

Performance test on resistance to chloride ion corrosion in concrete structure added with special protection

Through accelerated chloride corrosion test in the concrete structure, the chloride ion concentrations at different depths of the concrete added with special protection and without special protection at different corrosion times are tested, and the effects of special protection on the diffusion coefficient of chloride ion and chloride ion concentration on the surface of the concrete are studied. The reduction coefficient of the chloride ion diffusion coefficient and the reduction coefficient of the surface chlorine ion concentration are introduced to carry out performance test on the effects of the special protection. And the test results show that: The special protection can reduce the diffusion coefficient of the chloride ions in the concrete by 31.3% and lower the chloride ion concentration on the surface of the concrete by 22.67%. And the special protection can improve the service life of the concrete structure in the environment of chloride ion corrosion to a relatively large extent.

Keywords: Concrete structure, chloride ion, special protection, performance test

1. Introduction

In general situation, the high alkaline environment in the concrete can form very dense oxide film on the surface of the reinforcing rebar, so as to protect the reinforcing rebar^[1-2]. However, in the coastal environment, the intrusion of the chloride ions into the concrete will lead to the deactivation of the reinforcing bar and the occurrence of rust, which may further result in the cracking of the protective layer of the concrete structure, leading to the reduction in the carrying capacity of the reinforced concrete structure and the decrease in the service life. At present, the hazards of the corrosion of the reinforcing bar have gained more and more attention. How to slow down the invasion of the chloride ions^[3-4], lower the corrosion rate of the reinforcing bar and reduce the structural damage caused by the corrosion of the reinforcing bar has become a worldwide problem. The reinforcing bar coating, the electrochemical protection, the reinforcing bar corrosion inhibitor and other methods have been widely applied in the protection of the

reinforced concrete structures in the corrosion environment. Among a number of the protection measures, the addition of the reinforcing bar corrosion inhibitor and the special protection is the most simple, economical and long-term effective method^[5-6]. Although reinforcing bar corrosion inhibitor has been widely applied and extensively studied in the durability research of the reinforced concrete structures, addition of the corrosion inhibitor into the concrete structure cannot slow down the corrosion of the chloride ion. In addition, it can play the role only when the concentration of the chloride ion on surface of the reinforcing bar reaches a certain level^[7]. At the current stage, the studies on the corrosion inhibitor are mostly qualitative analysis on the effect of the corrosion inhibitor through the relevant test, and lack of the quantitative calculation on the resistance to the corrosion of the chloride ion corrosion of the corrosion inhibitor. Hence it is impossible to provide the prediction results on the durability service life of the reinforced concrete structure after the corrosion inhibitor is used^[8-9]. At the same time, the current durability studies on the reinforced concrete structures are mostly targeted at the high strength concrete in the marine environment. However, the studies on the concrete structure with relatively low strength in the coastal concrete structures have not been reported yet^[10].

In this paper, experimental studies are carried out mainly on the durability of the concrete structures with relatively lower strength, such as the concrete structures in coastal areas, after adding the special protection. Through the test of the accelerated chloride ion corrosion in the concrete structures for 180 days, the law of changes of the chloride ion concentration in the concrete added with special protection over time is investigated. The effects of the special protection on the diffusion coefficient of the chloride ion and the surface chloride ion concentration are analyzed. The reduction coefficient of the chloride ion diffusion coefficient and the reduction coefficient of the surface chlorine ion concentration are introduced to carry out performance test on the effects of the special protection. And further predictions are made on the durability and the service life of the concrete structure added with the special protection.

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2. Test on the resistance to chloride ion corrosion in concrete structure added with special protection

2.1. TEST MATERIALS AND MIX PROPORTION

The cement is P.O42.5 ordinary portland cement; the sand is medium sand with good gradation, and the fineness modulus is 2.5; the coarse aggregate is the gravel with the maximum particle diameter of 20mm; and the reinforcing bar is class I plain round plain round bar, with the diameter of 6mm. Taking into account that the strength grades of the concrete of the concrete structures in the coastal areas are mostly C20 and C25 at present, the strength grade of the concrete test specimens that are selected in the test is C25, with the water-cement ratio of 0.6. And the concrete mix is shown in Table 1.

