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Research on Corroded Concrete Bridge Works in Climate Change and Proposed Solutions

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ABSTRACT

Finding preventive measures against concrete corrosion and technical solutions to improve the performance, quality and long life of bridges in climate change is an issue with great importance to the construction industry, especially in the context of increasing climate change in the Mekong Delta region. This paper focuses on studying the causes of concrete corrosion and measures to prevent and overcome the corrosion of reinforced concrete bridges in the context of climate change. The usual solution is that we use some kind of coating on the reinforcement to limit corrosion such as cement - bitumen, cement - polystyrol, cement - paint. If the above measures are not able to protect reinforced concrete from the risk of corrosion, we should apply some other special scientific measures. These measures require expert advice. Depending on the specific project, there will be different methods because it depends on many factors such as topography, surrounding environment, concentration of corrosive agents, etc

Keywords: Corrosion, reinforced concrete, bridge, climate change, solutions.

I. INTRODUCTION

In addition to the factor caused by the load, reducing the load-bearing capacity of the structures, we also need to consider the factors from the surrounding environment. In which the impact of chemical compounds plays an important role in the process of corrosion of reinforced concrete, causing a decrease in the load-bearing capacity of the structures in general and the bridges in particular. Vietnam is a coastal country, located in a tropical climate area, humidity and salt content in the air is very high. At the same time, our country is in the process of industrialization and modernization, industrial emissions are also a significant factor affecting the corrosion of concrete. Therefore, the study of corrosion, combined with the impact of loads to make the assessment and diagnosis of the working state of the bridges is being urgently required, serving the maintenance and operation activities of the bridges [1].

A bridge is an artificial construction; the process of corrosion and damage of the bridge is due to the impact of natural factors such as humidity, salt and Cl-, SO2, CO2 ions, etc. This is a common problem in the construction and transportation industry, and can lead to a deterioration in the safety and durability of bridges (abutments, piers, bridge spans, bridge girders, bridge bearings, bridge decks, etc.) [2].

The abutment, piers and spans are the important main structures of the bridges with the function of carrying the load and keeping the bridges stable. Corrosion of abutments and spans is a condition in which these structures are corroded by the effects of the surrounding environment, especially when it comes into contact with seawater or freshwater containing salt. When these structures corrode, their structure weakens, which can lead to bridge collapse and endanger passengers. To prevent corrosion of abutments, piers, and spans, corrosion protection measures are commonly used, such as anti-corrosion coating, wear protection, or use of superior corrosion resistance materials to make these structures.

The collected data shows that the frequency and cost of repair works for damage and deterioration caused by corrosion are increasing [1]. In Japan, a study shows that 90% of buildings exposed to the marine environment have insufficient concrete protection, and a large proportion of structures that are only 10 years old have been damaged. In the United States, based on monitoring of 586,000 highway bridges, 15% of which have weak structural deterioration, mainly due to extensive corrosion. In Vietnam, the effects of corrosion are more pronounced than in other countries in the world, due to the climatic conditions of high temperature, high humidity, high chloride ion concentration. Many structures are seriously affected by the corrosion process after a short period of use, especially in the context of climate change [3].

In the world, there have been many studies on bridge corrosion [4-15] which can lead to damage and destruction of bridge structures. Research results also refer to solutions to prevent, overcome and repair the consequences of corrosion for bridge works, but only stop at research for specific conditions or specific cases. Therefore, this paper focuses on studying the corrosion of reinforced concrete bridges in the context of climate change and proposes remedial solutions to improve the efficiency of bridge construction management and exploitation in Vietnam.

II. CAUSES OF REINFORCED CONCRETE BEING CORRODED

A. Causes of corrosion of reinforcement in concrete

Reinforced concrete is the most popular and successful material in the history of the construction industry with approximately 12 billion tons of reinforced concrete produced annually, more than any man-made material in the world. Usually, when the reinforced concrete structure is properly designed and carefully cast, the structure is stable throughout its service life.

