ABSTRACT

The reinforcing steel corrosion in concrete structures has undoubtedly become a serious threat to structure designers. Furthermore, it has become economic burden to many government agencies as lot of public funds are wasted due to this corrosion. From the literature present, we know that the iron in the steel has natural tendency to revert eventually to its most stable oxide state, so once initiated, it becomes difficult to completely abandon the corrosion. The adaptation of corrosion protection measures in new construction such as use of good design and construction practices, adequate concrete cover depth, low permeable concrete and coated reinforcing steel, use of pozzolanic materials such as fly ash in concrete and coated reinforcing steel helps in prevention of steel reinforcing corrosion to great extend. Moreover, understanding the phenomenon involved in corrosion and use of techniques to monitor the corrosion by different methods helps in taking instantaneous measures against the corrosion. This paper is the review of processes involved in corrosion, monitoring the corrosion and preventing the corrosion.

Keywords: Alkanity, Carbonation, Chlorides, Concrete, Corrosion

INTRODUCTION

Cement concrete has clearly emerged as the material of choice for the construction of a large number and variety of structures in the world today (Kumar et al 2013). Corrosion of steel bars is the major cause of failure of concrete structures and about two tons of concrete is used per capita of the world population every year. From the literature survey and case studies it has been reported that 40% of failure of structures is on the account of corrosion of embedded steel reinforcement in concrete (Shetty 1982). Therefore, it has been realized that durable structures will reduce the cement consumption. Corrosion can severely reduce the strength and life of structures and in humid conditions pollutants from atmosphere percolate through the concrete cover and cause corrosion of

steel. After the initiation of corrosion in reinforcing steel, products of corrosion expand and occupy a volume of about 6–10 times greater than that of steel resulting in the formation of cracks and finally in the failure of structures as shown in Figures no.1

![Image of Oxidation state verses increase in volume](image_url)

**Fig 1**: Oxidation state verses increase in volume

**CAUSES OF CORROSION**

The two most common causes of reinforcement corrosion are localized breakdown of the passive film on the steel by chloride ions and general breakdown of passivity by neutralization of the concrete, predominantly by reaction with atmospheric $\text{CO}_2$. Sound concrete is an ideal environment for steel but the increased use of deicing salts and the increased concentration of carbon dioxide in modern environments principally due to industrial pollution, has resulted in corrosion of the rebar becoming the primary cause of failure of this material. The scale of this problem has reached alarming proportions in various parts of the world. Following are the contributing factors leading to corrosion:

1. **Loss of alkanity due to carbonation**

   It is well known that if bright steel is left unprotected in the atmosphere, brown oxide rust quickly forms and will continue to grow until a scale flakes from the surface.

   This corrosion process will continue unless some external means is provided to prevent it (Neerav). One method is to surround the steel with an alkaline environment having a pH value within the range 9.5 to 13. At this pH value, a passive film forms on the steel that reduces the rate of corrosion to a very low and harmless value. Thus, concrete cover provides chemical as well as physical protection to the steel.

   However, alkalinity can be lost as a result of reaction with acidic gases (such as carbon dioxide) in the atmosphere and leaching by water from the surface. Concrete is permeable and allows the slow ingress of the atmosphere, the acidic gases react with the alkalis (usually calcium, sodium and potassium hydroxides), neutralizing them by forming carbonates, sulphates and at the same time reducing the pH value. If the carbonated front penetrates sufficiently deeply into the concrete to
intersect with the concrete reinforcement interface, protection is lost and since both oxygen and moisture are available, the steel is likely to corrode. The extent of the advance of the carbonation front depends, to a considerable extent, on the porosity and permeability of the concrete and on the conditions of the exposure. In the case of carbonation, atmospheric carbon dioxide (CO₂) reacts with pore water alkali according to the generalized reaction:

$$\text{Ca} (\text{OH})_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O}$$

It consumes alkalinity and reduces pore water pH to the 8–9 range, where steel is no longer passive.

