Factors affecting Corrosion of Steel Reinforcing Concrete

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Abstract

Reinforced concrete uses steel to provide the tensile properties that are needed in structural concrete. It prevents the failure of concrete structures which are subjected to tensile and flexural stresses due to traffic, winds, dead loads, and thermal cycling. However, when reinforcement corrodes, the formation of rust leads to a loss of bond between the steel and the concrete and subsequently delamination and spalling. If left unchecked, the integrity of the structure can be affected. Reduction in the cross sectional area of steel reduces its strength capacity. This is especially detrimental to the performance of tensioned strands in pre-stressed concrete. Reinforcement bars carries the bulk of the tensile load and imparts a degree of cracking resistance to the concrete which itself is compressively loaded. The corrosion of steel reinforcement bars in concrete is a big universal problem. The damage which happens from corrosion may due to a large extent reduce the serviceability and structural integrity of reinforced concrete.

Keywords: Concrete, steel, Corrosion

١.INTRODUCTION

Corrosion is a destruction of material because of its reaction with the environmental conditions the most predominant among various factors of corrosion is the atmospheric corrosion which causing the rusting of steel. Appreciable corrosion only starts when the relative humidity of the air exceeds around ٦٥٪. In dry, pure air and below freezing point of water there is no danger of the corrosion. Corrosion may be defined as the involuntary destruction of substances such as metals and mineral building materials by surrounding media.

Concrete is one of the most versatile and widely used as construction material throughout the world. Reinforced concrete structures has to withstand the environmental conditions throughout its life-span if properly prepared and placed. It has been demonstrated by the large number of concrete structure built over the last ١٠٠ years in different part of the world.

The construction of reinforced concrete structures were taken up during the formative years of the ٢٠th century. The steel embedded in the concrete structure whether as reinforcement or pre-stressed tendon, being ferrous material, is prone to corrosion which cannot be totally eliminated. All developed countries have carried out necessary preventive measures including revision of the concrete codes by incorporation of suitable durability practices in seventies and eighties.

Corrosion of steel results in reduction of cross-section area of steel and cracks and splitting of cover concrete. Due to reduction of cross-section, the load carrying capacity is reduced, in addition to reduction of elongation properties and fatigue strength.

The corrosion of steel reinforcement in concrete is complex, but basically it is an electrochemical reaction similar to that of a simple battery. The composition of mild steel varies along its length and potential anodic and cathodic sites can be set up at various points.

٢. Aims and Objectives

Corrosion of steel reinforcement is a major problem influencing the long-term performance of reinforced concrete structures that is why I want to know all factors that affecting on steels in concrete structures, more specifically, there is a specific objective which relate to the different stages of the research project which it is Illustrating all factors that effect on steel corrosions in concrete structures

٣. Corrosion of steel in concrete

This chapter discusses the basics of corrosion and how it applies to steel in concrete. To start with a basic question; why does steel corrode in concrete? A more sensible question is why does not steel corrode in concrete? We know from experience that ordinary carbon steel reinforcing steel bars corrode (rust) when air and water are present. As concrete is porous and contains moisture why doesn't steel in concrete usually corrode?

The answer is that concrete is alkaline. Alkalinity is the opposite of acidity. Metals corrode in acids; they can be protected from corrosion by alkalis. This is generally the case in concrete.

When we say that concrete is alkaline we mean that the concrete contains microscopic pores which contain high concentrations of soluble calcium, sodium and potassium oxides. These form hydroxides, which are very alkaline, when water is present. This creates a very alkaline condition of pH ١٢–١٣. The composition of the pore water and the movement of ions and gases through the pores is very important when analyzing the susceptibility of reinforced concrete structures to corrosion.

The alkaline condition leads to a 'passive' layer forming on the steel surface. The passive layer is a dense, impenetrable film, which, if fully established and maintained, prevents further corrosion of the steel. The layer formed on steel in concrete is probably part metal oxide/hydroxide and part mineral from the cement. A true passive layer is a very dense, thin layer of oxide that leads to a very slow rate of oxidation (corrosion). There is some discussion as to whether or not the layer on the steel is a true passive layer as it seems to be thick compared with other passive layers and it consists of more than just metal oxides but as it behaves like a passive layer it is generally referred to as such.