Normally, reinforcement is completely protected in the alkaline environment of concrete thanks to the high content of calcium oxide, sodium oxide and dissolved potassium oxide. Alkaline compounds in concrete keep the pH at 12-13 which helps to form a thin protective film on the surface of the reinforcement. Under normal conditions, the thin film is capable of protecting the reinforcement against the attack of corrosive agents from the environment. This mechanism is called the "passive defense mechanism" of reinforced concrete.

There are two mechanisms that can break the self-protection of reinforced concrete structures and are considered to be the main factors leading to corrosion of reinforcement in concrete, namely carbonation and chloride ion penetration.

a) Carbonation of reinforced concrete

The concentration of dissolved calcium hydroxide solution (Ca(OH)2) in the pores of the concrete structure is the result of the cement hydration process which helps to keep the pH at a safe range of 12-13. As mentioned, in the alkaline environment, the reinforcement is completely protected from corrosive agents thanks to the thin film on the surface (2-20 nanometers thick). However, the carbonation process in the presence of CO2, water and Ca(OH)2 produces calcium carbonate and neutralizes the alkaline environment in the concrete according to the reaction shown in equation (1).

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \qquad (1)$$

After the neutralization process, when the pH in the concrete drops below 9, the "passive defense mechanism" of the concrete no longer exists and the reinforcement begins to corrode. The corrosion process begins when steel rust appears and develops on the surface of the reinforcement and causes cracks at the locations adjacent to the concrete. The crack growth develops gradually under the attack of corrosive agents until the adhesion between concrete and reinforcement (spalling) is completely broken as shown in Figure 1.

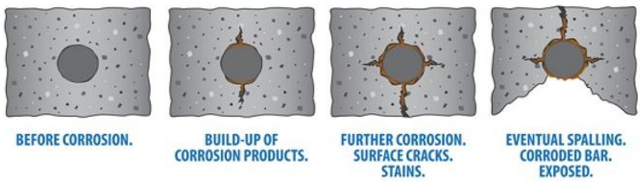

FIGURE 1. CORROSION OF REINFORCED CONCRETE OVER TIME [16]

The rate of carbonation depends on the impact of environmental factors such as air humidity, temperature, CO2 content and physical and mechanical properties of concrete such as alkalinity and permeability. The ideal conditions to promote active carbonation is when the air humidity is at 60-75%. Moreover, the rate of carbonation increases gradually as the CO2 content in the air and temperature increase. On the other hand, cement content is an important factor to increase alkalinity and slow down carbonation.

In addition, the thickness of the protective concrete layer also plays an important role in reducing the corrosion process. Carbonation is a slow process, especially when the ambient temperature is normal. The speed of this process can be measured and prevented. However, it is a serious problem for buildings with a long life (≥ 30 years).

b) Chloride ion penetration

Chloride can exist in concrete mixes in several ways. Chloride may be cast into the structure through the (discontinued) CaCl2 additive, or chloride ions may exist in a mixture of sand, aggregate, or water, either intentionally or unintentionally. However, the main cause of chloride corrosion in most buildings is the diffusion of chloride ions from the environment, such as: 1) Structures in direct contact with the salt-rich marine environment; 2) The use of defrosting salts or chemical compounds containing chlorides. (Figure 2)

FIGURE 2. CHLORIDE DISSOLVED IN WATER SEEPS THROUGH NEGATIVE CONCRETE OR TO STEEL THROUGH CRACKS [16]

Similar to the carbonation process, the chloride penetration process does not directly corrode the reinforcement, except that they break the protective film on the reinforcement surface and promote the development of corrosion. In other words, chloride acts as a catalyst for the corrosion of concrete. However, the chloride ion corrosion mechanism differs from carbonation in that chloride ions penetrate through the protective concrete layer and attack the reinforcement even when the pH in the mixture remains high (12-13).

Local corrosion due to concentration of ion Cl- on the surface of reinforcement in reinforced concrete. There are four mechanisms of chloride ion penetration through the concrete barrier: 1) Capillary attraction; 2) Permeation due to high concentration of chloride ions on the concrete surface; 3) Penetration under surface tension; and 4) Displacement due to potential difference.

c) Reciprocal relationship between carbonation and chloride ion penetration

In practice, reinforced concrete structures often work under the mixed effects of both above mechanisms. Chloride aluminate (AlCl-4), created from the reaction between chloride ions and cement has the effect of reducing the amount of chloride, thereby slowing down the corrosion process. However, when carbonation lowers the pH in the concrete, AlCl-4 breaks down. As a result, structures subjected to both of these mechanisms are simultaneously much more sensitive to corrosion and more difficult to control.