TABLE 1. CONCRETE MIX PROPORTION

Material	Cement	Water	Sand	Gravel	Special protection
No special protection	325	195	684	1165	0
Blended special protection	325	195	684	1165	12

The special protection is grayish powder, which is used after it is mixed with the cement and stirred evenly. The standard quantity of usage is 300 of the cementitious material, and the amount of usage is no less than 12kg per cubic meter. The special protection blending content in this test which is calculated in accordance with the mix proportion shown in Table 2 is 12kg per cubic meter.

2.2. FABRICATION OF THE TEST SPECIMEN

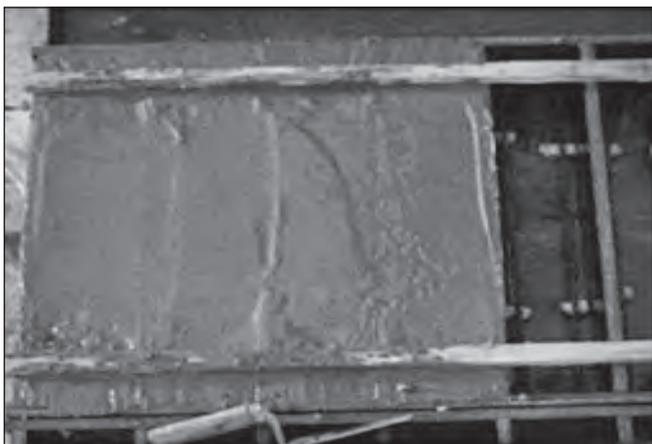


Fig. 1: Test specimens in the pouring test

Twenty-four hours after the pouring of the test specimens, the mould unloading is carried out. After the mould unloading, the test specimens are placed in the standard curing room at the temperature of $(20 \pm 2)^{\circ}\text{C}$ and the relative humidity of 97% for curing for 28 days. And the test specimens fabricated in the test on 28 d in this paper has the compressive strength of 27MPa.

2.3. CHLORIDE ION CONCENTRATION TEST

After the curing of the test specimen IS completed, the side equipped with the reinforcing bar is reserved for exposure and the other side is sealed with the epoxy resin (Fig. 2). Subsequently, it is placed in the NaCl solution at the mass fraction of 5%. And complete immersion test is carried out at room temperature. One test specimen with the special protection and one without the special protection are taken out each at the corrosion time of 30, 60, 90 and 180d respectively to test the law of the distribution of the chloride ion concentration inside the test specimen.



Fig. 2: Test specimen after being coated with the epoxy resin

After each test specimen is taken out, a percussion drill is used to drill the powder along the direction of the corrosion once every 5 mm. The mean value of the depth of sampling each time is taken as the representative value of the chloride ion corrosion depth of the test specimen. The total depth of the powder taken is 50 mm. For each portion of the powder test specimen (Fig. 3), 1g is weighed and placed into 50mL of the distilled water. After full oscillation, the mixture is allowed to stand for extraction for 48h (Fig. 4).



Fig. 3: Samples of the concrete powder



Fig. 4: Static extraction of the chloride ion

After the distribution of the chloride ion concentration with the depth is determined, the chloride ion concentration and the diffusion coefficient of the chloride ion on the surface of the concrete can be obtained by the curve fitting through Fick's second law using the equation (1) as the following, that is

$$C = C_s \left[1 - \operatorname{erf} \left(\frac{x}{2\sqrt{Dt}} \right) \right] \quad (1)$$

In which: C stands for the concentration of the chloride ion in the concrete, which is generally expressed by the mass percentage of the chloride ion in the cement or concrete; C_s stands for the concentration of the chloride ion on the surface of the concrete, which is related to the category of the environment where the concrete structure is in, the water cement ratio of the concrete and other factors; x stands for the depth of the corrosion of the chloride ion; t stands for the time that the concrete structure is exposed to the chloride ion environment; D stands for the diffusion coefficient of the chloride ion in the concrete, which is a physical quantity that describes the migration status of the chloride ions in the concrete; and $\operatorname{erf}(\cdot)$ stands for the error function, $\operatorname{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z \exp(-z^2) dz$.

