement matrix pore solution reaches its saturation concentration, ettringite crystal growth will occur in the narrow closed pores, and large produce crystallization pressure in this process is the main reason for the expansion of the cement matrix. As the expansion continues, cement matrix and aggregate interfacial cracks will expand and have significant macro expansion. During the crack expansion, the ettringite or gypsum in cracks in the erosion products crystallizes and precipitates, and the crystallization pressure in the process is very small, basically does not cause swelling.

3. Whole process of corrosion expansion and cracking of reinforced concrete members caused by chloride salt

3.1 Transmission of chloride ion in concrete

There are many transmission ways of chloride ion in concrete, especially chloride corrosion of concrete members under complex stress environment. The main driving force of chloride ion transport in concrete is convection and diffusion.

Diffusion is mainly caused by concentration difference, while convection is more complex, including pressure, capillary adsorption, and electric field force. Diffusion mainly includes steady-state diffusion and unsteady-state diffusion. Steady-state diffusion is described by Fick's first law, e.g. (1):

$$J = -D\frac{\partial C}{\partial x} \tag{1}$$

The first formula is one-dimensional diffusion, in which J is diffusion flux, D is diffusion coefficient of chloride ion in transmission medium, C is surface chloride ion concentration, and X is transmission depth.

Fick's second law is used to describe the unsteady diffusion, as Formula (2):

$$\frac{\partial C}{\partial t}=\frac{\partial C}{\partial x}\left(D\frac{\partial C}{\partial x}\right) \tag{2}$$

The parametric meanings in the formula are the same as those in Formula (1).

Fick's second law can be solved analytically under the following assumptions.

First, the chloride ion concentration on the surface of concrete structure is constant $C_{x=0}=C_s$.

Second, the concrete structure is a semi-infinite medium relative to the exposed surface.

Third, the chloride ion concentration at any time at infinite distance from the exposed surface is the initial concentration, i.e. $C^{t=0}_{x>0}=C_0C_{x=00}=C_0$. Under the above three assumptions, the expression of the analytical solution is shown in Formula (3):

$$C(x,t)=C_0+(C_s-C_0)\left[1-erf\left(\frac{x}{2\sqrt{Dt}}\right)\right] \tag{3}$$

Because there are few considerations about chloride ion transport in concrete under saturated state, the scope of application is limited. Moreover, the areas where chloride ion erosion is serious under real conditions are not all immersed in the concrete under saturated state of chloride salt. Therefore, chloride ion transport in concrete under unsaturated state is particularly important.

Convection is a very important process for reinforced concrete members in dry-wet alternating region, which makes the interior of concrete under the action of chloride concentration field gradient, temperature field gradient, and pore-liquid saturation field gradient, thus accelerating chloride ion transport in concrete. The transport of chloride ion in concrete in dry-wet alternating region is essentially the transport of chloride ion with solution in unsaturated porous media. Convection and diffusion are the main modes of chloride ion transport. For a long time, in order to simplify the form, domestic and foreign research institutions tend to use Fick's second law and its analytical solution of constant boundary conditions to calculate chloride transport in concrete in dry-wet alternating zone. However, the above analytical solution is applicable to the ion diffusion problem caused by ion concentration gradient in static solution. It has a good correlation with the detection data of long-term immersion test of concrete specimens in solution with constant chloride concentration. However, when fitting the detection data of concrete specimens in complex environments such as wet-dry alternation (such as wave splash zone and tidal range zone), it is difficult to obtain satisfactory results in data distribution or curve shape.

The recommended depth of convection zone under different environmental conditions of ordinary concrete and high performance concrete is given by indoor and outdoor tests as shown in Table 1.

Table 1. Proposed depth of convection zone in concrete under various environmental conditions (mm)

Classification of concrete	Environment condition	Atmospheric region	Wave base area	Tide zone	Underwater area
Ordinary concrete	Field exposure	5	10	10	5
	Indoor acceleration	2	7.5	5	1
Marine concrete	Field exposure	5	7.5	7.5	5
	Indoor acceleration	2	2.5	2.5	1

3.2 Electrochemical corrosion mechanism of steel bar

In general, the corrosion of reinforcing bars in concrete is usually natural electrochemical corrosion. The steps are as follows:

The anode reaction equation is as follows:

$$Fe\rightarrow Fe^{2+}+2e^{-} \tag{4}$$

As shown in Formula (4), in the anode area of the steel bar surface, the iron on the steel bar surface loses electrons and is oxidized to ferrous ions.

The cathodic reaction equation is:

$$O_2+2H_2O+4e^{-}\rightarrow 4OH^{-} \tag{5}$$

In the cathode area formed on the surface of steel bar, the above process is slowly carried out and $(OH)^-$ is formed.

Formation of corrosion products:

$$4Fe(OH)_2+O_2+2H_2O\rightarrow 4Fe(OH)_3 \tag{6}$$

$$2Fe(OH)_3\rightarrow Fe_2O_3+3H_2O \tag{7}$$

$$6Fe(OH)_2+O_2\rightarrow 2Fe_3O_4+6H_2O \tag{8}$$

As mentioned above, the Fe^{2+} on the surface of the steel bar anode diffuses into the concrete pore solution, and reacts with the cathode to form brown $Fe(OH)_2$, which gradually oxidizes to ferric hydroxide, which eventually exists in the form of ferric oxide in the presence of oxygen on the surface of the steel bar, and ferrous hydroxide does not completely oxidize to black ferric oxide in the absence of oxygen on the surface of the steel bar.

The influence of chloride ion on rust process:

Not all chloride ions in concrete can accelerate steel corrosion, because in the process of concrete pouring, these exotic chloride ions can react with some components of concrete, and produce complex water-insoluble compounds such as

$3CaO \cdot Al_2O_3 \cdot CaCl_2 \cdot 10H_2O$·and

$CaO \cdot Al_2O_3 \cdot CaCl_2 \cdot 32H_2O$.

At this time, chloride ions do not exist in free form, but in the compounds, and this chloride ion does not corrode steel bars.

Therefore, only when free or free chloride ions appear in concrete, the presence of these chloride ions can cause pitting corrosion on the surface of steel bars, leading to local corrosion of steel bars.

The effects of these free chloride ions on the corrosion of steel bars in concrete are as follows:

When concrete is poured, due to the formation of a dense oxide film on the surface of reinforcing bars in the alkaline environment made by $Ca(OH)_2$, which contains iron oxide with Si-O bond.

The oxide film is relatively stable in the alkaline environment and has a protective effect on reinforcing bars.