Corrosion scientists and engineers spend much of their time trying to find ways of stopping corrosion of steel by applying protective coatings. Other metals such as zinc, polymers such as acrylics or epoxies are used to stop corrosive conditions getting to steel surfaces. The passive layer is the corrosion engineer's dream coating as it forms itself and will maintain and repair itself as long as the passivating (alkaline) environment is there to regenerate it if it is damaged. If the passivating environment can be maintained it is far better than any artificial coatings like galvanizing or fusion bonded epoxy that can be damaged or consumed, allowing corrosion to proceed in damaged areas.

However, the passivating environment is not always maintained. Two conditions can break down the passivating environment in concrete without attacking the concrete first. One is carbonation and the other is chloride attack.

٤. The corrosion process

Once the passive layer breaks down then areas of rust will start appearing on the steel surface. The chemical reactions are the same whether corrosion occurs by chloride attack or carbonation. When steel in concrete corrodes it dissolves in the pore water and gives up electrons: The anodic reaction:

$Fe \rightarrow Fe^{٢+} + ٢e^-$ (٢،١)

The two electrons ($٢e^-$) created in the anodic reaction must be consumed elsewhere on the steel surface to preserve electrical neutrality. In other words we cannot have large amounts of electrical charge building up at one place on the steel. There must be another chemical reaction to consume the electrons. This is a reaction that consumes water and oxygen: The cathodic reaction:

$٢e^- + H٢O + ٠،٥\ O٢ \rightarrow ٢OH^-$ (٢،٢)

This is illustrated in Figure ٢،١. You will notice that we are generating hydroxyl ions in the cathodic reaction. These ions increase the local alkalinity and therefore will strengthen the passive layer, warding off the effects of carbonation and chloride ions at the cathode. Note that water and oxygen are needed at the cathode for corrosion to occur.

The anodic and cathodic reactions ((٢،١) and (٢،٢)) are only the first steps in the process of creating rust. However, this pair of reactions is critical to the understanding of corrosion and is widely quoted in any discussion on corrosion and corrosion prevention for steel in concrete. If the iron were just to dissolve in the pore water (the ferrous ion $Fe^{٢+}$ in equation (٢.١) is soluble) we would not see cracking and spalling of the concrete. Several more stages must occur for ‘rust’ to form. This can be expressed in several ways and one is shown here where ferrous hydroxide becomes ferric hydroxide and then hydrated ferric oxide or rust:

$Fe^{٢+} + ٢OH^- \rightarrow Fe(OH)^{٢}$ *Ferrous hydroxide* (٢,٣)

$٤Fe(OH)_{٢} + O٢ + ٢H٢O \rightarrow ٤Fe(OH)٣$ *Ferric hydroxide* (٢,٤)

$٢Fe(OH)٣ \rightarrow Fe٢O٣{\cdot}H٢O + ٢H٢O$ *Hydrated ferric oxide (rust)* (٢,٥)

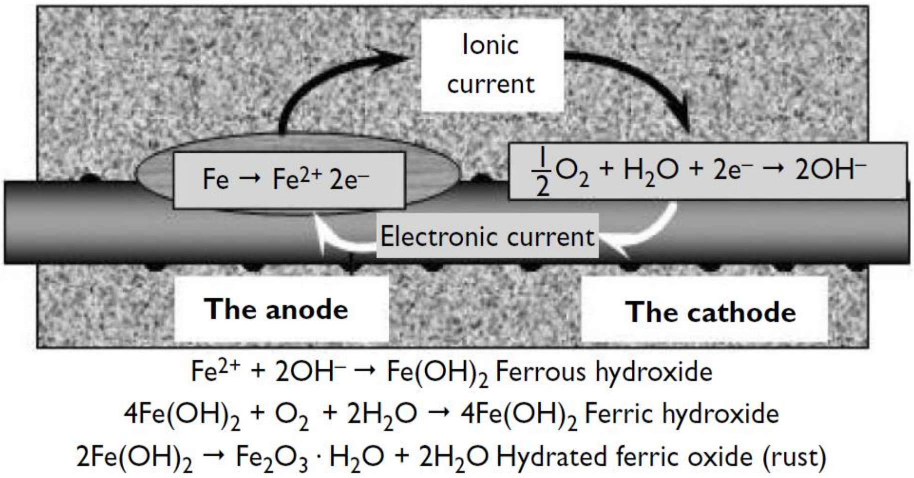

Figure ٢، ١ The anodic, cathodic and oxidation and hydration reactions for corroding steel.