3. Prediction of service life of the concrete structure added with special protection

The service life of the reinforced concrete structures refers to the time course of the reinforced concrete structure from the beginning of the use after the construction is completed to the failure of the structure, which is generally considered to be composed of three stages, that is, the corrosion induction period, the corrosion development period and the corrosion failure period. The corrosion induction period t_i in the chloride salt environment stands for the time required from the exposure of the concrete structure to the chloride environment to the time when the concentration of the chloride ions on the steel surface of the reinforcing rebar reaches the critical chloride ion concentration in the concrete.

And the corrosion development period t_c stands for the time required from the corrosion of the reinforcing rebar to the formation of the penetrating cracks in the protective layer of the concrete. The corrosion failure period is relatively short, which generally can be neglected.

In the academic community, the service life in the corrosion induction period is generally considered as the design life of the concrete. However, this kind of calculation method has ignored the development period of the corrosion and the calculation result is excessively conservative. In this paper, the definition of the service life in the two phases, that is, the corrosion induction period and the corrosion development period, is defined as the service life of the concrete structure, as shown in Fig. 5. Hence the service life t_{cr} of the concrete structures can be expressed as the following

$$t_{cr} = t_i + t_c \quad (2)$$

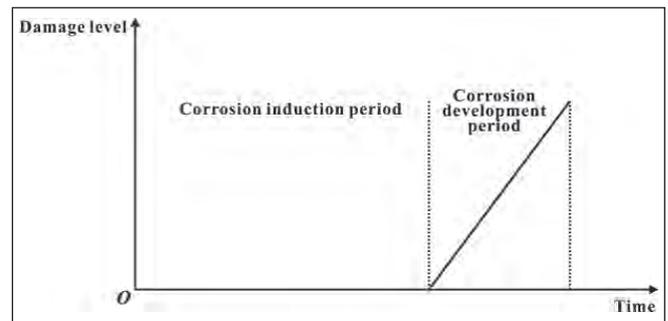


Fig. 5: Service life of the concrete structure

In this paper, the change of the diffusion coefficient of the chloride ion with time is ignored. The equation (1) is solved to obtain the calculation formula in the corrosion induction period t_i at the following

$$t_i = \frac{x^2}{4D} \left[\operatorname{erf}^{-1} \left(1 - \frac{C_{cr}}{C_s} \right) \right]^2 \quad (3)$$

In the equation: C_{cr} stands for the chloride critical concentration that induces the corrosion of the reinforcing bar.

Simplified calculation in the corrosion development period t_c can be carried out in accordance with the equation as the following, that is

$$t_c = \frac{\delta_{cr}}{\lambda} \quad (4)$$

In the equation: δ_{cr} stands for the critical corrosion depth of the reinforcing bar upon the cracking of the concrete protective layer; λ stands for the average corrosion rate of the reinforcing bar in the environment of the chloride ion corrosion before the cracking of the concrete protective layer.

The critical corrosion depth of the reinforcing bar can be calculated in accordance with the equation as the following

$$\delta_{cr} = 0.012 + \frac{x}{d_0} + 0.00084f_{cu,k} + 0.018 \quad (5)$$

In the equation: d_0 stands for the diameter of the reinforcing

bar before the corrosion; $f_{cu,k}$ stands for the standard value of the concrete compressive strength.

The average corrosion rate of the reinforcing bar is as the following

$$\lambda = 0.0116i \quad (6)$$

In the equation: i stands for the corrosion current density of the reinforcing bar.