The invasion of chloride ions leads to the decrease of the pH value of pore solution on the surface of reinforcing bars, and the destruction of the passivation film exposes the iron matrix.

As a result, it constitutes an electric charge between the passivation film potential differences and forms the corrosion cells in the porous solution electrolyte environment, thus accelerating the local pitting corrosion of steel bars, and expanding the destruction of passive film on the surface of steel bars. As an anode of iron matrix, reaction occurs:

$Fe-2e=Fe^{2+}$. Fe^{2+} can react with chloride ions to form $FeC1_2$, which accelerates the anodic reaction of iron matrix, also called depolarization.

At this time, soluble $FeC1_2$ can react with OH^- in porous solution to form white $Fe(OH)_2$ precipitation.

The content of chloride ion has not decreased, but further reduces the PH value on the surface of steel bars. Some scholars have also given the relationship between chloride ion content in concrete and corrosion rate of steel bars.

From the above analysis, it can be seen that chloride ion plays a very important role in the corrosion process of steel bars, which greatly accelerates the corrosion of steel bars and leads to the early destruction of concrete structures.

The chemical reaction equation is as follows:

$$Fe^{2+} + 2Cl^- + 4H_2O \rightarrow FeCl_2 \cdot 4H_2O \tag{9}$$

$$Fe_2 \cdot 4H_2O \rightarrow Fe(OH)_2 + 2HCl + 2H_2O \tag{10}$$

3.3 Cracking process of concrete cover under rust expansion

For a large number of marine buildings, reinforced concrete members are often subjected to the dual effects of load and chloride erosion. For the concrete with strict control of materials, chloride ions enter the concrete through various channels in the marine environment, which poses a great threat to the reinforcement in the concrete. Chloride ions are very strong deactivators, and can easily be absorbed on the surface of the reinforcement to accelerate the corrosion of steel bars. When chloride ions accumulate on the surface of steel bars to a certain extent, the corrosion of steel bars will be greatly accelerated. With the accumulation of corrosion products of steel bars, the concrete around steel bars will be squeezed, which will eventually lead to the spalling of concrete protective layer. The spalling concrete exposes the steel bars to the corrosive environment and further accelerates the corrosion of steel bars, thus making the damage of reinforced concrete members ahead of time. The whole process of expansion and cracking of reinforced concrete members in chloride environment is mainly introduced from three aspects: chloride ion erosion mechanism, the conditions of steel corrosion, and cracking of concrete protective layer caused by corrosion.

Concrete is a kind of artificial stone which is formed by mixing cement, water, sand, stone and admixture and pouring into moulds after curing and hardening. But in the initial setting period of concrete, there are inherent micro-cracks and micro-voids in concrete due to the shrinkage of cement blocks, water percolation, and aggregate sinking. Micro-cracks themselves are weak links of concrete. Under the action of rust expansion force, they gradually develop into macro-cracks. The damage process of concrete caused by steel corrosion mainly includes the following four stages.

Free expansion stage: In this stage, the corrosion products of steel bars are used to gradually fill the micro-voids in the interface between steel and concrete. The corrosion amount of steel bars in this stage is less than or equal to the amount of corrosion needed to fill the voids, so the concrete around the steel bars will not produce stress in this stage.

Stress generation stage: When the corrosion amount of steel bar exceeds the corrosion amount needed to fill the void, stress will occur at the interface between steel bar and concrete, and circumferential tensile stress will occur on the concrete on the surface of steel bar. The stress depends on the corrosion amount of steel bar. With the deepening of corrosion degree, circumferential compressive stress of concrete will become larger and larger.

Crack formation stage: With the accumulation of corrosion, when the circumferential tensile stress of concrete exceeds the tensile strength of concrete, cracks will occur on the concrete around the reinforcement.

Crack propagation stage: While filling cracks, corrosion products cause cracks in the concrete around the reinforcement to develop continuously, which makes the concrete near the protective layer crack seriously, thus accelerating the corrosion of the reinforcement.

The existing research results show that, under the condition of no external stress, with the accumulation of corrosion products between steel bar and concrete interface, the cracking of concrete protective layer can be divided into four stages. Because the non-uniform corrosion often occurs in the actual components, the first stage is that the protective layer of steel bar in the corner area produces the first internal crack on the thickest side of the corrosion layer, which is called internal cracks.

With the increase of rust expansion, internal cracks occur in the surrounding pressure of steel bars in the non-corner area, which is called internal crack development stage. With the further accumulation of rust products, cracks occur on the surface of the protective layer of steel bars in the corner area, but at this time, cracks between the internal and external do not penetrate.

This stage is called external cracks. With the severity of corrosion, internal and external cracks penetrate, and finally the protective layer peels off, which exposes the internal steel bars to the external corrosion environment, accelerates the structural damage, and greatly shortens the service life of the structure.

The corrosion of steel bars will cause expansion crack of concrete protective layer, and corrosion of steel bars will accelerate after the occurrence of corrosion cracks, which will enhance the durability of concrete structural members.

Therefore, the research on corrosion cracking of protective coat caused by steel corrosion is of great significance to the durability of concrete members.

The process of cracking of protective coat caused by steel corrosion is quite complicated. It is more difficult to observe this process because it occurs in the interior of concrete.

In order to determine the corrosion rate of reinforcing bars in each stage of corrosion expansion and cracking of protective coat of reinforced concrete members, it mainly includes three aspects: theoretical deduction, experimental research, and simulation analysis.

These studies mainly focus on the relationship and influencing factors between the development of steel corrosion and concrete surface cracking, and the expression of steel corrosion rate at the time of concrete cracking.

4. Experimental Study on Chloride Ion Transport in Concrete Under Different Stress Levels

4.1 Experimental design

For most of the existing marine structures, various reinforced concrete members are often subjected to the dual effects of erosion environment and load, which leads to the early destruction of reinforced concrete members.

In recent years, the damage of durability of structures caused by the erosion of harmful substances is ubiquitous.

Domestic and international research has invested a lot of energy in this field.

The theory of the transport of harmful substances in concrete under a single environment has been greatly developed, and a relatively ideal theoretical model has been obtained, especially about the transport of chloride ions in concrete.

But in the real environment, the durability of reinforced concrete structures is poor, and the reduction of service life is caused by a combination of many factors, including load factors, environmental and climatic factors etc.

Among them, many scholars are studying the influence of load factors on the transmission characteristics of harmful substances in concrete.

There are still great differences in the means and conclusions of the research.