The full corrosion process is illustrated in Figure ٢،١. Unhydrated ferric oxide $Fe_{٢}O_{٣}$ has a volume of about twice that of the steel it replaces when fully dense. When it becomes hydrated it swells even more and becomes porous. This means that the volume increase at the steel/concrete interface is six to ten times as indicated in Figure ٢،٢. This leads to the cracking and spalling that we observe as the usual consequence of corrosion of steel in concrete and the red/brown brittle, flaky rust we see on the bar and the rust stains we see at cracks in the concrete.

Several factors in the explanation given in this section are important and will be used later to explain how we measure and stop corrosion. The electrical current flow, and the generation and consumption of electrons in the anode and cathode reactions are used in half-cell potential measurements and cathodic protection. The formation of protective, alkaline hydroxyl ions is used in cathodic protection, electrochemical chloride removal and re-alkalization. The fact that the cathodic and anodic reactions must balance each other for corrosion to proceed is used in epoxy coating protection of re-bars.

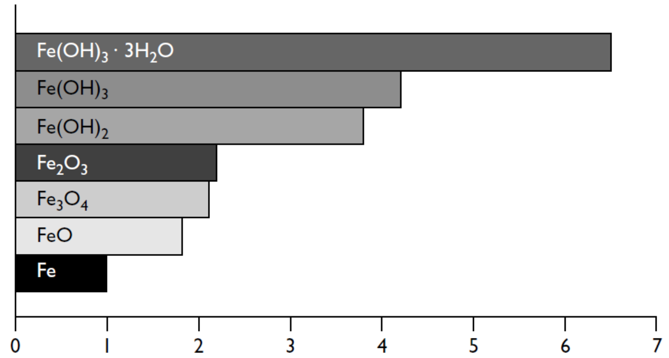

Figure ٢، ٢ Relative volume of iron and its oxides from Mansfield Corrosion

٥. Black rust

There is an alternative to the formation of 'normal' red rust described in reactions (٢،٣) to (٢،٥) earlier. If the anode and cathode are well separated (by several hundred millimeters) and the anode is starved of oxygen (say by being underwater) the iron as $Fe^{٢+}$ will stay in solution. This means that there will be no expansive forces as described earlier to crack the concrete so corrosion may not be detected.

This type of corrosion (known as 'black' or 'green' rust due to the color of the liquid when first exposed to air after breakout) is found under damaged waterproof membranes and in some underwater or other water saturated conditions. It is potentially dangerous as there is no indication of corrosion by cracking and spalling of the concrete and the reinforcing steel may be severely weakened before corrosion is detected. Re-bars may be hollowed out in such deoxygenated conditions particularly under membranes or when water is permanently ponded on the surface.

Examples of re-bars attacked in this way are shown in Figure ٢،٣. These bars were taken from underneath damaged waterproof membranes.

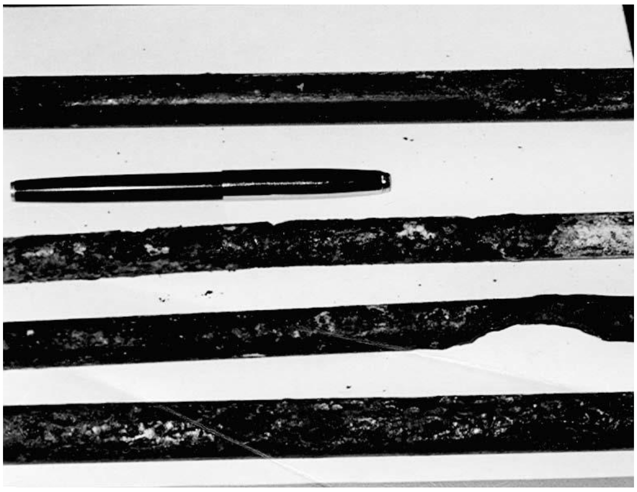

Figure ٢,٣ Reinforcing bars taken from under the end of a waterproofing membrane. They have been subjected to low oxygen conditions and therefore one of them shows severe local wasting. There was no expansive oxide growth.

Rust staining on the concrete surface may be indicative of this type of attack, but obviously if water is getting under a membrane and excluding oxygen it is unlikely that the iron in solution will get to the concrete surface where it will then precipitate out to form rust stains.