For the corrosion current density, through the regression analysis of the corrosion rate of reinforcing bar in the concrete, the chloride ion concentration and temperature on the surface of the reinforcing bar, as well as the electric resistivity of the concrete, the expression can be obtained as the following

$$i = 0.926 \exp \left[7.98 + 0.7771 \ln(1.69C) - \frac{3006}{T} - 0.000116R + 2.24t^{-0.215} \right] \quad (7)$$

In the equation: C stands for the chloride concentration around the reinforcing bar, which can be calculated in accordance with the equation (1); T stands for the temperature on the surface of the reinforcing bar; t stands for the corrosion time of the reinforcing bar; and R stands for the electric resistance of the protective layer of the concrete.

R can be expressed as the following

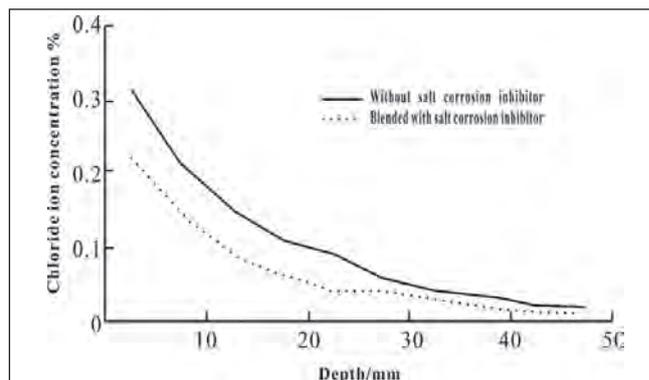
$$R = \exp[8.03 - 0.549 \ln(1 + 1.69C)] \quad (8)$$

It is assumed that the addition of the salt corrosion inhibitor will not affect the electric resistance and corrosion current of the protective layer of the concrete, and then the equation (5) - (8) can be substituted into the equation (4) to obtain the corrosion development period t_c .

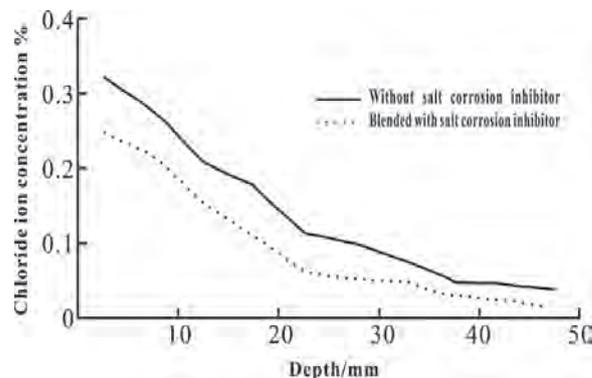
4. Test results and analysis

4.1. EFFECT OF THE SPECIAL PROTECTION ON THE DISTRIBUTION OF THE CHLORIDE ION CONCENTRATION

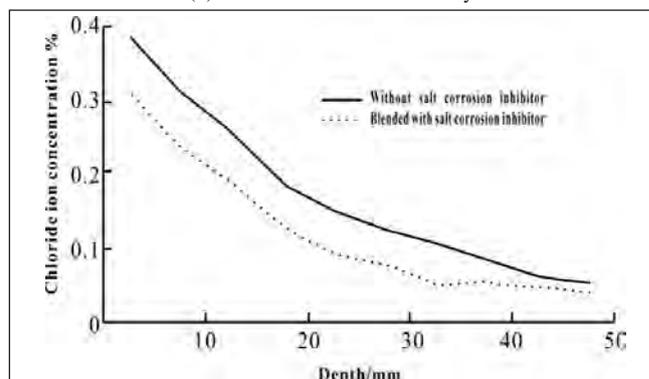
Fig. 6 shows the curve of the change in the concentration of the chloride ions with the depth of the corrosion in the test specimen added with the salt corrosion inhibitor at different corrosion times and the test specimen without the salt corrosion inhibitor. And it can be seen from Fig. 6 that, with the increase in the penetration depth, the concentration of the chloride ion decreases gradually. And the law of the distribution basically conforms to the variation rule of the chloride ion concentration in the concrete structure as described by Fick's second law. With the increase in the corrosion time, the concentration of the chloride ion at the same depth in the concrete shows an increasing trend. In addition, the chloride ion concentration shows relatively great growth trend in the range of 20mm from the surface of the concrete, and the slope of the curve is relatively large. After the penetration depth exceeds 30mm, the increase in the concentration of the chloride ion becomes slow, and the change in the concentration of the chloride ion is not large, hence the curve is relatively flat.