2. Loss of Alkanity due to Chlorides

The passivity provided by the alkaline conditions can also be destroyed by the presence of chloride ions, even though a high level of alkalinity remains in the concrete. The chloride ion can locally de-passivate the metal and promote active metal dissolution. Chlorides react with the calcium aluminate and calcium alumino ferrite in the concrete to form insoluble calcium chloroaluminates and calcium chloroferrites in which the chloride is bound in non-active form. However, the reaction is never complete and some active soluble chloride always remain in equilibrium in the aqueous phase in the concrete (Neilson silva). It is this chloride in solution that is free to promote corrosion of the steel. At low levels of chloride in the aqueous phase, the rate of corrosion is very small, but higher concentration increases the risks of corrosion.

[Fig 2: Schematic representation of basic processes of corrosion of steel in concrete]

**FACTORS AFFECTING CORROSION OF STEEL IN CONCRETE**

The corrosion behavior of reinforcement steel in concrete is a function of parameters of steel, concrete as well as the properties of their interfacial zone, i.e. it is determined by the composition of the pore solution of the concrete and chemical properties of steel. The other parameters of concrete which would affect corrosion of steel through their influences of pore solution are listed below:
1. Steel

Different types of steel have different microstructures and compositions, so different types of steel usually have different corrosion behavior in concrete. The corrosion rate in stainless steel is of few orders of magnitude, less than that of steel. Moreover, chloride tolerance of stainless steel is several times higher than that of steel bar in concrete.

2. Pore solution of concrete

The pore solution in concrete is an electrolyte which is physically absorbed in the pore of the concrete, due to which capillary force is produced. It reacts with the steel reinforcement and under certain conditions leads to the corrosion damage at the steel surface. The composition of the pore solution varies with cement used and age of the concrete. The chemical composition of the pore solution influences the conductivity of the concrete and corrosion process. If a certain amount of chloride is present in the pore solution it will become corrosive, even though its pH value may still be high.

3. Permeability of Concrete

Larger pore sizes lead to more severe corrosion damage in the steel. If the concrete has low permeability, then the aggressive species would have difficulty to access the reinforcement and possibility of corrosion in the reinforcement would be low. Further, the permeability of concrete increases with increase in water-cement ratio.

4. Moisture

The influence of concrete moisture content on the rate of corrosion of steel in concrete is well known. If there is no water in concrete there should be no corrosion problem with reinforcement. Since electrochemical reaction are mainly responsible for the reinforcement corrosion, moisture is an essential substance in the corrosion of steel in concrete.

5. Components of Concrete

Any factor that affects the pore solution and the porosity of the concrete would affect the corrosion of steel in concrete. This includes types and quantities of binder, aggregate and w/c ratio. Results indicate that for equal periods of exposure, corrosion is generally higher for rebar in concrete with high w/c ratio than those with low w/c ratio concrete (Pech-Canul Ma and Castro P 2002). Workmanship and curing are other important factors that influence the corrosion process of steel in concrete.

6. Concrete Resistivity

The electrical resistivity of hardened cement paste, mortar and concrete have been widely reported as significantly affecting the corrosion of reinforcing in concrete. Normally the electrical resistivity of concrete ranges from $10^0$ to $10^7$ Ωcm depending on the concrete composition and moisture content.

7. Thickness and defects of cover concrete

The thickness of cover concrete determines the time for aggressive species to reach the steel rebar in concrete. Sometimes the service life of reinforced concrete structures can be extended greatly simply by increasing the thickness of the cover concrete.
Fig 3: Example of delamination of concrete of concrete cover

8. Temperature

Temperature can influence corrosion rate of reinforcement in concrete. All the processes involved in corrosion can be influenced by temperature increase since temperature increases the corrosion rate. It was reported that two folds higher corrosion rate could be reached by only 10°C.

FORMATION OF CRACKS

To understand the formation of cracks in concrete, consider a general corroded steel bar. As we know once corrosion initiated, the corrosion products started depositing on surface of bar. With the passage of time, the volume of products increases many folds. These exert tensile force on surrounding concrete and a stage reaches where this pressure increases the concrete pressure, developing the cracks in concrete.