٦. Causes and mechanisms of corrosion in concrete

٦.١ Introduction

There are two main causes of corrosion of steel in concrete. This chapter will discuss how chloride attack and carbonation lead to corrosion and how the corrosion proceeds once it has started. The mechanism of corrosion damage is explained. There will also be discussion of the variations that can be found when carrying out investigations in the field.

The main causes of corrosion of steel in concrete are chloride attack and carbonation. These two mechanisms are unusual in that they do not attack the integrity of the concrete. Instead, aggressive chemical species pass through the pores in the concrete and attack the steel. This is unlike normal deterioration processes due to chemical attack on concrete. Other acids and aggressive ions such as sulphate destroy the integrity of the concrete before the steel is affected. Most forms of chemical attack are therefore concrete problems before they are corrosion problems. Carbon dioxide and the chloride ion are very unusual in penetrating the concrete without significantly damaging it. Accounts of (for instance) acid rain causing corrosion of steel embedded in concrete have been shown to attack the steel and not the concrete.

٦.٢ Carbonation

Carbonation is the result of the interaction of carbon dioxide gas in the atmosphere with the alkaline hydroxides in the concrete. Like many other gases carbon dioxide dissolves in water to form an acid. Unlike most other acids the carbonic acid does not attack the cement paste, but just neutralizes the alkalies in the pore water, mainly forming calcium carbonate that lines the pores:

$CO_{٢}$ + $H_{٢}O$ → $H_{٢}CO_{٣}$ (٣,١)
Gas Water Carbonic acid

$H_{۲}CO_{۳}$ + $Ca(OH)_{۲}$ → $CaCO_{۳} + ۲H_{۲}O$ (۳،۲)

Carbonic acid Pore solution

There is a lot more calcium hydroxide in the concrete pores that can dissolve in the pore water. This helps maintain the pH at its usual level of ۱۲–۱۳ as the carbonation reaction occurs. However, as carbon dioxide proceeds to react with the calcium (and other) hydroxides in solution, eventually all the calcium hydroxide reacts, precipitating the calcium carbonate and allowing the pH to fall to a level where steel will corrode. This is illustrated in Figure ۳،۱(a) and (b) which show the pH drop across the carbonation front and the corrosion rate of steel as the pH changes.