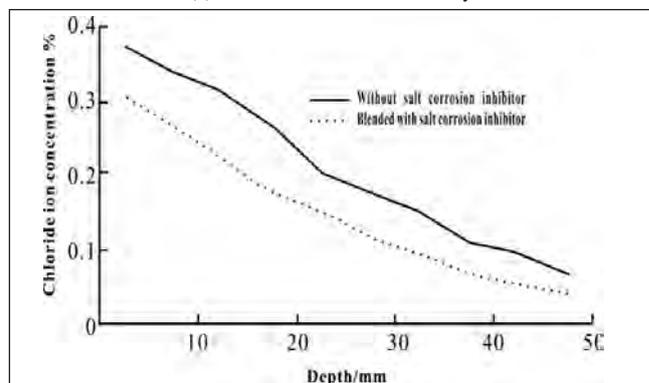
(a) Corrosion time is 30 days



(b) The corrosion time is 60 days



(c) The corrosion time is 90 days



(d) The corrosion time is 180 days

Figure 6: Curve of the distribution of the chloride ion concentration of the test specimens added with and without salt corrosion inhibitor at different corrosion times

In addition, through the comparison of the concentration of chloride ions in the test specimen added with the salt corrosion inhibitor and without the salt corrosion inhibitor on 30, 60, 90 and 180 d, it can be seen that the addition of the salt corrosion inhibitor can effectively slow down the diffusion of the chloride ion in the test specimen of the concrete, so as to reduce the concentration of the chloride ion in the test specimen and the concentration of the chloride ion on the surface of the concrete. The difference in the chloride ion concentration in the test specimen on 30d is not large. In particular, after the penetration depth exceeds 30mm, the difference in the chloride ion concentration is even smaller. The reason is that under the condition of relatively short time, the concentration of the chloride ion in the concrete is not large. And the difference in the chloride ion concentration in the test specimen added with the salt corrosion inhibitor and the test specimen without the salt corrosion inhibitor is very small. Hence, the effect of the salt corrosion inhibitor cannot be shown very significantly. The chloride ion concentration in the test specimen added with the salt corrosion inhibitor after 90d is much lower than that in the test specimen without the salt corrosion inhibitor, and the difference is significant. The reason is that with the increase in the time, the chloride ion concentration in the concrete is increased gradually. And the difference of the chloride ion concentration in the test specimen added with the salt corrosion inhibitor and test specimen without the salt corrosion inhibitor becomes relatively large. Hence it suggests that with the increase in the corrosion, the effect of the resistance to the corrosion of the chloride ion of the salt corrosion inhibitor becomes more significant.

4.2. EFFECT OF THE SALT CORROSION INHIBITOR ON THE CHLORIDE ION DIFFUSION COEFFICIENT

In accordance with the chloride ion concentration measured at different depths, the Fick's second law can be used to carry out the non-linear fitting, and the diffusion coefficient of the chloride ions at different corrosion times can be obtained, as shown in Table 2.