Therefore, on the basis of summarizing the previous studies, the transport characteristics of chloride ions in concrete under axial compression are studied experimentally.

This experiment simulates the deterioration process of reinforced concrete members in ocean splashing area by means of dry-wet cycling method, and explores the influence of different size of axial compressive stress on the process of chloride intrusion into reinforced concrete short columns under chloride environment.

It mainly includes the size and pouring of specimens, loading device and loading scheme of specimens, and sampling and measurement of specimens.

The test objects are 18 150mm*150mm*300mm reinforced concrete short columns completed by pouring.

The concrete strength is C25; the proportion of test blocks is water: cement: sand:

gravel = 188:384:640:1189; the reinforcement and other basic information of the columns are shown in Table 2 below.

Table 2. Basic information for reinforced concrete specimens

Strength grade of concrete	28-day compressive strength value f_c (Mpa)				Protective layer /mm	Curing condition	Portrait	f_y (Mpa)
	1	2	3	Mean value				
C25	32.28	34.68	37.34	34.77	25	28 days of water conservation	4Φ4	300

Test method: Accelerated migration method: The chloride ion migration is accelerated by dry-wet cycle.

The concrete dry-wet circulation method is: wrapping the self-made water storage bag around the concrete specimen, and injecting 3% salt solution into the inner part. Dry-wet cycle is carried out in different time with a dry-wet time ratio of 2:1.

The sample is soaked in a water storage bag for one day, and then the salt solution is released. Natural air-drying is carried out for two days and three days as a cycle. The monthly wet-dry cycle is used as a cycle, and core samples are drilled every 1mm on its surface to determine chloride ion concentration and replace salt solution once.

In order to study the influence of different stress levels on chloride ion transport characteristics in concrete, the total test period is one year. In order to study specifically, drilling powder samples are taken in three different test periods, namely, four months, eight months and twelve months, so as to obtain the transport model of chloride ion under stress.

Continuous load method: The specimen column is placed in the middle of the creep meter, the top jack is used to compress the creep meter to the bottom spring to the design load, and the screw on the creep meter column is fixed, so that the reaction of the compression spring can exert load to achieve the purpose of sustained load on the specimen column.

Monitoring method: Galvaplus instrument is used to measure the corrosion status of steel bar in concrete.

The general idea of the experiment is to use the experimental method of comparison between groups and within groups. According to the magnitude of loading force, the experiment is divided into four groups.

Each group of experiments makes two samples for simultaneous test. Two samples in each group are stacked together. The upper part is used to measure the chloride diffusion depth under different wet and dry cycles. It is measured once every four months and is compared with the diffusion depth of other groups under the same conditions.

The influence of axial force on chloride diffusion is studied, and the corrosion of steel bar in concrete is detected at any time.

4.2 Determination results of chloride ion content

A one-year wet-dry cycling test is carried out on specimens with loading values of 0%, 20%, 40% and 60%, respectively. Drilling powder is sampled for four months, eight months and twelve months as shown in the table below.

Table 3: Chloride ion content in concrete at different depths at 0% stress level

Depth range (mm)	Chloride ion content (mg/kg)			Chloride ion content (%)		
	4 months	8 months	12 months	4 months	8 months	12 months
0~1	757.8	2245.8	3141.4	0.086	0.253	0.354
1~2	776.6	3552.4	4151.1	0.088	0.398	0.524
2~3	564.4	3352.8	4284.6	0.064	0.378	0.483
3~4	295.7	2987.6	3875.8	0.034	0.336	0.437
4~5	318.5	2460.4	3704.9	0.036	0.276	0.417
5~6	136.5	2164.8	3157.1	0.016	0.244	0.355
6~7	133.6	1782.9	3319.4	0.016	0.201	0.374
7~8	79.9	1442.2	3002.7	0.008	0.163	0.338
8~9	67.4	1168.8	2408.7	0.007	0.132	0.272
9~10	45.2	871.6	2030.8	0.005	0.098	0.227
10~11	37.9	650.2	1338.5	0.004	0.074	0.151
11~12	26.3	537.4	1070.8	0.002	0.06	0.121

12~13	29.3	419.8	914.3	0.003	0.048	0.103
13~14	29.8	262.2	590.8	0.003	0.028	0.067
14~15	26.7	209.8	391.5	0.002	0.024	0.045
15~16	20.7	138.4	275.8	0.002	0.014	0.032
16~17	20.5	174.5	184.6	0.002	0.018	0.02
17~18	21.3	157.4	144.4	0.002	0.017	0.016
18~19	17.9	153.2	107.8	0.002	0.017	0.012
19~20	16.9	125.8	82.4	0.001	0.014	0.009
20~21	15.8	191.1	86.9	0.001	0.020	0.009
21~22	15.5	179.1	59.4	0.001	0.02	0.006
22~23	13.8	144.5	50.6	0.001	0.017	0.005
23~24	13.8	150.6	47.1	0.001	0.016	0.005
24~25	12.7	104.6	42.1	0.001	0.012	0.004

Table 4: Chloride ion content in concrete at different depths at 20% stress level

Depth range (mm)	Chloride ion content (mg/kg)			Chloride ion content (%)		
	4 months	8 months	12 months	4 months	8 months	12 months
0~1	400.9	2649.6	2075.1	0.045	0.298	0.233
1~2	479.1	2772.9	2829.2	0.053	0.312	0.318
2~3	418.6	2154.9	2471.3	0.047	0.242	0.278
3~4	362.7	1633.5	1903.3	0.04	0.183	0.214
4~5	276	1407.6	1565.4	0.031	0.158	0.176
5~6	216	1173.5	1389	0.024	0.132	0.156
6~7	189.1	850.4	1176.4	0.021	0.095	0.132
7~8	130.1	839.7	862.2	0.014	0.094	0.097
8~9	87.3	520.2	888.5	0.009	0.058	0.099
9~10	55.3	338.8	761.4	0.006	0.038	0.085
10~11	41.1	311.1	674.5	0.004	0.035	0.075
11~12	27.6	243.9	501.8	0.003	0.027	0.056
12~13	22.5	190.6	454	0.002	0.021	0.051
13~14	22.1	133.6	331	0.002	0.015	0.037
14~15	20.5	104.7	245.4	0.002	0.011	0.027
15~16	19	105.2	233.4	0.002	0.011	0.026
16~17	21.8	84.7	163.3	0.002	0.009	0.018
17~18	16	88.5	148.2	0.001	0.009	0.016
18~19	15.3	93.4	143.8	0.001	0.01	0.016
19~20	15.1	95.5	124.6	0.001	0.01	0.014
20~21	17.3	105.9	101.9	0.001	0.011	0.011
21~22	16.8	102.5	97.8	0.001	0.011	0.011
22~23	16.9	89.2	93.9	0.001	0.01	0.01
23~24	16.2	86.3	83.5	0.001	0.009	0.009
24~25	13.9		76.8	0.001	0	0.008