B. Signs of detecting corroded reinforcement

Steel reinforcement is corroded when there are signs: 1) Appear concrete crack with width from 2mm to 10mm running along the main steel bar, when tapping on concrete, there is a popping sound; 2) Yellow rust appears along the crack; 3) Punching the cracked concrete location shows that the steel has rust, swelling in volume; and 4) Broken concrete in pieces exposing heavily rusted reinforcement.

C. Areas affected by reinforcement corrosion

In flooded areas: The main form of destruction of reinforced concrete structures is sulphate corrosion of concrete, caused by SO2-4 ions present in sea water, creating volumetric expansion of ettringite, which causes concrete cracking. The cracks are usually reticulated.

In the high and low tide water area (including the breaking wave parts): In this area, the phenomenon of corrosion and destruction of the structure is comprehensive, reflected in: Most of the structures after about 5 to 7 years of working in this environment, cracks with a width of 1 to 10 mm, running along the reinforcing bars heavily rusted by corrosion, appeared. In many places, the layer of rust is too thick to separate the protective concrete layer, the reinforcement is exposed and rust is very heavy.

In the coastal area: the phenomenon of corrosion and destruction of the structure is local, often occurs strongly for the structure located in the location subject to frequent rain, wind and humidity such as sub-zones, balconies, stairs, beams, columns, etc. On the surface of the protective concrete layer, cracks usually appear on average 5 to 10 mm wide running along the reinforcing bars. With a slab structure, the floor is often peeled off in large chunks of the protective concrete layer, exposed reinforcement and heavily rusted.

Corrosion incidents of bridge reinforced concrete are illustrated in Figure 3 (a, b, c, d, e, f).

a)

b)

c)

d)

e)

f)

Figure 3. Corrosion in reinforced concrete at construction sites [16-19]

III. MEASURES TO PREVENT AND TREAT REINFORCED CONCRETE BRIDGE CORROSION IN CONDITIONS OF CLIMATE CHANGE

A. Measures to prevent corrosion of reinforced concrete

To deal with this problem of corrosion, we should find materials that specialize in anti-corrosion. Currently, Vietnam still has some anti-corrosion products, so combining all those materials together can handle the corrosion.

In standard TCXDVN 327: 2004 "Concrete and reinforced concrete structures - Requirements for protection against corrosion in the marine environment" technical requirements for: design, material selection, construction are given to ensure corrosion resistance for concrete and reinforced concrete structures [20].

a) About design requirements

Supportive safeguards include:

- Increase the concrete grade by 10 MPa and the waterproofing by one level or increase the thickness of the protective concrete layer by 20 mm;

- Using expensive and rare stainless steel, so the use of this steel will significantly increase the construction cost (Fe - Cr alloy improves the oxidation resistance of steel; if adding Cu, Cr or Ni, it will increase high resistance to atmospheric corrosion).

- Galvanizing steel reinforcement has anti-corrosion effect with zinc, because zinc has a protective effect on steel reinforcement. The nature of the galvanizing process is at this time to form a Zn - Fe battery, at this time zinc is the negative electrode, so it is electrochemically corroded before the electrolyte is present. However, Cl- ions have a smaller corrosive effect on zinc than iron, so they protect the surface of the reinforcement and increase the life of the building (Figure 4).

Figure 4. Galvanized Ø6 - Ø8 coil iron

- Paint coating on steel is a measure to protect reinforcement by metal permeation (diffuse coating). Use anti-rust paints derived from epoxy, cement and polymer cement. Requires anti-rust paint to have the ability to chemically bond with steel, good adhesion to concrete and reinforcement. Some typical examples are 1) Silicate enamelling: Enamel requires an expansion coefficient equal to that of steel. Often used vitreous enamel, porcelain enamel, glass coating, ... this glaze is melted on the metal surface. Enamel coating is mainly used for steel, but also sometimes used for cast iron, copper, copper alloy, aluminum; 2) Reactive coating: the coating is formed by direct chemical reactions occurring on the metal surface.