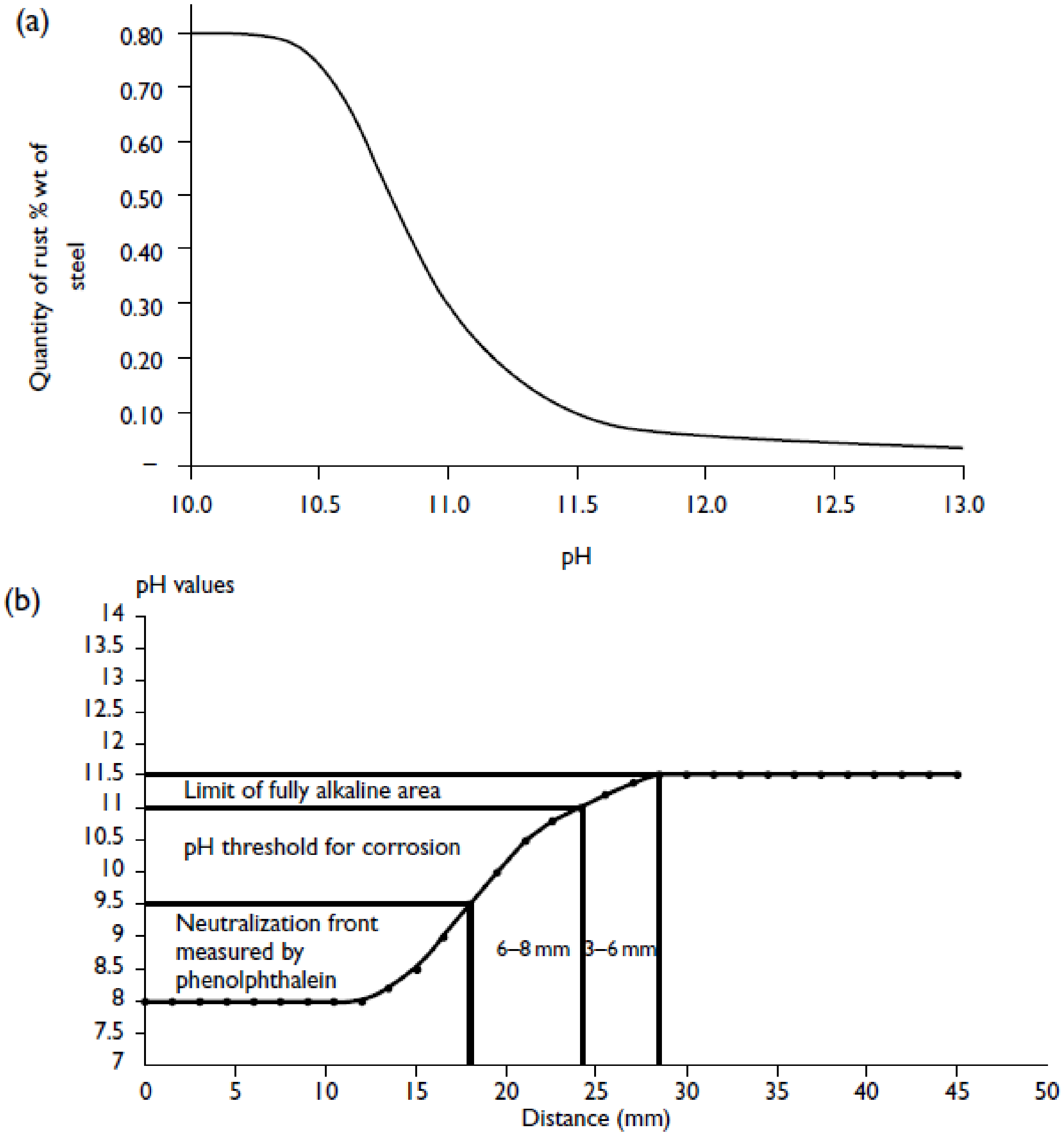

Figure ۳،۱ (a) Corrosion of steel in aqueous solutions as a function of pH, showing the effect of the passive layer above pH ۱۲،۵. (b) The pH levels for carbonation, corrosion and phenolphthalein indicator.

Carbonation damage occurs most rapidly when there is little concrete cover of the reinforcing steel. It can also occur when the cover is high but the pore structure is open, pores are well connected together and allow rapid $CO_{\text{٢}}$ ingress and when alkaline reserves in the pores are low. This occurs when there is a low cement content, high water cement ratio and poor curing of the concrete.

A carbonation front proceeds into the concrete roughly following the laws of diffusion. These are most easily defined by the statement that the rate is proportional to the thickness:

$$(dx / dt) = (D_{.}/x) \qquad (\text{٣,٣})$$

where x is distance, t is time and D_o is the diffusion constant.

The diffusion constant D_o is determined by the concrete quality. At the carbonation front there is a sharp drop in alkalinity from pH ١١–١٣ down to less than pH ٨. At that level the passive layer, which we saw in Chapter ٢ was created by the alkalinity, is no longer sustained so corrosion proceeds by the general corrosion mechanism as described in the Chapter ٢.

Many factors influence the ability of reinforced concrete to resist carbonation induced corrosion. As the carbonation rate is a function of thickness, good cover is essential to resist carbonation. As the process is one of neutralizing the alkalinity of the concrete, good reserves of alkali are needed, that is, a high cement content. The diffusion process is made easier if the concrete has an open pore structure. On the macroscopic scale this means that there should be good compaction. On a microscopic scale well cured concrete has small pores and lower connectivity of pores to the $CO_{\text{٢}}$ has a harder job moving through the concrete. Microsilica and other additives can block pores or reduce pores sizes.

Carbonation is common on old structures, badly built structures (particularly buildings) and reconstituted stone elements containing reinforcement (often having a low cement content and being very porous). Carbonation is rare on modern highway bridges and other civil engineering structures where water cement ratios are low, cement contents are high with good compaction and curing and enough cover to prevent the carbonation front advancing into the concrete to any significant extent. On these structures the chlorides usually get there first. Wet dry cycling will accelerate carbonation by allowing $CO_{\text{٢}}$ in and then supplying the water for it to dissolve in. This gives problems in some countries where the cycling between wet and dry seasons seems to favor carbonation.

When a repairer talks of repairing corrosion due to ‘low cover’ he usually means that the concrete has carbonated around the steel leading to corrosion. As the cover is low it was a quick process. If the concrete were of the highest quality carbonation may not have been possible and low cover might not have mattered.