MONITORING OF CORROSION

There are several methods available for detecting and evaluating the corrosion in reinforcement steel. However, half-cell potential [HCP] has been recognized by many researchers as the main method to detect the corrosion activity in RCC structures (Verma et al). In this method potential difference is measured between steel reinforcement and an external electrode with a voltmeter. The half-cell consists of a metal rod immersed in a solution of its own (Cu/CuSO₄ or Ag/AgCl). The metal rod is connected with reinforcement steel by a voltmeter. Some surface preparations including wetting to ensure good electrical connection are necessary. The main
application of this method is in-situ. External electrode and steel reinforcement are connected through a wet concrete cover. Interpretation of results of half-cell potential measurement for reinforced concrete structures requires high skills and experience, as this only provides information regarding the probability of corrosion instead of rate and nature of corrosion. Availability of oxygen, cover thickness and concrete resistivity are few factors influencing the results of half-cell potential test. This method evaluates the potential difference on the exposed surface of concrete structures. The potential can be measured at any point on the surface or average of several measurements taken from different points on the same surface may be considered for evaluating the probability of corrosion. More negative value of measured half-cell potential indicates more probability of corrosion. This half-cell potential is also known as open circuit potential and is measured at several distinct points over a given area to be surveyed.

The major drawback is that HCP requires a localized breakout of the concrete cover to provide an electrical connection to the steel reinforcement. HCP results are highly influenced by the composition of the deteriorated concrete. Therefore, interpretation criteria might be different for different deterioration types. Shortcomings of HCP measurements result from the fact that the potentials are measured not near rebar but on concrete surface.

PREVENTION METHODS

1. Keep concrete always dry, so that there is no \( \text{H}_2\text{O} \) to form rust. Also aggressive agents cannot easily diffuse into dry concrete. If concrete is always wet, then there is no oxygen to form rust.
2. A polymeric coating is applied to the concrete member to keep out aggressive agents. A polymeric coating is applied to the reinforcing bars to protect them from moisture and aggressive agents. The embedded epoxy-coating on steel bars provide a certain degree of protection to the steel bars and thereby, delay the initiation of corrosion. These coatings permit movement of moisture to the steel surface but restrict oxygen penetration such that a necessary reactant at cathode is excluded (khalid).
3. Stainless steel may be used in lieu of conventional black bars to resist the corrosion.
4. Using a Fly Ash concrete with very low permeability, delays the arrival of carbonation and chlorides at the level of the steel reinforcement. Fly Ash is a finely divided silica rich powder that, in itself, gives no benefit when added to a concrete mixture, unless it can react with the calcium hydroxide formed in the first few days of hydration. Together they form a calcium silica hydrate (CSH) compound that over time effectively reduces concrete diffusivity to oxygen, carbon dioxide, water and chloride ions (Smith).
5. A portion of the chloride ions diffusing through the concrete can be sequestered in the concrete by combining them with the tricalcium aluminate to form a calcium chloro-aluminate (Friedel’s salt). It can have a significant effect in reducing the amount of available chlorides thereby reducing corrosion.

6. Electrochemical injection of the organic base corrosion inhibitors, ethanolamine and guanidine into carbonated concrete retards corrosion.

7. The rougher the steel surface, the better it adheres to concrete. Oxidation treatment (by water Immersion and ozone exposure) of rebar increases the bond strength between steel and cement paste to a value higher than that attained by clean rebar. In addition, surface deformations on the rebar (such as ribs) enhance the bond due to mechanical interlocking between rebar and concrete.

8. Electrochemical Chloride Extraction (ECE) is a relatively new technology for which long-term service data are limited. This method employs a temporary anode that is operated at current density orders of magnitude higher than for cathode protection, such that anions, including chlorides, electro migrate away from the embedded steel cathode. Not all chlorides are removed, but sufficient amounts are displaced from the steel-concrete interface on of steel in concrete that are available. (PCS hayfield 1986).

CONCLUSION

Corrosion of steel in concrete continues to be a major issue for asset managers in the world. Hundreds of papers are being published in this area every year regarding corrosion behavior, influences of factors, techniques for monitoring, laboratory simulation and acceleration and service life prediction. A great deal of progress has been made on the above aspects through decades of efforts and contributions made by corrosion engineers and material scientists. However, there are many unresolved issues which need to be further studied.

REFERENCES