Destruction Mechanism and Protective Measurements of Saline Soil on Reinforced Concrete

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Abstract. The corrosion of reinforced concrete in a saline soil corrosive environment mainly contains the erosion of Cl^- and SO_4^{2-}. In this paper, the failure principle of reinforced concrete in saline soil environment in recent years has been summarized. Moreover, the related works on the corrosion mechanism of reinforced concrete under saline soil environment in recent years have been introduced.

Keywords: Saline Soil; Reinforced Concrete; Corrosion Mechanism.

1. Introduction

The content of soluble salts in saline soil is more than 0.3%, and these salts always possess collapsibility, salt swelling and corrosiveness. Saline soil is widely distributed in China, the area is about 2.0×10^5 km^2, which accounts for about 2.1% percentage of total land area of China. Common saline soils include the coastal saline soil, eastern semi-arid-semi-humid saline soil, central arid saline soil, western strong arid saline soil and extra-dry basin saline soil. According to the type of anion groups in saline soil, the saline soil can be divided into: chloride saline soil, carbonates saline soil, and sulfate saline soil, in which sulfate saline soil is the most widely distributed.

2. Damage mechanism of saline soil

The saline soil always contains Cl^-, Mg^{2+}, Ca^{2+}, SO_4^{2-}, CO_3^{2-} and other ions. Due to the existence of these ions, they can react with hydrated products and cause different degrees of damage to reinforced concrete. Among these ions, Cl^- and $SO4^{2-}$ make the serious corrosion on the reinforced concrete.

In saline soils, when the molar ratio of chloride ions to acid ions is less than 0.6, the saline soil is defined as sulfate saline soil. The corrosion of SO42- to reinforced concrete is a complex process, which contains chemical reaction and physical action. SO_4^{2-} corrosion is a kind of expansive damage, which can induce to the crack of concrete, concrete spalling, and exposing of steel. All these results can make bad effects on the service life of concrete structure.

2.1 Corrosion mechanism of sulfate saline soil

2.1.1 Chemical action

The resources of sulfate contain two types: (1) the concrete itself contains SO_4^{2-}, which can react with hydrated products to form ettringite, gypsum, tombstone, and other corrosions. (2) the SO_4^{2-} comes from environment, which invades into concrete and reacts with hydrated products. According to the generated products' crystalline, the corrosion mechanisms are different. Although the type and crystalline of generated products are different, the volume of products will increase during the formation process. According to the type of generated product's crystalline, the destruction forms of SO_4^{2-} can be divided into the following forms:

① Ettringite crystal form

When the concentration of SO_4^{2-} in concrete is low, the SO_4^{2-} in the environment invading into concrete will react with the hydrated product $Ca(OH)_2$ to form gypsum. The formed gypsum can further react with calcium sulfoaluminate hydrate to form ettringite (Aft).

The solubility of Aft is very low and it contains a lot of bound waters. The volume of Aft is about 2.5 times of the volume of calcium sulfate hydrate. Therefore, this solid phase reaction can increase the volume significantly. The shape of generated Aft is needle bar and can extend to the surrounding environment, inducing to a large internal stress and make the crack of concrete.

②Gypsum crystal form

When the concentration of SO_4^{2-} in concrete is higher than 1000 mg/L. In addition to the generated Aft, gypsum crystals will be also generated. When the concentration of SO_4^{2-} is further increased (higher than 8000 mg/L), the main product will become to gypsum.

The appearance of gypsum will increase the volume by 1.24 times [3], which can significantly increase the internal stress of concrete, and the risk of concrete expansion and cracking will also be increased significantly. At the same time, the stability of hydration products C-S-H will be influenced due to the consumption of $Ca(OH)_2$. So the strength and durability of concrete will be deteriorated.

③Magnesium salt crystal form

Compared with other sulfates, magnesium sulfate will make the most significant damage to concrete. Because besides SO_4^{2-}, Mg^{2+} is also an erosion resource. Both of them will accelerate the deterioration of concrete.

The formation of gypsum and ettringite will increase the risk of concrete's cracks. For $MgSO_4$ both of Mg^{2+} and SO_4^{2-} will react with $Ca(OH)_2$ and decrease the content of CH. The consumption of CH will disrupt the environment balance of C-S-H, inducing the decomposition of C-S-H. This will greatly reduce the cohesion and the strength of concrete.