Carbonation is easy to detect and measure. A pH indicator, usually phenolphthalein in a solution of water and alcohol, will detect the change in pH across a freshly exposed concrete face. Phenolphthalein changes from clear at low pH (carbonated zone) to pink at high pH (uncarbonated concrete). Measurements can be taken on concrete cores, fragments and down drilled holes. Care must be taken to prevent dust or water from contaminating the surface to be measured but the test, with the indicator sprayed onto the surface, is cheap and simple. Figure ٣,١(b) shows a typical carbonation front in concrete.

٦.٣ Chloride attack

Chlorides can come from several sources. They can be cast into the concrete or they can diffuse in from the outside. Chlorides cast into concrete can be due to:

- Deliberate addition of chloride set accelerators (calcium chloride CaCl٢ was widely used until the mid-١٩٧٠s);
- Use of seawater in the mix;
- Contaminated aggregates.

Chlorides can diffuse into concrete due to:

- ✓ Sea salt spray and direct seawater wetting;
- ✓ deicing salts;
- ✓ Use of chemicals (structures used for salt storage, brine tanks, aquaria, etc.).

Much of our discussion will center on the diffusion of chlorides into concrete as that is the major problem in most parts of the world either due to marine salt spray or use of deicing salts. However, the cast in chlorides must not be overlooked especially when they are part of the problem. This often happens in marine conditions where sea water contaminates the original concrete mix and then diffuses into the hardened concrete.

٦.٤ Chloride transport through concrete

Like carbonation, the rate of chloride ingress is often approximated to Fick’s law of diffusion. There are further complications here. The initial mechanism appears to be suction, especially when the surface is dry, that is, capillary action. Salt water is rapidly absorbed by dry concrete. There is then some capillary movement of the salt laden water through the pores followed by ‘true’ diffusion. There are other opposing mechanisms that slow the chlorides down. These include chemical reaction to form chloroaluminates and absorption onto the pore surfaces. The detailed transport mechanisms of chloride ions into concrete are discussed in Kropp and Hilsdorf (١٩٩٥).

The other problem with trying to predict the chloride penetration rate is defining the initial concentration as the chloride diffusion is a concentration gradient, not a front. In other words we can use the square root relationship for the carbonation front as the concrete either is or is not carbonated, but we cannot use it so easily for chlorides as there is no chloride ‘front’, but a concentration profile in the concrete. Typical chloride profiles are shown in Figure ٣،٢ (a) and (b). Figure ٣،٢ (a) shows a ‘classical’ diffusion curve. Figure ٣،٢ (b) shows the more erratic profiles in a multi-story car park. The higher chloride concentrations at the deepest increments may be close to the soffit of the slab where chloride is concentrating due to evaporation.