TABLE 2. DIFFUSION COEFFICIENT OF THE CHLORIDE ION

Category of the test specimen category	Diffusion coefficient at different immersion time (d)/(10 ⁻¹¹ ·m ² ·s ⁻¹)			
	30	60	90	180
Without salt corrosion inhibitor	8.13	6.44	5.14	4.03
Blended with salt corrosion inhibitor	5.59	4.41	3.30	2.95

Fig. 7 shows the curve of the change in the diffusion coefficient with the time. It can be seen from Fig. 7 that, for the test specimens added with the salt corrosion inhibitor and without salt corrosion inhibitor, the chloride diffusion coefficient shows an exponential decrease with the increase in the corrosion time. And the law of the changes is in accordance with the existing research result. The reason is

that with the increase in the immersion time, the structure of the cement slurry in the concrete has changed, and its porosity has been constantly reduced, resulting in the decrease in the permeability of the chloride ion accordingly, which is manifested as the reduction of the diffusion coefficient of the chloride ion with the increase of the immersion time. However, the diffusion coefficient decreases significantly in the initial stage, and the rate of decrease in the diffusion coefficient becomes slow after a certain period of time.

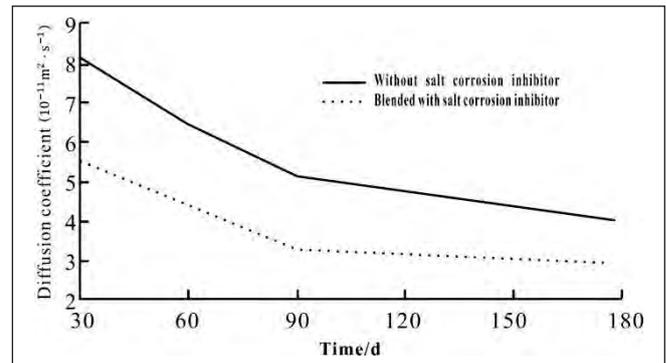


Fig. 7: Curve of the difference in the diffusion coefficient of the chloride ion with the time

The reduction coefficient of the chloride ion diffusion coefficient α is introduced to evaluate the effect of the salt corrosion inhibitor on the diffusion coefficient of the chloride ion, that is, the following can be obtained

$$\alpha = \frac{D_1 - D_2}{D_1} \times 100\% \quad (9)$$

In the equation: D_1 stands for the diffusion coefficient of the chloride ion in the concrete without the salt corrosion inhibitor; and D_2 stands for the diffusion coefficient of the chloride ion in the concrete added with the salt corrosion inhibitor.

From the data in Table 2, the value of α can be obtained from the calculation in accordance with the equation (9), as shown in Table 3. It can be seen from Table 3 that, the change in the increase of α with the time is not large. And the mean value can be obtained as the reduction coefficient of the chloride ion diffusion coefficient of the concrete added with the salt corrosion inhibitor coefficient, that is to say, $\alpha = 31.3\%$.

TABLE 3. REDUCTION COEFFICIENT OF THE CHLORIDE ION DIFFUSION COEFFICIENT

Reduction coefficient of the chloride ion diffusion coefficient at different immersion times (d) / %				Mean value / %
30	60	90	180	
31.25	31.42	35.74	26.80	31.30

4.3. EFFECT OF THE SALT CORROSION INHIBITOR ON THE SURFACE CHLORIDE ION CONCENTRATION

In accordance with the measured chloride ion concentration at different depths, the Fick's second law can be used to

carry out the non-linear fitting to obtain the concentration of the chloride ion on the surface of the concrete at different corrosion times, as shown in Table 4.

TABLE 4. CONCENTRATION OF THE SURFACE CHLORIDE ION

Category of the test specimen	Surface chloride ion concentration at different immersion times (d) /%			
	30	60	90	180
Without salt corrosion inhibitor	0.3267	0.3470	0.3914	0.4041
Blended with the salt corrosion inhibitor	0.2219	0.2788	0.3115	0.3251

Fig. 8 shows the curve of the change in the surface chloride concentration with the time. It can be seen from Fig. 8 that, the concrete chloride concentration on the surface of the concrete added with the salt corrosion inhibitor and without the salt corrosion inhibitor shows an exponential increase trend with the increase in the corrosion time. The variation law is in line with the existing research results. The increase in the chloride ion concentration on the surface of the concrete without the salt corrosion inhibitor on 30~60d is relatively slow, which is relatively fast on 60~90d; while the increase in the chloride ion concentration on the surface of the concrete added with the salt corrosion inhibitor on 30~60d is relatively fast, which is relatively slow on 60~90d. This suggests that after the addition of the salt corrosion inhibitor, the law of the distribution of the chloride ion concentration on the surface has changed. The chloride ion concentration on the surface of the concrete added with the salt corrosion inhibitor and without the salt corrosion inhibitor after 90d tends to be stabilized.

