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Effect of Chloride Erosion on Corrosion of Reinforced Concrete: A Review

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Abstract: *The corrosion of reinforced concrete in chloride environment has an important influence on the structural life of concrete. In this paper, the corrosion mechanism, influencing factors of corrosion resistance of concrete and reinforced concrete in chloride environment including water-cement ratio, aggregate volume fraction and crack width et al. were reviewed in detail. The problems that need to be further solved are also put forward. The review is believed to can provide references for the improvement of reinforced concrete corrosion.*

Keywords: *Reinforced concrete; Chloride ion corrosion; Mechanism; Influencing factors*

1. Introduction

As a traditional building material, reinforced concrete has the characteristics of excellent mechanical properties and good durability. In the process of use, scholars have found that reinforced concrete usually cannot reach the expected service life, in which the lack of durability is the main reason. Especially in the special environment, the resulting safety problems increase and the maintenance and reinforcement of buildings have also caused a lot of economic losses. It was reported that the main causes of concrete damage in the world according to their importance are steel bar corrosion, freeze-thaw cycle damage and physical and chemical action under harmful material erosion" [1]. Thus it can be seen that steel bar corrosion is the primary cause of concrete structure durability damage.

Compared with the corrosion caused by carbonization and other conditions, the corrosion time caused by chloride salt is shorter and the effect is more significant. Consequently, the steel bar corrosion is the main reason for the decrease of concrete structure durability, and chloride erosion is one of the main reasons for concrete structure durability failure [2]. Based on this, the mechanism of steel bar corrosion caused by chloride ion, the influences of water-cement ratio, aggregate volume fraction, mineral admixtures on chloride corrosion resistance of concrete, as well as the influence factors of steel bar corrosion resistance of concrete under chloride erosion were reviewed. It is believed that the review can provide reference for further research on corrosion-resistant reinforced concrete materials.

2. Mechanism of steel bar corrosion caused by chloride ion

The durability of reinforced concrete structure decreases obviously in chloride environment. Scholars have found that chloride ion is not the main element of corrosion, but more plays the role of catalyst [3]. The whole process of corrosion can be divided into the following stages: (1) The chloride ion diffuses into concrete and gradually accumulate in the pores and cover the surface of steel bar. (2) Destruction of oxide film of steel bar. When the concentration of chloride ion increases, the oxide film on the surface of steel bar is acidified continuously and the pH value decreases continuously, which finally leads to the destruction of the oxide film. (3) Corrosion of steel bar and cracking of protective layer. The corrosion of steel bar is an electrochemical corrosion process, and the reactions at the poles are as follows:

$$\text{Anode:}\quad Fe \longrightarrow Fe^{2+} + 2e^{-} \tag{1}$$

$$\text{Cathode:}\quad 2H_2O + O_2 + 4e^{-} \longrightarrow 4(OH)^{-} \tag{2}$$

The anodic product Fe^{2+} combines with the OH^- produced by the cathode to form Fe $(OH)_2$, which further reacts with oxygen to form Fe $(OH)_3$. The response is as follows:

$$Fe^{2+} + OH^{-} \longrightarrow Fe(OH)_2 \tag{3}$$

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

The residual Fe will continue to react with Fe $(OH)_3$ to form $nFe_2O_3 \cdot mH_2O$ and the product Fe_3O_4 which has not been completely oxidized. The volume of the product in the whole corrosion process is about 3 times of the amount of steel bars consumed by the reaction. The expansion of the total volume of steel bar and rust increases the force on the concrete cover, which causes the cover to crack when it reaches the ultimate strength of concrete. At the same time, the oxygen and water vapor seeping into the cracks accelerate the corrosion process, which eventually leads to the shedding of the concrete cover and the failure of the structure as a whole.

3. Influencing factors of chloride corrosion resistance of concrete

3.1. Water-cement ratio

Some scholars have found that the chloride resistance of concrete can be improved by reducing the water-cement ratio of concrete. Qian et al. [4] found that the smaller the water-cement ratio is, the higher the compressive strength of the concrete specimen is and the less the internal pores are. This shows that if the concrete shows a relatively dense state, the hindrance of chloride ion penetration into the concrete will become greater and greater [5]. The diffusion effect of ions showed an exponential trend with the increase of water-cement ratio under the condition of chloride erosion. Jin et al. [6] used chloride immersion experiment to fit the distribution curve of chloride ion concentration with erosion depth based on Fick's second law. It is concluded that at the same depth, the higher the water-cement ratio is, the higher the chloride ion concentration is. However, the water-cement ratio has a smaller effect on chloride ion diffusion coefficient when the water-cement ratio is too small.

