Analysis of Corrosion Prevention Measures for Reinforced Concrete in Cross-sea Bridges

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Abstract. Due to the bad environment and the poor anti-corrosion effect of reinforced concrete, cross-sea bridges is easy to cause bridge damage. Therefore, to ensure that the cross-sea bridge reaches a normal service life, a series of anti-corrosion measures must be taken to deal with reinforced concrete. This paper aims at the corrosion problem of cross-sea bridges and researches the protection effect of different anti-corrosion measures. At the same time, this paper provides a detailed understanding of the corrosion principles, application scenarios, and actual prices, based on which a comparative analysis of the whole-life costs of optional additional anti-corrosion measures is carried out. The paper concludes that the corrosion of concrete has both physicochemical effects and that the corrosion of steel reinforcement is dominated by the involvement of iron in the primary cell reaction. External coating protection can be applied to completed bridges, and corrosion-resistant reinforcement and concrete as well as applied current protection methods can be used for bridges under design. This paper analyses the corrosion of cross-sea bridges in general situation, systematically describes the respective corrosion mechanisms of steel and concrete in the marine environment, points out the specific advantages and shortcomings of the various types of corrosion protection measures for steel and concrete, and proposes that protection should be increased at the time of design rather than spending a large amount of money on repairs after the corrosion damage happened. Also, provide a guide in the design and maintenance of the overseas bridges.

Keywords: Cross-sea bridge, reinforcing steel, concrete, corrosion.

1. Introduction

In recent years, the reinforced concrete industry has been in a stage of rapid development and has been widely used in the field of Bridges. However, reinforcement steel and concrete in the Marine environment for a long time will cause very serious corrosion, resulting in structural damage to the bridge. At present, there are still many cross-sea bridges facing concrete durability problems at home and abroad. Nearly half of the bridges were damaged by corrosion in the early 20th century due to the extensive use of de-icing salts in the United States [1]. In addition, the Krk Bridge in Croatia, completed in 1980, is located in the southwest of the city of Zagreb, the bridge is located in an environment of seawater content of close to 3. 5%, in only six years of use, the bridge corrosion is serious, and forced to re-strengthen [1]. A similar phenomenon has occurred in China. The Shimen Bridge in Chongqing, completed in 1985, was found during an overhaul in that the piers were severely corroded and the concrete was cracked, which cost a lot of money[2]. This is mainly because people for the bridge corrosion problem failed to give enough attention, resulting in many reinforced concrete structures successively experiencing disease and deterioration so that the structure inevitably appeared in a variety of different degrees of hidden problems, defects, or damage, which in turn led to the reduction of structural durability, or even failure [3]. Therefore, to ensure the normal use of the bridge, it is necessary to carry out anti-corrosion treatment of reinforced concrete.

At present, countries wish to increase the service life and simplify maintenance without changing the design of reinforced concrete foundations for sea-crossing bridges, and corrosion prevention measures for them have been studied in some detail and with a great variety. However, such research generally involves only the improvement of its materials or the help of additional measures, such as the use of high-performance concrete, anti-corrosion coatings, and other traditional methods [4]. The climate is so complex and variable that the use of a single method is unlikely to be suitable for all projects. New corrosion protection measures such as composite corrosion protection techniques and multifaceted corrosion protection measures are gradually changing this limitation and improving the corrosion protection capability of the project [4]. Most of the constructions use only a single additive or admixture, which has many limitations. Drawing on the experience of foreign advanced technology and composite technology, composite anticorrosion additives mainly improve the concrete structure of its density, and strength, reduce defects, enhance its ability to resist corrosion, and add a rust-blocking component to prevent the invasion of harmful media, etc. [4].

Given these circumstances, this paper aims to explore various forms of corrosion prevention measures for steel and concrete, to figure out their principles, applications, and prices, and to compare them with each other on this basis. In addition, this paper mainly explores the most likely situation in the actual construction and gives the corresponding reasonable improvement suggestions and remedial measures.