Table 5: Chloride ion content in concrete at different depths at 40% stress level

Depth range (mm)	Chloride ion content (mg/kg)			Chloride ion content (%)		
	4 months	8 months	12 months	4 months	8 months	12 months
0~1	338.7	1875.3	1404.7	0.038	0.211	0.157
1~2	603	2704.5	2576.4	0.067	0.304	0.289
2~3	573.5	2460.4	2654.9	0.064	0.276	0.298
3~4	511.5	2009.6	2654.8	0.057	0.226	0.298
4~5	438.7	1648.2	2681.5	0.049	0.185	0.301
5~6	427.2	1357.4	1938.5	0.047	0.152	0.218
6~7	349.5	909.4	1523.8	0.039	0.102	0.171
7~8	309.1	765.2	1701	0.034	0.086	0.191
8~9	238.8	582.2	1371.8	0.026	0.065	0.154
9~10	205.8	499.7	1017	0.023	0.056	0.114
10~11	164	337.9	992.8	0.018	0.038	0.111
11~12	117.7	291.2	685.1	0.013	0.032	0.077
12~13	81.1	174	456.4	0.009	0.019	0.051
13~14	52.4	123	312.1	0.005	0.013	0.035
14~15	45.3	126.1	244.6	0.005	0.014	0.027
15~16	40.3	94.1	165.8	0.004	0.01	0.018
16~17	32.4	99.8	124.7	0.003	0.011	0.014
17~18	30.3	90.8	94.1	0.003	0.01	0.01
18~19	25.9	80.8	70.4	0.002	0.009	0.007
19~20	24.4	80.3		0.002	0.009	--
20~21	25	85.4		0.002	0.009	--
21~22	23.7	82.2		0.002	0.009	--
22~23	23.8	81.6		0.002	0.009	--
23~24	24.5	96.6		0.002	0.01	--
24~25	24.9	93.2		0.002	0.01	--

Table 6: Chloride ion content in concrete at different depths at 60% stress level

Depth range (mm)	Chloride ion content (mg/kg)			Chloride ion content (%)		
	4 months	8 months		4 months	8 months	
0~1	281.7	1158.5	766.4	0.031	0.13	0.086
1~2	451	1915.1	1773.6	0.05	0.215	0.199
2~3	672.8	2201.8	2265.6	0.075	0.247	0.254
3~4	627.7	1984.7	2177	0.07	0.223	0.244
4~5	706.8	1909.8	2146.3	0.079	0.214	0.241
5~6	607.3	1754.8	2123.1	0.068	0.196	0.238
6~7	557.1	1758.8	1969.8	0.062	0.197	0.221
7~8	474.9	1577.7	1573.2	0.053	0.177	0.177

8~9	448.6	1304.5	1438.2	0.05	0.153	0.161
9~10	319.7	1184.1	1330	0.038	0.133	0.149
10~11	280.2	979.8	1024	0.031	0.11	0.115
11~12	209.5	786.3	912.8	0.023	0.088	0.102
12~13	170	719.4	755.8	0.019	0.08	0.084
13~14	129.8	523.3	597.6	0.014	0.058	0.067
14~15	74.2	389.9	450.7	0.008	0.039	0.05
15~16	70.5	228.8	359.3	0.007	0.025	0.04
16~17	53	198.3	271.5	0.005	0.021	0.03
17~18	44	151.7	170.7	0.004	0.017	0.019
18~19	42.9	144.3	128	0.003	0.016	0.014
19~20	33.3	143.7	91.5	0.003	0.015	0.01
20~21	30.9	114.2	68	0.003	0.013	0.007
21~22	27.1	114.2	57.9	0.003	0.013	0.006
22~23	26.9	125.3	55.7	0.003	0.014	0.006
23~24	23.4	114.9	51.5	0.002	0.012	0.005
24~25	22	114.2	62.6	0.002	0.011	0.007

4.3 Detection of steel corrosion in concrete in chloride environment

Using Galva Pules steel bar corrosion rate tester, the steel bar in loading component is measured at 8 months.

Analyzing the measured experimental data, it can be seen that among 153 valid data of steel bar corrosion current density, the value of corrosion current density is the most in the range of 0-0.5uA/cm^2, 85 of which account for 55.56% of the total effective measuring points, and 67 of which account for 43.73% of the total test points in the range of 0.5-5uA/cm^2.

The corrosion current density of only one test point is more than 5uA/cm^2.

The evaluation criteria of steel corrosion are shown in the table below.

Table 7: Criteria for evaluating corrosion of steel bars

Test result	Corrosion rate
0～0.5uA/cm^2	Slight
0.5～5uA/cm^2	Slow
5～15uA/cm^2	Moderate
>15uA/cm^2	Fast

According to the evaluation criteria in the table, it can be seen that the corrosion rate of loading columns is very low at 8 months, most of which are located in slight intervals. It can be seen that the steel bars in concrete are basically rusty. It can be seen from the experimental data obtained from the above monitoring that the chloride ion concentration on the surface of steel bars cannot reach the critical chloride ion concentration when steel bars are corroded due to the dry-wet cycle within a short period of time (one year).

5. Analysis of Chloride Ion Transport Characteristics in Concrete under Different Stress Levels

5.1 Distribution rule of chloride ion content under different stress levels

For reinforced concrete structures such as coastal bridges and wharfs, besides bearing loads, they also bear the erosion of chloride ions. Scholars at home and abroad have done a lot of research on the corrosion characteristics of chloride ions under non-stress conditions, and have achieved fruitful results.

However, the existence of load has a great impact on the transmission characteristics of chloride ion concrete.

Different load forms and load levels cause different changes in the microstructure of concrete, thus changing the macro-permeability of concrete and affecting the erosion process of harmful substances.

There are many ways of chloride ion transport in concrete, including diffusion, permeation, capillary adsorption, electro-migration etc.

The existence of load changes some key factors in these processes, thus affecting chloride ion transport in concrete.

Based on the experimental data measured in the previous chapter, the effects of different stress levels on chloride ion transport characteristics are analyzed, including chloride ion content at different depths, surface chloride ion concentration, peak chloride ion concentration, and chloride ion diffusion coefficient.