2.1.2 Physical action

When the SO_4^{2-} invades into the concrete, the SO_4^{2-} will form crystal, the formed crystal will induce to the spalling of concrete and make damage to concrete.

2.1.3 The related research about SO_4^{2-} attack

Currently, the research on sulfate erosion of concrete mainly focuses on the erosion damage. Monteiro [4] studied the effect of concrete's mix proportion and condition on the sulfate attack resistance of concrete. It can be found that when the added $CaSO_4$ was excessive, the concrete was destroyed in a short time. However, when the concrete was added 25% and 45% fly ash, the expansion ratio of concrete was obviously reduced; Researcher Luo[5] studied the effect of concrete's strength on its mechanical properties in sulfate and chloride saline environments. It was found that the sulfate attack resistance property of concrete was improved with the strength of concrete increasing. Based on the STADTIUM, Sarkar[6] added a new module (new numerical method) to simulate the degradation process of C-S-H gel in the sulfate environment. Moreover, continuous damage method was added in this model to simulate the mechanical damage of concrete.

There are also a lot of researches focused on improving the sulfate resistance of concrete. Among these studies, through adding admixtures is an effective method to improve concrete's sulfate resistance property and it has been a research hotpot. Many studies found that compared with concrete mixing with slag and fly ash, the concrete mixing with silica fume showed the best sulfate resistance property. Researcher [8] studied the effect of silica fume on the properties of concrete. They found that the introduced silica fume could increase the early strength of concrete, meanwhile the final strength of concrete was also improved. Therefore, the sulfate resistance property of concrete mixing silica fume improved obviously. Moreover, researcher [9] studied the effect of water-reducing agent's type on concrete's sulfate resistance property, they found that compared with naphthalene-based water reducing agent, the concrete containing polycarboxylate superplasticizer showed better sulfate resistance property.

2.2 Corrosion mechanism of chloride saline soil

In chloride saline soil, the molar ratio of chloride to sulfate is greater than 4. The corrosion of Cl^- is mainly chemical action [10, 11]. The intrusion of Cl^- not only destroys the passivation film on the surface of steel but also forms a corrosion battery. The intrusion of Cl^- increases the electrical conductivity, which greatly accelerates the corrosion of steel and seriously affect stability and safety of the building structure.

There are two main ways for the intrusion of Cl^-: (1) The intrusion of Cl^- is due to the concentration gradient difference between the environment and concrete. (2) The other way for the intrusion of Cl^- is due to the added admixtures, mixing water and aggregates containing Cl^-.

2.2.1 Chemical action

(1) The destroy of passivation film on the surface of the steel: Cl^- is a kind of active anion, when Cl^- invades into concrete, it will destroy the passivation film and break the equilibrium state between passivation's dissolution and repair, which will accelerate the destruction of reinforced concrete.

(2) Formation of battery to corrode the steel: when the passive film on the surface of steel is broken, the iron matrix of the steel will be exposed. It will produce potential difference between steel with passive film and steel without passive film. Some small corrosion pits are formed on the surface of exposed steel. Because the surface area of steel with passive film is much larger than steel without passive film, the development of the corrosion pits is greatly accelerated.

(3) Depolarizing effect: The intrusion of Cl^- not only breaks the passive film on the surface of steel, but also accelerates the electron transfer. Cl^- reacted with Fe^{2+} to form $FeCl_2$, this chemical reaction accelerates the corrosion of surface of steel. Moreover, the Cl^- intruding into concrete will not be consumed and can further react with Fe^{2+}, which can cause great harm to steel in concrete.

2.3 Critical concentration of Cl^-

According to previous studies, for reinforced concrete the wrapped concrete can protect the steel. Because the strong alkaline solution of concrete can form passive film to isolate the cations and prevent steels from being damaged by cationic oxidation. However, when the concentration of Cl^- reaches a certain value, the passive film on the surface of steel will be broken and the steel will be exposed and corroded. The corresponding concentration of Cl^- is defined as the critical Cl^- concentration.