- Inhibits corrosion of steel reinforcement. Inhibiting reinforcement corrosion by corrosion inhibitors has been used for a long time. The addition of an inhibitor to concrete is considered as a measure to protect reinforcement against corrosion. Corrosion inhibitors interact with reinforcement in concrete to protect against salt corrosion. By reacting chemically with iron, it creates a barrier on the surface of the reinforcement, preventing the penetration of chloride ions, on the other hand, it improves the properties of concrete and has the effect of accelerating the hardening of concrete as a fast solid additive.

- The cathode protection method is an effective measure used to prevent corrosion of reinforcement in concrete in recent times. Cathodic protection for reinforced concrete works is to maintain a passive film or re-passivate the reinforcement when the "passive" screen has been broken when the pH is < 11 or the ion content on the surface of the reinforcement is about 0.2. - 0.4% by weight of cement. In addition, the cathode protection current also causes chlorine ions to go away from the surface of the reinforcement and thus reduce the destructive effect of the "passive" screen of chlorine ions. The cathodic protection method is applied to reinforced concrete structures in water, in soil and in air. The method of cathodic protection by external current is more used for structures in the air, while the method of cathodic protection by sacrificial anode is used for structures located in water. In the external current method is used to bias the reinforcement cathode (which shifts the potential of the reinforcement to the negative side) from 3 to 15 mA/m2. The sacrificial anode can be aluminum alloy or zinc alloy.

The above methods are widely studied and applied. They have anti-corrosion effect on most metals, on concrete and against steel corrosion in reinforced concrete structures in gaseous, liquid and solid environments in wet conditions or humid atmospheres. However, each measure only works for certain types.

b) About material requirements

For cement: can use types of cement with the requirement that C3A in clinker ≤ 10%.

For sand: it is necessary to control the amount of dissolved Cl- ≤ 0.05% by weight of sand for normal concrete, test according to TCXDVN 262:2001.

For rocks: it is necessary to control the amount of dissolved Cl- ≤ 0.01% by mass of large aggregate, test according to TCXDVN 262:2001.

For concrete mixing water: it is necessary to control the Cl- ≤ 500mg/l for normal reinforced concrete.

For additives: depending on each specific case, the appropriate type of additive is indicated.

c) About construction requirements

Construction of reinforced concrete structures in saline and brackish water environments is carried out in accordance with TCVN 4453:1995 and other specialized codes [21]. During the construction process, in addition to the above requirements, it is necessary to comply with some additional technical requirements specified in TCXDVN 327:2004, including: preservation and erection of reinforcement, erection of formwork; concrete construction; repair defects during construction.

d) Solution to use calcinitrite as an additive to inhibit corrosion of reinforcement in concrete

Among the supportive protection measures, the use of inhibitors is considered an effective measure, easy to apply and suitable to the technical and economic conditions of Vietnam. Calcium nitrite (CN) has been used as a popular additive to inhibit corrosion of reinforcement in the world for the past 30 years, but in Vietnam, almost calcium nitrite has not been applied until 2002, due to lack of research. Research and apply technology fully in Vietnamese conditions to have a solid basis for its wide application in practice.

In recent years, the application of CN as an additive to inhibit corrosion of reinforcement in concrete is a highly effective solution. Below is a summary of some research results and application of CN in practice.

The mechanism of preventing corrosion of steel reinforcement of CN has been explained quite clearly, according to which CN protects against corrosion by the following 4 methods [22-24]:

First, CN oxidizes iron (II) labile oxide to iron (III) oxide according to the following reaction:

$$2Fe^{2+} + 2NO^{-}_{2} + 2OH^{-} Fe_2O_3 + H_2O + 2NO \qquad (1)$$

$$2Fe^{2+} + 2NO^{-}_{2} + 2OH^{-} Fe_2O_3 + H_2O + 2NO \qquad (2)$$

Second, the nitrite ion will strengthen the iron (III) oxide passivation film by adsorbing on the steel surface and further solidifying this passive film;

Thirdly, nitrite ion also completely covers the iron (II) oxide defect sites, minimizing the penetration of chloride ions through the protective film;

Fourth, if the Cl ion finds a defect on the surface of the reinforcement, corrosion begins to occur. When the iron chloride compound (rust) will separate from the steel surface, new iron (II) ions will continue to be exposed in the concrete environment. NO-2 ions can quickly surround new iron(II) ions protecting them from the penetration of Cl- ions.