Distribution of chloride ion content with depth:

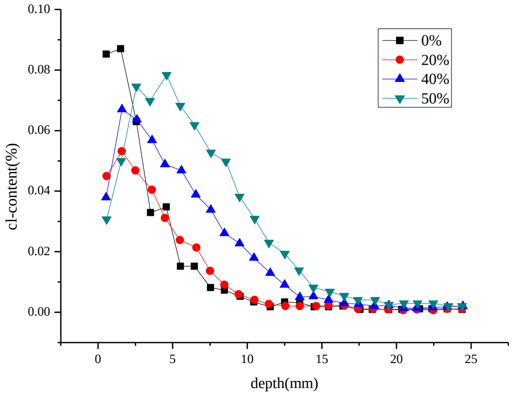

Figure 1: Chloride ion content in specimens under different stress levels during dry-wet cycling for 4 months

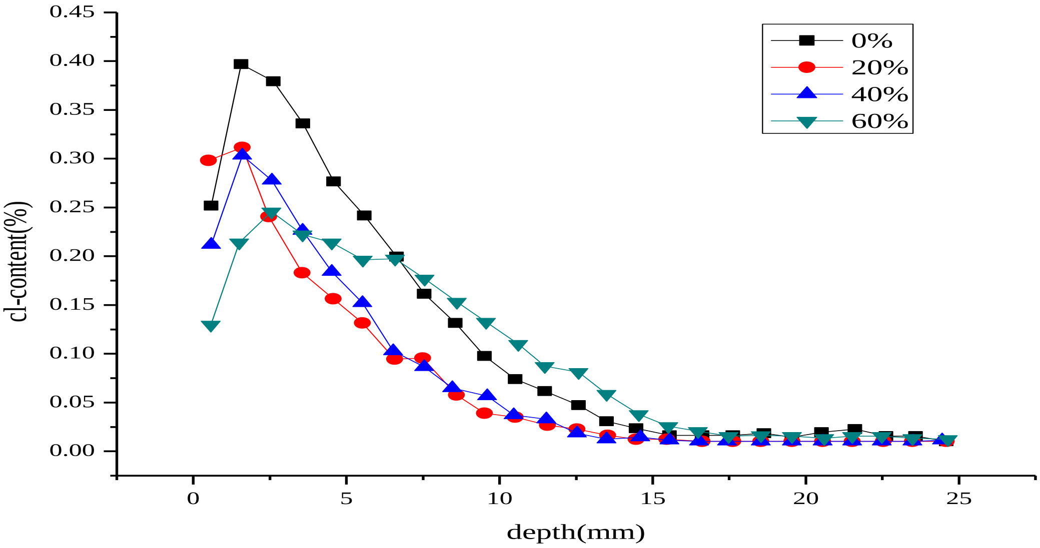

Figure 2: Chloride ion content in specimens under different stress levels during dry-wet cycling for 8 months

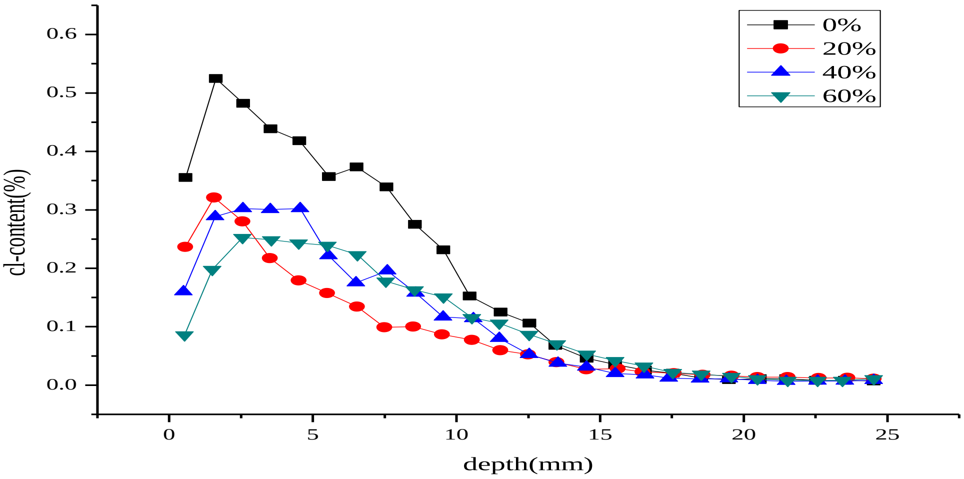

Figure 3: Chloride ion content in specimens under different stress levels during dry-wet cycling for 12 months

Under the action of load, three groups of chloride ion content curves with depth as shown in Figures 1-3 above are obtained by drilling powder sampling after one year's dry-wet cycle test (dry-wet-1). By studying the above experimental curves, the following rules are obtained:

From the experimental data of four months, eight months and twelve months, it can be seen that: firstly, the transport depth of chloride ion is about 11mm in four months, 14mm in eight months, and 17mm in twelve months, which indicates that the transport depth of chloride ion increases gradually with the increase of time (the increase of wet and dry cycles); secondly, with the increase of time, the chloride ion content at the same depth in the effective transport depth gradually increases, including surface chloride ion concentration and convection peak concentration, but it is not linear.

Variation of chloride ion content with stress level: From the data of wet-dry cycle for four months, it is seen that: first, with the increase of stress level, the content of chloride ion increases at the same depth, and with the increase of stress level, the transport depth of chloride ion increases slightly; second, from the data of eight months and twelve months as shown in Figures 2-3, it can be seen that in the same period, the chloride ion content at 0% stress level is larger than that of other stress levels.

After removing the chloride ion content at 0% load level, it is found that the chloride ion content at the same depth is still increasing with the increase of load level from 20% to 60%, and the chloride ion content at 40% load level changes from the initial load level close to 20% to the load level close to 60%. It can be seen that in the early stage of loading, due to the increase of external load, micro-cracks in concrete gradually develop and chloride ion transport in concrete increases. However, with the increase of time, cracks in concrete gradually heal themselves, and the creep of concrete under continuous load has not been taken into account in the research process of other scholars.

Therefore, the conclusion does not take into account the long-term effect of the load. A one-year test shows that the long-term existence of load makes concrete more and more compact under the action of compressive stress, thus eliminating the law presented earlier.

The chloride ion content in the same depth of specimens with zero stress level is higher than that in other depths with the increase of time.