In the environment of saline soil, it is important to clarify the critical concentration of Cl^-. There are many methods to define the critical concentration of Cl-[12]: (1) Through calculating the mass percentage of Cl^- in concrete; (2) Using the ratio of the concentration of free Cl^- to the concentration of OH^-. (3) Utilizing the molar concentration of free Cl- in the solution of concrete.

The research on the critical concentration of Cl^- can be tracked back to 1967. Hausman measured the corrosion potential and found that the critical concentration of Cl^- was less than 0.1 mol/L. Later, a large number of researchers used different methods to study the critical concentration of Cl^- in reinforced concrete [12-15]. Such as Coni[12] used the potentiodynamic test method to study the critical Cl^-; Xiaobing Song[15] used potentiostat to study the critical concentration of Cl^-. It can be found that under different testing conditions and testing methods the obtained critical concentration of Cl^- is different.

2.4 Diffusion model of Cl^-

When the Cl^- invades into the concrete, the Cl^- will exist in the following three forms[16-21]: (1) Existing in the form of chemical combination through reacting with the hydration product of cement. (2) Existing in the form of physical combination (3) Existing in the pore solution of concrete without combination. The transport of Cl^- is a combination of different transport modes, the transport speed of Cl^- will directly affect the corrosion of reinforced concrete, which will greatly affect the durability of concrete.

Many researchers have carried out a lot of researches on the diffusion model of Cl^-. Researchers obtained the relationship between Cl^- diffusion coefficient and time by studying the diffusion process. Moreover, the concentration distribution of Cl^- in concrete was also clarified. On this basis, some researchers used the immersion test to study the relationship between the diffusion coefficient D of Cl^- and concrete mix proportion parameters (including water/cement ratio and aggregate composition, etc.).

There are many types of aggressive ions in saline soil. Therefore, it is necessary to consider the damage and failure process of concrete under the synergistic effect of multiple ions. When the concrete was under the saline soil environment containing both Cl^- and SO_4^{2-}, the diffusion process of Cl^- in concrete was studied and found that the mass fraction of Cl^- in C20 and C40 was higher than that of SO_4^{2-}. Moreover, the distribution of Cl^- in the vertical and radial directions of concrete is not uniform. P. J. Tumidajski compared transfer process of Cl^- in the OPC and slag concrete, respectively. They found that compared with single Cl^-'s erosion, the added SO_4^{2-} decreased the erosion depth of OPC. However, the added SO_4^{2-} increased the erosion depth of Cl^- in slag concrete.

3. Protective measurements

For preventing the damages brought by the saline soil, there are many commonly methods for preventing and controlling the corrosion of concrete in saline soil environment. They are shown as below:

3.1 Improving the properties of concrete

Improving the properties of concrete is an effective method to enhance the sulfate resistance of concrete. The high-performance concrete was prepared through selecting different grades of sand, stone and adding the suitable admixture. The prepared high-performance concrete has a denser structure and lower porosity, which could significantly prevent the intrusion of harmful ions (Cl^-, SO_4^{2-}). However, it is more suitable for the high-performance concrete to be used under saline soil with low concentration of harmful ions. For improving the performance of concrete, there are more requirements for the original materials, preparation process, and the addition of admixtures.

3.2 Surface coating

Reducing the permeability of concrete is a common method to improve the corrosion resistance of concrete. Coating can effectively increase the compactness of the concrete' surface. There are some commonly used coating materials, such as resin-based material (the main component is epoxy resin) and water-based material (water-soluble polymers, which can form a protective film after drying). Among these materials, epoxy resin coating is used more widely. However, the epoxy resin is often affected by the environment.

3.3 Cathodic protection

Through wrapping active metal and alloys (common sacrificial anode alloys include zinc alloy, magnesium alloy and aluminum alloy) on the surface of steel, these wrapped active metals or alloys can work as anodes and replace the steel to be corroded (loss the electron), so the steel is protected. Moreover, through adding an impressed current is another effective method to protect the steel. The added external electric field can adsorb the Cl^- to the surface of concrete, and the Cl^- can be removed through precipitation or react with metal scraps on the concrete surface.

4. Conclusion

A lot of achievements have been made in the research on the corrosion of reinforced concrete in saline soil environment. However, most of them still have limitations and lack of certain characterization methods. The further research should use more electrochemical methods to study the corrosion process of reinforced concrete in saline soil environment.

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