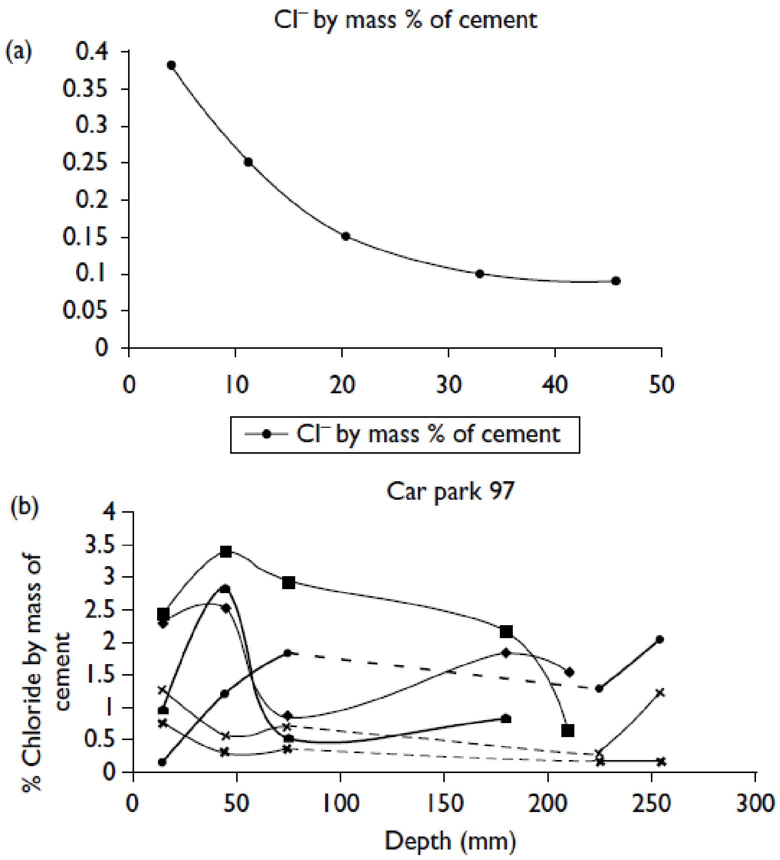

Figure. ٣،٢ (a) Chloride profile of a highway bridge from Broomfield. (b) Chloride profiles from a car park depth from Trend.

Figure ٣،٣., the effective recycling of chloride ions makes chloride attack more difficult to remedy as chlorides are therefore harder to eliminate.

Obviously a few chloride ions in the pore water will not break down the passive layer, especially if it is effectively re-establishing itself when damaged.There is a well-known ‘chloride threshold’ for corrosion given in terms of the chloride/hydroxyl ratio. This was first investigated by Hausmann (١٩٦٧).

Hausmann used a simple Monte Carlo (random number) calculation to show that if chloride ions and hydroxyl ions are competing to fill a break in the passive layer, the chloride ion starts to break down the passive layer when the chloride concentration exceeds ٠،٦ of the hydroxyl concentration. Haussman compared his theoretical calculations with laboratory tests with calcium hydroxide solutions. This is illustrated in Figure ٣،٤. The ٠،٦ Cl^- /OH ratio *approximates* to a concentration of ٠،٤٪ chloride by weight of cement if chlorides are cast into concrete and ٠،٢٪ if they diffuse in. In the United States a commonly quoted threshold is ١ pound of chloride per cubic yard of concrete. Although these figures are based on experimental evidence, the actual numbers are a function of practical observations of real structures.

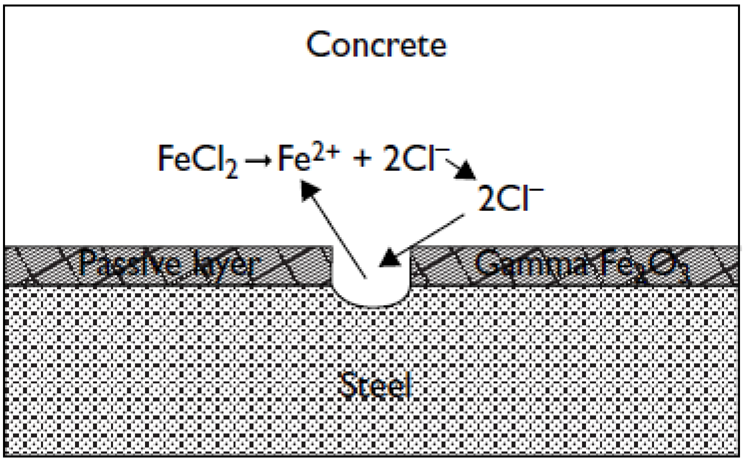

Figure ٣،٣. The breakdown of the passive layer and ‘recycling’ chlorides.

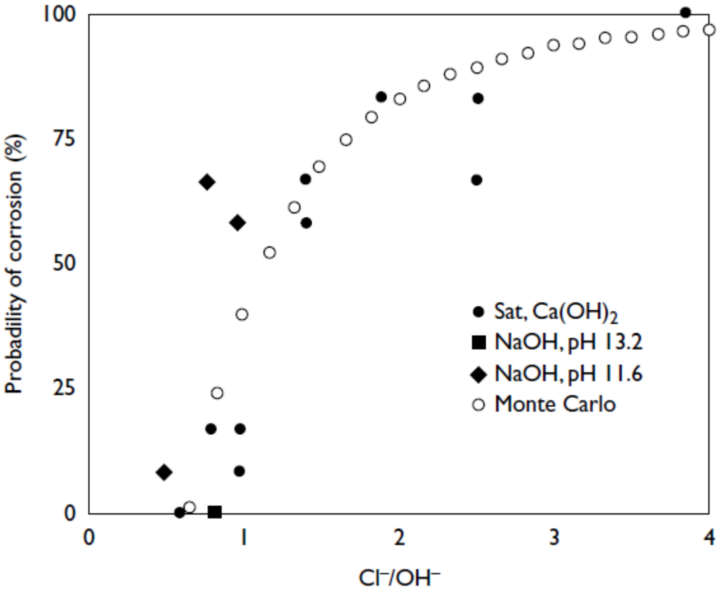

Figure ٣،٤. Probabilities of chloride-induced steel corrosion determined experimentally in high-pH solutions and predicted by a Monte Carlo Calculation.