5.2 Surface chloride ion concentration under different stress levels

The exploration of chloride ion concentration on the surface is an important process in the study of chloride ion transport in concrete. For reinforced concrete structures in full immersion environment, chloride ion transport is mainly achieved through diffusion process. The diffusion power mainly comes from concentration difference. The greater the chloride ion concentration on the surface, the greater the concentration difference between internal and external chloride ions, the greater the dispersion of chloride ion, and the faster the chloride ion transport in concrete.

The concrete structure specimens are poured and maintained in the same batch, and corroded in the same dry-wet cycle. The only difference is the applied load. From Figure 4, it is seen that the chloride ion content on the inner surface of the same cycle decreases linearly with the increase of the stress level imposed by the specimens. When the stress action time is short, the slope is small, and the concentration of surface chloride ion decreases slowly. However, with the increase of time, the slope is large, and the downward trend is obvious in the linear relationship between the concentration of surface chloride ion and the stress level at 12 months.

From Figure 5 below, it can be seen that when the load level is 0%, the chloride ion content increases logarithmically with the increase of time.

Comparing with the time-varying law of chloride ion surface concentration under dry-wet cycling without stress, the model proposed by Xu Ke is as follows:

$$C_s(t) = C_0 + C_{sm}\left[1 \quad e^{0.09327(1 \quad 0.26296^{\beta})t}\right] \tag{11}$$

C_0 refers to initial chloride ion concentration of concrete, unit: %; C_{sm} indicates the surface chloride ion concentration stability value, unit: %; dry-wet time ratio is $\beta = t_g/t_s$.

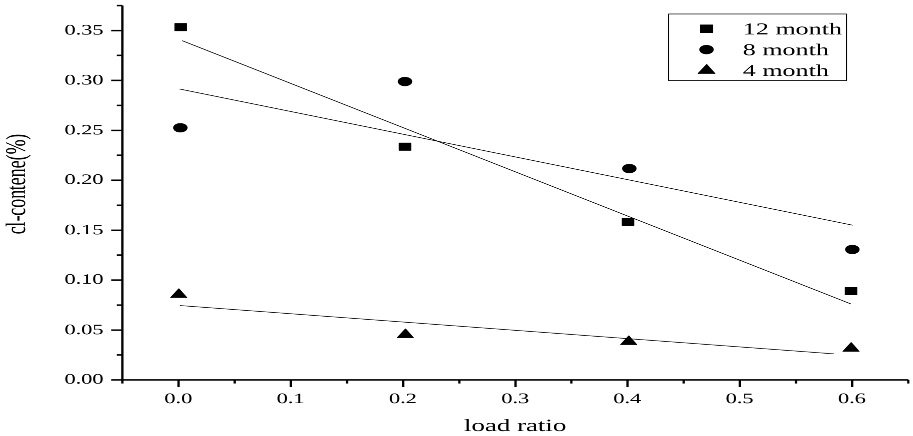

Figure 4: Surface chloride ion content under different stress levels in the same period

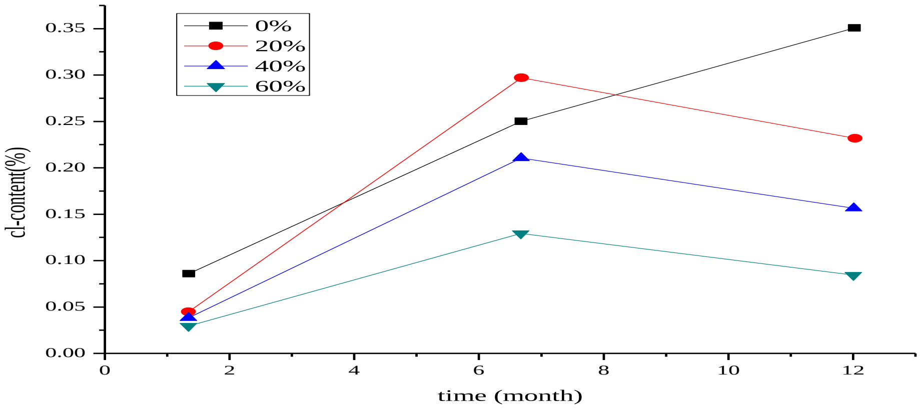

Figure 5: Surface chloride ion content in the same period

It can be seen that the above model can be well applied to the time-varying surface chloride ion concentration under the stress-free level in this experiment, but the existence of load changes this rule. As shown in the curve of 20%, 40% and 60% in Figure 5, under the action of stress, the surface chloride ion concentration increases first and then decreases with the increase of stress level; moreover, with the increase of stress level, the magnitude of the addition decreases.

5.3 Effect of different stress levels on convection zone

Convection zone depth △X: The transport of chloride ions in components under dry-wet cycling will produce obvious convection phenomena on the surface of concrete. There will be convection zone and convection peak value. The mechanism of convection is more complex. Because dry-wet cycling mainly involves two processes, dry and wet, the adsorption of capillaries and concentration difference will play a certain role. Although the specimens are continuously loaded, they still adopt the dry-wet cycle system to accelerate the chloride ion transport in concrete, so there are obvious convective zones. From the experimental data of four months, eight months and twelve months (Figures 1-3), it can be seen that: first, the stress level is 0%, and the convective zones of chloride ion transport in 20% specimens are mainly concentrated in two millimeters of 0-2mm; second, in four months and eight months, the convective zone of the specimens with 40% stress level mainly concentrates in the range of 0-2mm. With the increase of time, the convective zone ranges from 0-5mm in twelve months; third, in the specimens with 60% stress level, the depth of the convective zone ranges from 0-5mm; fourth, with the increase of time, the range of the convective zone extends to 0-7mm in twelve months. The above analysis results show that, with the increase of stress level, the range of convection zone presents an increasing trend. With the increase of dry-wet cycle period, the range of convection zone also shows a deepening trend at high stress level.