2. Exploration of the Principle of Corrosion of Reinforced Concrete

2.1. Concrete Corrosion Mechanism

Concrete is a porous substance that has been immersed in the ocean for a long time. Due to these voids, chloride ions, magnesium salts, sulfate, and other substances can enter the concrete and erode it, leading to a significant reduction in its durability. Concrete corrosion includes physical, chemical, and microbiological corrosion[2]. Physical corrosion mainly refers to the corrosion caused by simple physical dissolution without chemical reaction, chemical corrosion refers to the chemical reaction between ions in seawater and ions contained in concrete, and microbial corrosion refers to the fact that some substances produced by microbial metabolism will cause corrosion to concrete.

Freeze-thaw damage of concrete is a physical corrosion, which mainly dislodges the concrete surface and reduces the mechanical properties of concrete[2]. The type of cement, water-cement ratio, pore filling degree, and concrete volume all affect the freezing resistance of concrete. In particular, the larger the volume of concrete, the better the freezing resistance and the less prone to freeze-thaw damage[2].

The most typical chemical corrosion of concrete is chloride ions erosion, where chloride ions react ion-chemically with hydroxides in the cement to form chlorides. Since chloride ions are larger than hydrogen ions, they take up more space and thus damage the concrete.

Some microorganisms in seawater can cause corrosion of concrete, also known as microbial corrosion, which is mainly manifested by the loosening of the concrete surface, contamination, and mortar detachment[2].

2.2. Corrosion Mechanism of Reinforcing Steel

Reinforcing steel and concrete together in the component, concrete mainly bears a compressive role, and reinforcing steel mainly bears a tensile role. Due to the hydration of cement, the environment after the reaction is strongly alkaline, the PH can reach 12, and the passivation film has just been generated[5], the specific hydration reaction is as follows:

$$2(\mathrm{CaO}-\mathrm{SO2}) + 6\mathrm{H2\ O} \rightarrow 3\mathrm{CaO}-2\mathrm{SO2}\ -3\mathrm{H2\ O}+3\mathrm{Ca(OH)2}\,,\, 2(\mathrm{CaO}-\mathrm{SO2}) + 4\mathrm{H2\ O} \rightarrow 3\mathrm{CaO}-2SO2\ -3\mathrm{H2\ O}+\mathrm{Ca(OH)2} \quad (1)$$

However, the passivation of reinforcement steel does not happen all the time. Because concrete is a porous substance, many corrosive ions in seawater will enter the concrete through the pores, and the accumulation over a long period will form a primary battery, causing corrosion of the reinforcement steel. The concrete corrosion reaction is as follows:

Neutral anodic reaction: $Fe \rightarrow Fe^{2+} + 2e^-$; the cathodic reaction: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$

Eventually, the ions produced at the cathode will react with the ions produced at the anode to produce ferrous hydroxide, and when there is too much oxygen, there will be an oxidation reaction to form iron hydroxide, which will become red rust iron trioxide after drying[5].

3. Common Corrosion Prevention Methods for Reinforced Concrete

3.1. Corrosion Prevention Measures for Reinforcing Steel

From the above, it can be seen that the corrosion of steel is mainly caused by primary battery reaction, which involves iron and seawater ions, so the prevention method is to reduce or isolate the occurrence of such a reaction. At the physical level, through various types of media to prevent ions in seawater from direct contact surface, the key lies in the treatment of concrete and steel. At the chemical level, under the premise of ions contacting the rebar, use chemical principles to delay or block the occurrence of the reaction, mainly sacrificial anode protection and impressed current cathodic protection.

3.1.1 Use of poorly permeable concrete

Calcium hydroxide, the raw material of ordinary concrete, with the chemical composition of $Ca(OH)_2$, generates a large number of hydroxide ions during hydration, producing an environment with a high pH value, which protects the steel reinforcement. However, since there are microscopic pores in concrete, various salt ions in seawater will enter the interior to neutralize or penetrate the protective layer [6] and corrode the steel. Therefore, reducing the water permeability of concrete can protect the reinforcement. This method requires appropriate modification of the proportion of each mixture during the mixing of concrete and adding mineral admixtures, this method has less extra cost.