Some scholars used other evaluation indexes to study the effect of water-cement ratio on chloride erosion, such as chloride ion migration coefficient, chloride ion binding ability and so on. Yu et al. [7] studied the chloride penetration depth of concrete specimens with different water-cement ratio using RCM method and found that the smaller the water-cement ratio is, the smaller the migration coefficient is, and the better the resistance of concrete to chloride ion penetration is. Li Peng [8] found that the chloride binding capacity of concrete increases with the decrease of water-cement ratio. They believed that when the water-cement ratio is reduced, the material structure will become more compact and the pores will be smaller, while the specific area per unit volume will be increased. As a result, the physical adsorption effect of chloride ions is enhanced, thus the binding ability of concrete to chloride ions.

3.2. Aggregate volume fraction

Some scholars have found that by increasing the aggregate volume fraction of concrete, the diffusion coefficient of chloride ion can be effectively reduced, then the chloride resistance of the material can be enhanced.

In view of the deficiency of the existing theoretical model of chloride ion diffusion in concrete, Zhou et al. [9] quantified the effects of water-cement ratio and aggregate volume fraction on chloride ion diffusion coefficient by sensitivity analysis. It was found that the increase of water-cement ratio or the decrease of aggregate volume fraction will lead to the increase of chloride ion diffusion coefficient in concrete. Wei et al. [10] measured the effects of different aggregate volume content on the resistivity of concrete by contactless resistivity meter. The resistivity reflects the transport capacity of ions in solution pores. The larger the volume of solid phase is, the weaker the ion transport capacity is, then the stronger the resistance to chloride ion erosion is. It was found that aggregate had a more obvious non-conducting effect with the larger aggregate content when the water-cement ratio was same. In addition, the resistivity of the material also showed an upward trend, and the resistance to ion erosion was enhanced. Overall, the chloride ion transport depth decreases linearly with the increase of aggregate content.

Generally, it can be concluded that the increase of aggregate volume fraction not only improves the bearing capacity of concrete itself, but also restrains the penetration of chloride ion.

3.3. Mineral admixture

Scholars have found that the addition of mineral admixtures can not only improve the performance of concrete, but also reduce cement consumption, save energy, and produce huge economic and environmental benefits.

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Many scholars have studied the effect of fly ash on the chloride resistance of concrete. Most scholars believe that there is the best amount of fly ash to inhibit the chloride corrosion of concrete, but the determination of the optimum content is still controversial. Hu et al. [11] found that the chloride binding capacity of concrete increased at first and then decreased with the increase of fly ash content, and the optimum content was 25%. Dhir et al. [12] found that the best amount of fly ash to inhibit the diffusion of chloride ion in concrete is 50%. When the content of fly ash is more than 50%, it increased the penetration of chloride ion in concrete. This is because a large amount of fly ash will reduce the value of pH in concrete, while a lower pH value will reduce the chemical curing ability of concrete to chloride ion. Feng et al. [13] also believed that 50% of fly ash had the best inhibitory effect on chloride erosion. Overall, it can be seen that the amount of fly ash mixed into concrete should not exceed 50% of the total cementitious material.

Some scholars have also studied the effects of other mineral admixtures on the chloride resistance of concrete. Erhan et al. [14] found that when the amount of slag powder is more than 50%, the electric flux of concrete has an obvious decline curve, indicating that the addition of mineral powder is of great help to improve the chloride resistance of concrete. Shi [15] compared the effects of silica fume and mineral powder on the chloride resistance of concrete by RCM method, and found that the concrete mixed with silica fume has better chloride resistance.

It was also found that the effect of chloride ion resistance is often better when using a variety of mineral admixtures. Shi et al. [16] used the electricity method and artificial sea immersion method to test the chloride resistance of concrete mixed with only 70% mineral powder and mixed with 21% fly ash and 49% mineral powder. The results showed that the effect of chloride resistance of concrete with multiple mineral admixtures was better than that of concrete with single mixtures. The combination of fly ash and mineral powder complement each other and give full play to their respective advantages.