Convection peak C_s, △X:

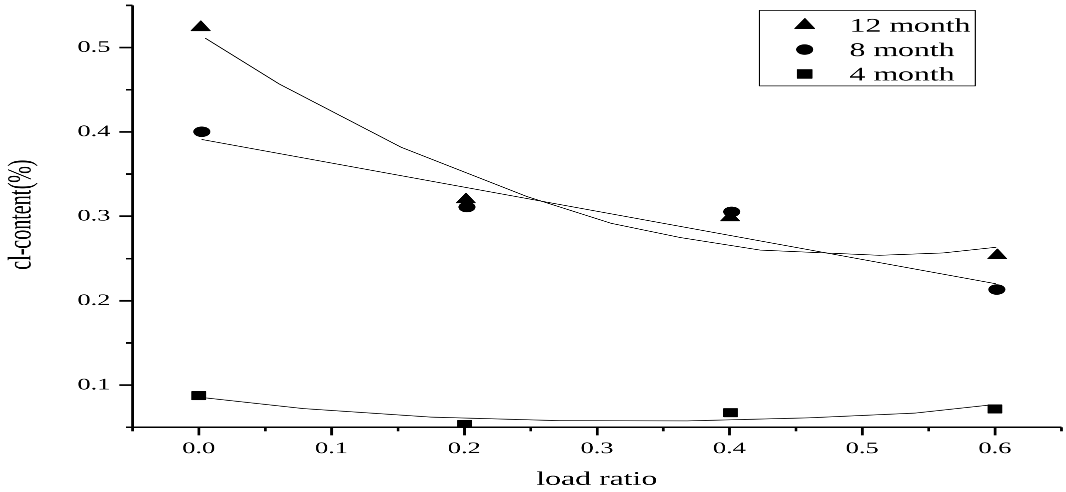

Figure 6: Peak chloride ion content at different stress levels in the same period

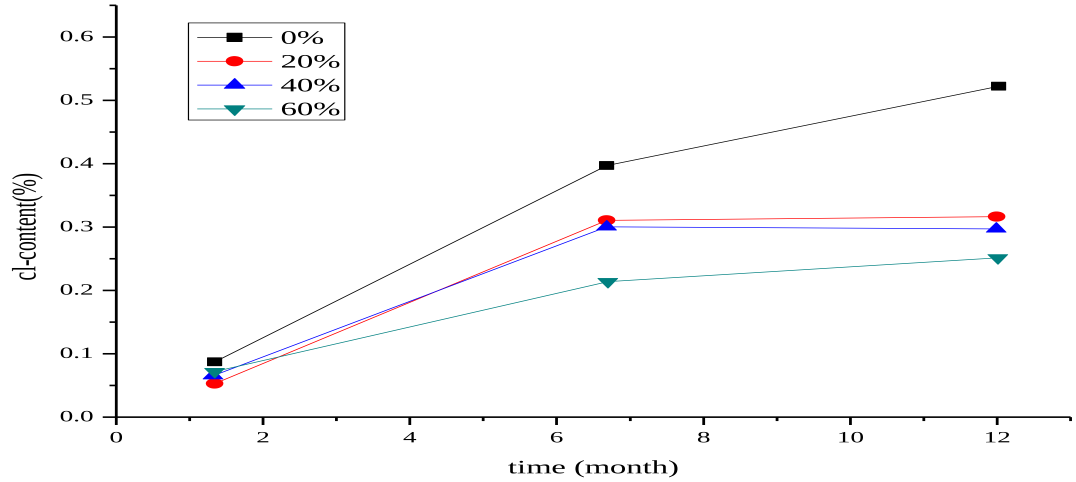

Figure 7: Peak chloride ion content in different periods at the same stress level

The chloride ion transport in concrete specimens under dry-wet cycling mainly consists of two processes: convection and diffusion. The peak concentration in the convection zone determines the initial concentration of diffusion. The speed of diffusion mainly depends on the concentration difference. Therefore, the factors influencing the peak concentration in the convection zone are particularly important.

From Figure 6, it can be seen that the peak chloride ion content increases with the increase of stress level, but the variation of peak chloride ion content is very small. This is different from the curve of surface chloride ion concentration changing with time.

Figure 7 shows that the peak chloride ion concentration at the same stress level increases with the increase of wet and dry cycle. However, with the increase of stress level, the chloride ion content changes little during the period of eight to twelve months.

5.4 Chloride diffusion coefficient at different stress levels

The diffusion coefficient of chloride ion can be calculated from Fick's second law according to the concentration of chloride ion measured at different depths of the specimen. The inverse calculation process is as follows: The analytical solution of Fick's second law can be obtained from theoretical calculation as follows:

$$C(x,t)=C_0+(C_s-C_0)\left[1-erf\left(\frac{x}{2\sqrt{Dt}}\right)\right] \quad (12)$$

In Formula (12), erf is error function, and D is chloride diffusion coefficient, mm^2/s.

The method of accelerating chloride ion transport in this experiment is dry-wet cycle, so there are obvious convection zones on the chloride ion content curve at different depths. Fick's second law can better describe the transport process under pure diffusion.

Therefore, the experimental results of this experiment should take out the data after the convection zone for back calculation, as follows:

$$C(x,t)=C_0+(C_{s,\ \Delta x}-C_0)\left[1-erf\left(\frac{x-\Delta x}{2\sqrt{Dt}}\right)\right] \qquad (13)$$

In Formula (13), C_s, △X is the convective peak, unit: %, △X is the depth of the convective zone, unit: mm. Particular attention should be paid to the initial chloride ion content in concrete during the pouring process, including the selection of water and materials.

The diffusion coefficients of chloride ion calculated from Fick's second law are as follows:

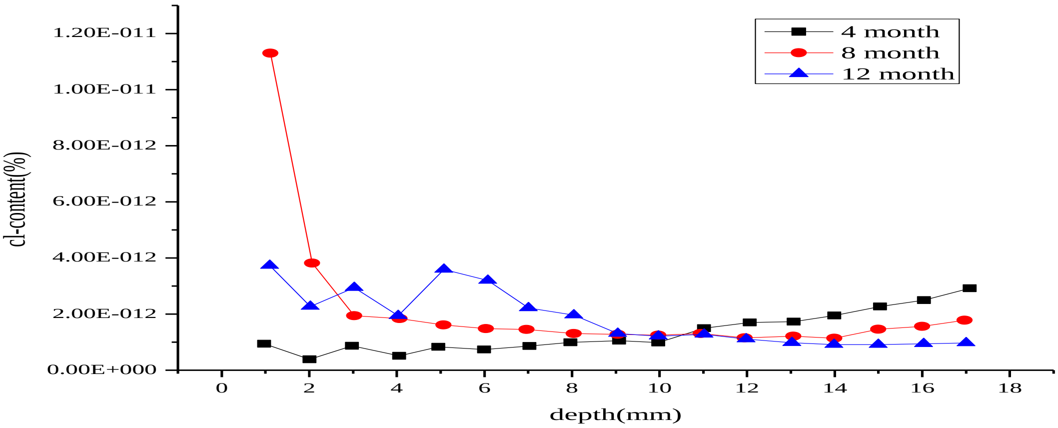

Figure 8: Chloride diffusion coefficients in different periods at 0% stress level