3.1.2 Sacrificial anode protection method

Normally, the iron in the rebar acts as the anode and the seawater provides the electrons as the cathode, and these two are connected to form a primary cell reaction that causes corrosion. At this time, use an extra metal which is more reducing than iron, connected in the rebar structure as the new anode level, due to its stronger activity, the chemical reaction will consume the external metal first, which protects the rebar. However, this method consumes a lot of anodes. For common anode materials such as aluminum, magnesium, and zinc, the average price is 1400-2800 USD / ton, and the corroded anode needs to be replaced in time. If the bridge scale is large, it will need a huge consumption of material. The anode alone is connected to the outside, which means this method can’t effectively cooperate with other measures, even if the internal steel is safe, it will still be corroded alone. However, they only need to be checked and replaced regularly at a later stage, which makes maintenance easy.

3.1.3 Imposed current protection method

The Imposed current cathodic protection involves inserting an external electrical level into the seabed to energize it, and let the rebar at a low voltage, which disrupts the conditions for the electrochemical reaction and prevents the corrosion reaction from occurring [7]. This method is very effective as it actively disrupts the chemical reaction. However, it requires a specialized team to control the electricity and make real-time monitoring, as well as pay attention to the potential environmental impact of the discharge, and requires long-term maintenance investment.

3.1.4 Reinforcement material and reinforcement coating

Due to the high design requirements of cross-sea bridges, high-performance steel bars are generally used, so ordinary construction steel bars are not discussed in this paper. High-performance rebar itself has a certain level of anti-corrosion properties, about 560 USD / ton. To further enhance its anti-corrosion properties, anti-corrosion alloy steel can be used, at the price of about 980 USD / ton. Its performance is significantly improved, but the unit price is also higher, and its large-scale use may lead to an overall high cost. The treatment of the outside of the steel bar can also effectively improve its service life. Galvanization can effectively isolate the inside and outside of the steel. The zinc oxide film is very dense, it is difficult to be corroded by elements in seawater, and the galvanizing process is mature, the finished product is about 800 USD / ton. Inorganic material spraying is also very effective, through electrostatic spraying of epoxy resin and other materials on the surface of the steel, it has almost no reaction with the outside world before the coating ages, the price of about 725 USD / ton.

3.2. Anti-corrosion Measures for Concrete

The practice of most projects shows that, under the action of natural environmental conditions, concrete may gradually appear to loosen, spalling, and other problems from the outside to the inside of the leakage. If not strengthened its repair and management, timely reinforcement and repair will make its endurance drastically reduced, ultimately leading to a substantial reduction in service life, endangering the safety of production and operation. Therefore, the work should recognize that seawater will affect the durability of concrete. At the same time, it also needs to find some effective measures and techniques to solve the problem of concrete corrosion [8].

3.2.1 External surface coatings

For the concrete structure of the seaside bridge, its surface coating should have excellent weather resistance, resistance to salt spray, and marine atmospheric corrosion in the effective protection period not serious chalking and discoloration, peeling, cracking, and other phenomena [9]. Through polyurethane cool, cementitious polymers, aliphatic poly service of the three coated concrete protective layer comparison data can be concluded, in terms of improving the ability of concrete resistance to chloride ion penetration, the three coatings of the ability of the size of the order of the aliphatic poly vein coating on the chloride ion diffusion coefficient of the most obvious reduction, polyurethane vinegar coating followed by cementitious polymer waterproofing coatings the lowest [10].

3.2.2 Use of crack-resistant concrete

Performance concrete is a kind of concrete with high durability, high strength, high workability, and dimensional stability. To make high-performance concrete, in addition to reasonable proportion design, correct raw material selection, and strict quality control of construction, the main thing is to add high-efficiency water-reducing additives and admixtures (such as slag, fly ash and silica fume, etc.) in the concrete mix. It can make the mix achieve the same degree of work as the unadulterated concrete to reduce the amount of water added, and the inclusion of admixtures can improve both the fluidity of concrete, but also improve its strength and durability [11].