4. Influencing factors of reinforcement corrosion resistance of concrete under chloride erosion

In the chloride environment, the corrosion of reinforced concrete is mainly related to the concrete itself and environmental conditions. The former is the performance of concrete itself. The effects of water-cement ratio, aggregate volume fraction and mineral admixture on chloride corrosion resistance have been discussed above. These factors affect the corrosion of steel bar by affecting the performance of concrete. On the other hand, the environmental conditions mainly depend on temperature, humidity, critical chloride concentration, types of chloride and so on. In this section, the effects of environmental conditions and other factors on the corrosion resistance of concrete are discussed in detail.

It was reported that the crack has an obvious effect on the corrosion rate. Chen et al. [17] took the reinforced concrete slabs under continuous load as the experimental object to study the effect of cracks on the corrosion rate of steel bars under the environment of chloride immersion. The results showed that when the crack width of concrete surface is not larger than 0.11mm, the chloride ion diffusion rate is less affected. However, the chloride ion diffusion rate increased significantly with the increase of crack width. The chloride ion diffusion rate was almost no longer affected by the change of crack width when the crack width increased to 0.3mm. The transition zone between steel bar and concrete interface also has an important influence on the corrosion of steel bar. Soylev et al. [18] have found that the occurrence of pores in the interface transition zone increased the corrosion probability and speed of steel bar due to vibration, water secretion, heterogeneity and so on.

Enevoldsen [19] found that the relative humidity of concrete had a great influence on the broken blunt steel bar. The corrosion reaction of steel bar will stop when the relative humidity is lower than a certain critical value. Some scholars [20] have come to the conclusion that when the relative humidity is 80%-90%, it is most suitable for the diffusion of the combination of ions and gases. As a result, the corrosion rate of steel bar is increased to the maximum value.

Many scholars have studied and discussed the influence factor of chloride ion critical value of steel bar corrosion in chloride environment. It was reported that the thickness of the protective layer was positively correlated with the critical chloride concentration of steel bars, and the water-cement ratio was negatively correlated with the critical chloride concentration of steel bars [21]. Ba et al. [22] found that the higher the water-cement ratio is, the lower the critical concentration of chloride ion is. The addition of mineral admixture reduced the critical concentration of chloride ion, but at the same time improved the chloride corrosion resistance of concrete.

The oxygen concentration in the material also has a great influence on the corrosion rate of steel bar.

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Zhou et al. [23] measured the corrosion current density and corrosion amount of steel bar under different oxygen concentration and environmental humidity. The results showed that the corrosion rate of steel bar increased with the increase of environmental humidity, but decreased rapidly when the humidity reaches 95%RH. The corrosion rate increased with the increase of oxygen concentration when the humidity and the internal saturation of concrete is high.

5. Conclusions

Taking the corrosion of reinforced concrete as the main research object, this paper introduces the mechanism of steel bar corrosion caused by chloride ion, and summarizes the influence factors of chloride corrosion resistance of concrete, eg., water-cement ratio, aggregate volume fraction, mineral admixture and so on. The main conclusions are as follows:

1) The smaller the water-cement ratio of concrete is, the stronger the resistance to chloride corrosion is. At the same time, it is necessary to control the influence of curing conditions.

2) The larger the aggregate volume fraction of concrete is, the stronger the chloride resistance is.

3) The proper addition of mineral admixture can significantly improve the chloride resistance of concrete. It is generally believed that the content of fly ash should not exceed 50%, and the compound addition of fly ash, mineral powder and silica fume has better anti-chloride erosion effect than that of single addition.

4) In addition to water-cement ratio, mineral admixture and other factors affect the corrosion of steel bar by affecting the chloride corrosion resistance of concrete. The concrete cracks, steel bar-concrete interface transition zone, concrete relative humidity, critical value of chloride ion, oxygen concentration also have important influences on steel bar corrosion.

The corrosion of reinforced concrete under the condition of chloride salt is a problem of the joint action of many factors. At present, most studies only start from one aspect, and less consideration is given to the joint action of several factors. In addition, there are differences in steel bar corrosion between laboratory environment and natural exposure conditions. In order to solve the difficulties in practical application, the corresponding relationship between them is also a key problem to be considered in the next step.

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