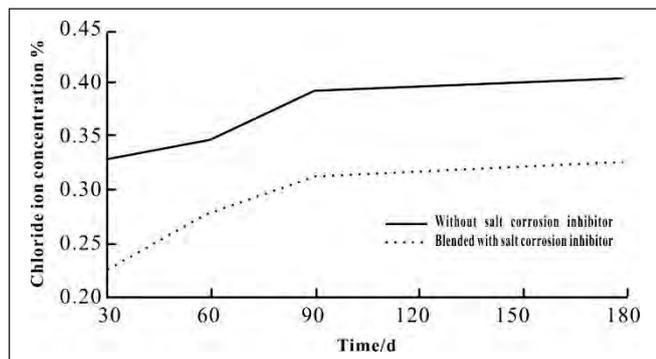


Fig. 8: Curve of the change in the surface chloride ion concentration with the time

The reduction coefficient of the surface chlorine ion concentration β is introduced to evaluate the effect of the salt corrosion inhibitor on the surface chloride ion concentration, that is, the following can be obtained

$$\beta = \frac{C_{s1} - C_{s2}}{C_{s1}} \times 100\% \quad (10)$$

In the equation: C_{s1} stands for the chloride ion concentration on the surface of the concrete without the salt corrosion inhibitor; and C_{s2} stands for the chloride ion concentration

on the surface of the concrete added with the salt corrosion inhibitor.

The data in Table 4 are introduced into the equation (10) to calculate and obtain the value for β , as shown in Table 5.

TABLE 5. REDUCTION COEFFICIENT OF THE SURFACE CHLORINE ION CONCENTRATION

Reduction coefficient of the surface chlorine ion concentration at different immersion times (d) /%				Mean value /%
30	60	90	180	
32.07	19.65	19.39	19.55	22.67

From Table 5, it can be seen that when the reduction coefficients of the surface chlorine ion concentration of the concrete on 60, 90 and 180d are compared to that on 30d, and the difference is relatively large. This is caused by the experimental error. At this point, the change of R with the time is neglected, and its mean value is taken as the reduction coefficient of the surface chlorine ion concentration of the concrete added with the salt corrosion inhibitor, that is, $\beta = 22.67\%$.

In accordance with the value of the reduction coefficient of the chloride ion diffusion coefficient α and the reduction coefficient of the surface chlorine ion concentration β obtained from the test, the service life of the concrete added with the salt corrosion inhibitor in the durability for the resistance to the chloride ion erosion can be obtained by calculation in combination with the relevant theory on the calculation of the reinforced concrete structure durability service life.

5. Conclusions

The concentration of the chloride ion in the concrete test specimen decreases with the increase of the corrosion depth, and the law of the distribution is in accordance with Fick's second law. For the concrete test specimens with the concrete strength grade of C25, the diffusion coefficient of the chloride ion in the concrete structure added with the salt corrosion inhibitor is reduced by 31.3%, so that the concentration of the chloride ion on the surface of the concrete is decreased by 22.67%. The addition of the special protection can effectively reduce the corrosion rate of the chloride ion on the concrete, thus extending the service life of the concrete structure in the corrosion induction period, but having little effect on the service life in the corrosion development period.

Acknowledgements

This work is supported by The "Thirteenth Five-Year Plan" of the "Study on the Teaching Reform of Civil Professional Education Based on the Green Skills Model" of Higher Education Scientific Research Institute of the Higher Education Society of Hebei Province (Grant No. GJXH2017-124).

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