For most of the concrete using a single additive or admixture, there are many limitations. Drawing on the experience of foreign advanced technology and composite technology, composite anti-corrosion additives can significantly improve the corrosion resistance of concrete structures, the main factor is that the additives contain concrete corrosion-resistant components, which can effectively enhance the corrosion resistance of concrete. The air-entraining and compacting components in the additives can effectively exclude the air inside the concrete, which in turn enhances the strength and compactness of the concrete, greatly reduces the corrosive media invasion pathway, and achieves the concrete's anti-erosion ability [4].

3.2.3 Silane impregnation

Their modified compounds are currently the most widely used and most effective protective agents. On the surface coated with organosilicon hydrophobic agent, similar to the surface of lotus leaf, water on which water can not be wet but forms water droplets, thus preventing the infiltration of harmful media (such as chloride ions) with water as the carrier, to achieve the purpose of protection of reinforced concrete. This kind of protective agent has the advantages of good waterproof, strong penetration, acid, and alkali resistance, UV resistance, and long-lasting protective effect (up to 30 years ~ 50 years), after treatment of the concrete to maintain the permeability, does not change the surface effect of the concrete, etc., and unlike film coatings will not be blistering off. The disadvantages are that it contains some toxic, harmful, or flammable components, which have some impact on the environment, and it cannot be penetrated by pressurized water, so it cannot be used on concrete structures in the water section [12].

3.3. Comparative Analysis

Table 1. The durability of different corrosion protection measures [13]

Serial number	Anti-corrosion measures	Extending the durability of structures
1	Use of poorly permeable concrete	---
2	sacrificial anode protection method	Not suitable for long-term use
3	Applied current protection method [12]	50 years or more
4	Stainless Steel Bar[12]	10 times longer lifespan
5	Coatings, paints[12]	15-20a
6	Use of crack-resistant concrete	---
7	Silane impregnation[12]	15-20a

Table 1 demonstrates a comparison of the durability of different corrosion protection measures, and it can be seen that there are differences in the amount of time that can be extended by different corrosion protection measures. First and foremost, stainless steel bar protects the structure for the longest period, increasing the structural life by a factor of 10. Secondly, the applied current protection method can extend the durability of the structure for more than 50 years. Finally, coatings, paints, and silane impregnation methods can extend structural durability by 15-20 years. Overall, the effectiveness of different corrosion protection measures varies considerably, and choosing the right corrosion protection method can significantly extend the durability of a structure.

4. Conclusion

In this paper, for the corrosion protection of reinforced concrete in cross-sea bridges, the corrosion mechanisms of steel and concrete are first investigated. Among them, concrete corrosion includes physical, chemical, and microbiological corrosion, and the main form of rebar corrosion is chemical cell corrosion. Subsequently, for these corrosion mechanisms, the main current corrosion prevention methods are examined in detail. Among them, steel reinforcement has a sacrificial anode protection method, applied current protection method, steel reinforcement strengthening as well as weakening concrete permeability. For concrete, there are external surface coatings, increased crack resistance, and silane impregnation. After comparing all aspects, the following conclusions were drawn.

(1) Sacrificial anode protection consumes a lot of anode-level materials and is not suitable for long-term use; Imposed current cathodic protection can provide good protection, and extend the durability of the structure up to 50 years. but this method requires long-term maintenance by professional staff. The use of galvanized steel or organic sprayed steel can effectively protect the steel, but the unit price is slightly higher.

(2) The use of paints, coatings, or silane impregnation to protect concrete can improve the durability of concrete at and relatively low cost; crack-resistant concrete is a high-strength concrete, and its cost is not high and can improve the strength and durability of the concrete, but the current application is few.

(3) The use of better materials and maintenance methods at the design stage, although it will result in a higher initial cost, can greatly extend the service life of the bridge, reduce the likelihood of major structural damage, and save the cost of replacing and repairing critical nodes at a later stage due to internal corrosion damage.

The comprehensive conclusion of this paper is that the planning of the sea bridge can be used in the design of corrosion-resistant steel and concrete, if possible, the use of an external current protection method, although the initial investment is large, but can effectively reduce the later maintenance. For the completion, no obvious structural problems of the bridge can be imposed on the outside of the coating for protection, this method of proper construction of the case can be in the case of reasonable costs to effectively extend the life of the bridge.

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