٧. FACTORS INFLUENCING CORROSION OF REINFORCEMENT

In reinforced cement concrete construction the corrosion of reinforcement takes place due to the presence of chlorides and sulphates beyond a critical limit and when sufficient alkalies is not obtained within the concrete to maintain steel in a positive condition.The following factors are responsible for corrosion of steel reinforcement in concrete structure.

٧.١. QUALITY OF CONCRETE

Concrete consists of coarse aggregate, fine aggregate, cement and water. The right quality of materials with proper w/c ratio, correct mixing, adequate compaction by tamping or vibration and proper curing results in good quality concrete. if any of the above mentioned steps are not done in a specified manner, then that will result in a not so good concrete and there is a chance of corrosion of reinforcement. High strength concrete, i.e. dense concrete is impervious to a large degree and generally resists the carrion of embedded steel.

٧.٢. COVER THICKNESS OF CONCRETE REINFORCEMENT

The reinforcement is protected by suitable concrete covering over it. The greater the cover thickness more is the degree of protection against the various climatic and other environmental conditions. For various structural members, the cover thickness should be different depending upon their importance and degree of exposure. Evenness of concrete cover over the reinforcement is also very important for its corrosion protection.

٧.٣. CONDITION OF REINFORCEMENT

The surface condition of the steel reinforcement, at the time of its placing in concrete, affects its corrosion rate. If the reinforcement is contaminated with salt or badly corroded, the corrosive action on reinforcement after placement in concrete is promoted rapidly.

٧.٤. EFFECT OF ENVIRONMENTAL AND OTHER CHEMICALS

Chemical either from environmental or from within the concrete making materials are the main source of deterioration process. Due to attack of chemicals, the concrete develops cracks, which is the first sign of deterioration. The effect of chemicals is mainly due to presence of salt, carbonation, chloride attack and reaction of sulphates with tricalcium aluminate ($C_{٣}A$) present in cement.

Concrete is an intimate mixture of cement, aggregate and water which in the green state is highly alkaline. The hydration of cement develops calcium hydroxide which increases the pH value up to ١٢٫٥. In such alkaline conditions, the reinforcing steel is covered with a film of oxide which protects the steel.

٧.٥. POROSITY OF CONCRETE

The penetration of aggressive chemicals is possible due to permeability or porosity of concrete. The porosity of concrete depends on size, distribution and continuity of capillary pores. This depends upon the w/c ratio for given degree of hydration. The porosity also depends upon other factors, such as

- Age of concrete
- Degree of compactness
- The size and grading of aggregate
- Type of cement

٧.٦. EFFECT OF HIGH THERMAL STRESS

Normal concrete can withstand temperature up to ١٠٠˚C. Beyond this temperature the deterioration of concrete starts. The concrete in industrial plants and power stations required special protective measures otherwise the concrete may develop thermal cracks. Cracked concrete structures are consequently affected by the environmental chemical and the process of corrosion starts.

٧.٧. FREEZING AND THAWING CONDITION

In cold regions, the moisture in the pores of concrete freezes. The ice formation gives rise to volumetric expansion which may excess bursting pressure of surrounding concrete mass. This results in development of cracks in concrete and can lead to corrosion of reinforcement.

٨.Conclusion

Corrosion of steel in concrete can be seen to be a significant problem for many reinforced concrete structures if moisture is present. If there is no salt to cause corrosion in the short term, carbonation will affect most structures over the centuries. If the structure cannot be kept dry then there is a range of techniques that can be used depending on the structure, its condition and the cause and extent of the problem. Repairing damage caused by corrosion is a multi-billion problem. Observations of numerous structures show that corrosion of reinforcing steel is either a prime factor, or at least an important factor, contributing to staining, cracking and/or spalling of concrete structures. The effects of corrosion often require costly repairs and continued maintenance during the life of the structure.

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