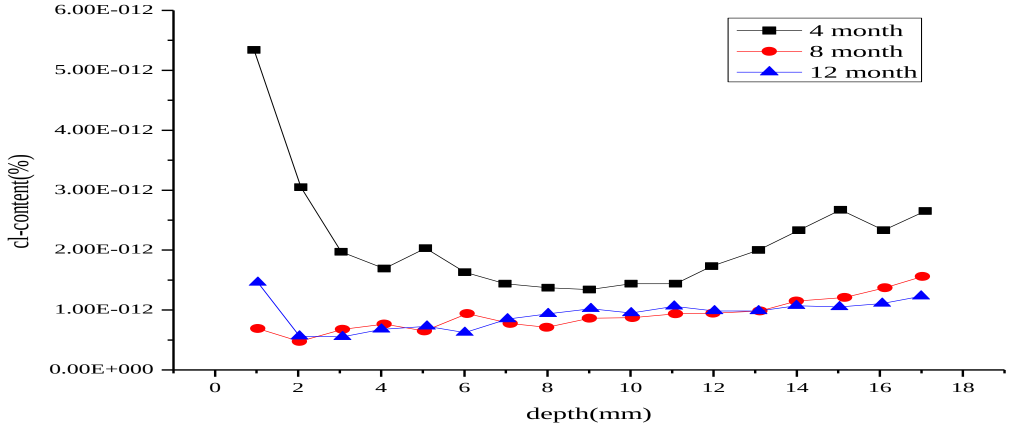

Figure 9: Chloride diffusion coefficients in different periods at 20% stress level

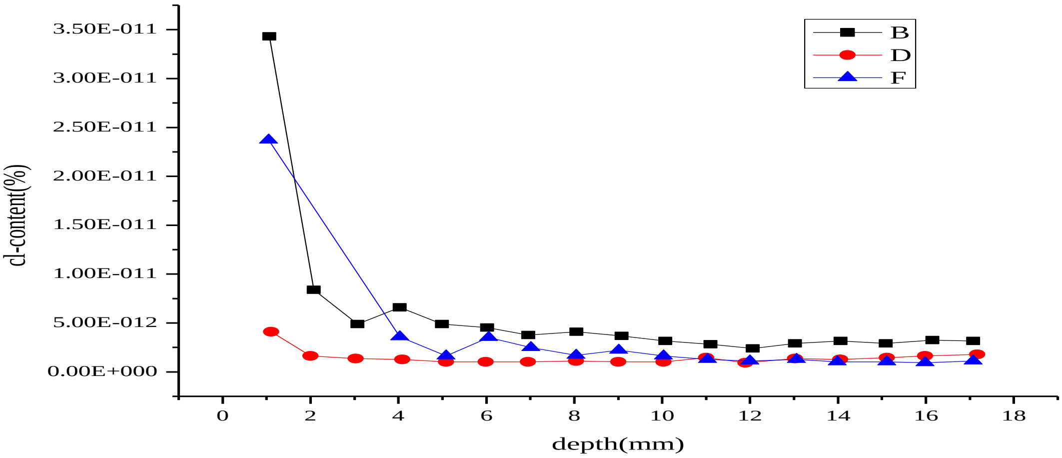

Figure 10: Chloride diffusion coefficients in different periods at 40% stress level

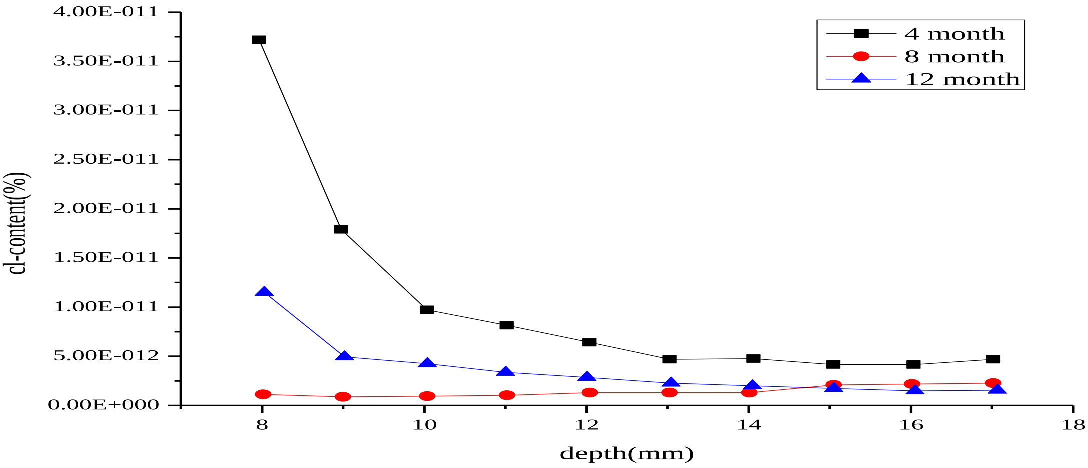

Figure 11: Chloride diffusion coefficients in different periods at 60% stress level

The results show that in the same wet-dry cycle period, except for the surface layer, the chloride diffusion coefficient changes slightly and tends to a stable value, but at different stress levels, the value has a certain change. The average value of chloride diffusion coefficient in the same period is obtained for different stress levels above.

6. Conclusion

The experimental results of chloride ion transport in concrete under different stress levels are analyzed.

The effects of stress levels on chloride ion transport depth in concrete, chloride ion transport speed in concrete, surface chloride ion concentration, depth of convection zone, convection peak value and chloride ion diffusion coefficient are analyzed.

Through the above analysis, it is found that at the initial stage of loading, the existence of compressive stress accelerates the transmission of chloride ions in concrete, and the higher the stress level, the faster the transmission. With the increase of loading time, the existence of stress hinders the transmission of chloride ions. In the same period, the transmission efficiency of chloride ions in concrete without stress is the highest.

During the second same period, the surface chloride ion concentration gradually decreases with the increase of compressive stress level, and the longer the time, the more obvious the downward trend.

The third peak chloride ion content has little change with the increase of compressive stress level.

Fourthly, with the increase of stress level, the range of convection zone tends to increase.

With the increase of dry-wet cycle period, the range of convection zone also tends to deepen under high stress level. Finally, at the same compressive stress level, the chloride diffusivity is basically unchanged with the increase of wet and dry cycles; in the same cycle, the chloride diffusivity increases with the increase of stress level, but does not show a linear relationship.

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