Besides the problems that have been studied quite clearly before such as: inhibitory mechanism, influence of CN on the structure of cement paste, the research results have clarified the problems of using CN in actual conditions of Vietnam is that CN has basically no adverse effect on the mechanical properties of the reinforced concrete mix. It is determined that CN has the effect of completely inhibiting the rusting of reinforcement or delaying the rusting time compared to the case without it and the effective content of CN applied in concrete meets the ratio [Cl-] / [NO-2] ≤ 2,0.

This result allows to calculate the required CN content from the beginning to match the aggressive properties of Cl- ions, the design life and the amount of NO-2 expected to be degraded during use. The NO-2 content in concrete degrades over time. This reduction is inversely proportional to the concrete grade and the thickness of the protective layer. The minimum amount of NO-2 to inhibit corrosion, an additional amount should be calculated to compensate for the amount of NO-2 that will be washed away over time. Determining CN can inhibit corrosion of reinforcement right at the concrete crack and with specific crack widths, determining the ratio of crack width/thickness of protective layer with CN to prevent the reinforcement from rusting 1.6 times greater than this ratio in concrete without CN.

e) Construction process of anti-corrosion concrete application

Checking materials, technical criteria on workability and strength of anti-corrosion concrete must at least meet the technical requirements of ordinary concrete as specified by the design. Producing anti-corrosion concrete on a conventional concrete production line in the field using CN.

Construction of anti-corrosion concrete: similar to conventional concrete construction techniques, in which emphasis is placed on ensuring the thickness and consistency of the protective concrete layer and treating hollow and pitting defects immediately after construction is finished. Install the corrosion probe in the applied concrete for long-term monitoring of anti-corrosion and construction protection: Each component has 2 probes attached to the bearing reinforcement, testing the concrete strength and measure the reinforcement corrosion potential at the beginning when the concrete is 28 days old and periodically every 1-2 years, up to 40-50 years.

B. Proposing solutions to overcome problems caused by corrosion

Corrosion of concrete in bridge works affects directly the life of steel-using structures and indirectly to manufacturers and suppliers of products and services due to the cost of anti-corrosion of steel and consumers will have to bear these costs. In daily life, we can easily recognize severely damaged bridge works. The social consequences include: 1) Safety: damage may cause fire, explosion, sag, the bearing capacity is reduced and may lead to collapse of the bridges; 2) In terms of health: product pollution from equipment is corroded, causing depletion of natural resources, directly polluting the environment and living water sources of nearby people; 3) Economic: directly affect the economy and cause damage to the state budget.

a) For small bridges and culverts

For small bridges: clear the flow, both upstream and downstream to ensure good drainage. Erosion-prone parts such as four cones, bridgehead road, abutment foot, power yard need to be repaired and reinforced before rainy and stormy seasons;

For culverts: must clear the pits and culverts, even before and during the rainy and stormy season, reinforce the head wall and the energy dissipation yard; If the culvert is located in the location where there are rocks and driftwood, measures must be taken to strengthen against soil, rocks and driftwood to fill the culvert.

b) For medium and large bridges

Regular and periodic inspection must be carried out in accordance with regulations as well as annual repair and reinforcement, especially for parts easily damaged by rain and flood;

For bridges in areas with rocks and drifting trees: to regularly check to remove trees and garbage, not to cling to piers and beam bottoms;

For rivers and streams with changes in flow: it is necessary to take measures to correct the flow and strengthen both banks and abutments appropriately;

For large bridges: must regularly monitor the wind speed on the bridge; In case the wind speed on the bridge is higher than the wind level as prescribed by the design, it must promptly close the bridge (pause traffic) and notify the traffic flow to ensure safety for people and vehicles.

For drainage ditches (including longitudinal trenches, top ditches, water steps and slopes): must clean plants, dredge mud and rocks, ensure good drainage. The damage of the trench affecting the drainage capacity must be repaired before the rainy and flood season.

For spillway, underground: must be patched, repaired face, flood, drainage yard upstream and downstream; paint and repair the signaling system, poles, water column and have standing forces at both ends of the underground when the water is flooded to control traffic. When the water recedes, it is necessary to check the condition of overflow and underground roads, and only circulate when it is safe.

C. Measures to overcome corrosion of reinforced concrete

The process of overcoming corrosion of reinforced concrete includes 4 steps:

Step 1: Concrete chisel: Check and determine the location to be treated (floor, column, beam...), then concrete all the cracked, exposed steel parts.

Step 2: Add steel: If the steel is too weak, add more steel to strengthen the structure (according to the design). The section of reinforcement that needs to be supplemented is determined according to calculations. Bonding old steel with new added steel by force welding, weld length, knot density complies with current regulations. Performed for both belt and main reinforcement.

Step 3: Cleaning and chemical treatment: Rusting of steel reinforcement with iron scrubber, iron scrubber, water jet machine. Spray a layer of rust-modifying material directly onto the reinforcement surface.

Step 4: Reconcrete concrete: Spray the adhesive layer with anti-corrosion epoxy paint on the reinforcement and concrete surface to enhance adhesion. If applying composite coating method, proceed to sweep each layer of composite and glass fiber to the surface. Then pour concrete or apply high strength mortar (with anti-corrosion chemicals mixed). After re-concreting, we proceed to apply 1 layer of corrosion inhibitor and 2 layers of waterproofing on the concrete surface.

One of the concrete anti-corrosion treatments is glass fiber composite coating. Currently, this composite coating method, also known as FRP coating, is the perfect choice in the construction of anti-corrosion treatment of chemical tanks, reinforced concrete columns under the sea. The outstanding advantages of composite anti-corrosion coating are 1) Composite (FRP) is composed of vinylpolyester resin combined with glass fiber reinforcement, so it is especially durable and has good resistance to harsh environmental conditions , duration can last up to decades of use; 2) Effective resistance to corrosion and waterproofing, ensuring impressive mechanical properties; 3) The composite coating has no welding seams, thus avoiding the leakage of the solution from the inside to the outside; 3) Allow to perform for complex surfaces, simple repair and maintenance on site; 4) Light weight, convenient in transportation and installation; 5) The investment cost of anti-corrosion coating is much lower than some other technical solutions, but the efficiency is surprisingly impressive.

The working principle of composite anti-corrosion coating is that FRP composite coating is capable of creating a solid protection layer for the surface (plastic, metal or concrete, etc.) from the impact of chemicals. cause adverse effects on service life as well as function. The principle of operation of this process is very simple. Composite is a material that resists chemical reactions extremely well, and when applied anti-corrosion treatment on the surface, it will form a solid layer of material. From there, it is responsible for preventing contact between chemicals and surfaces that can create chemical reactions.

IV. CONCLUSIONS

The phenomenon of concrete structure corrosion is a very serious problem. It greatly affects the safety of works, the health and life of the constructor, causing damage to the national economy and the surrounding environment. Therefore, preventing the corrosion of reinforced concrete structures, contributing to the protection of structural safety has been and is being considered as one of the major challenges for the construction industry today, especially in the context of climate change.

To increase the durability of reinforced concrete blocks, the best way to overcome this is to limit the causes of it. In the process of pouring fresh concrete before adding reinforcement, remember to minimize the holes. The best way is to use good, clean materials, mix in the right proportions and mix thoroughly to increase the plasticity and durability of the concrete block. In case of fearing that the pH of the concrete may decrease, causing corrosion of the reinforced concrete inside, we can handle it by using some paints to cover the reinforcement to limit corrosion such as: cement - bitumen, cement - polystyrol, cement - paint. If the above measures still cannot protect reinforced concrete from the risk of corrosion, we should apply some other special scientific measures. These measures require expert advice. Depending on the specific works, there will be different methods because it depends on many factors such as soil, topography, surrounding environment, climate change...

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