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# Reinforcement bar Corrosion - Causes and Management

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## Abstract-

Concretes are composite materials which decay as a result of steel corrosion in concrete structures is mostly accelerated in environments laden with chlorides and industrial effluent gases as well as harsh chemicals employed in and those generated from wastes in agricultural industries. This review summarises the effects of various environmental pollutants which promote deterioration of concretes with resultant corrosion of reinforcing bar (rebar). An overview of traditional and current methods for significant reduction of this mode of material deterioration is described. Discussions on management tools for rebar corrosion in agricultural and marine environments have been highlighted. Repair methods include the traditional application of patch repair mortar which has been modified with polymeric materials to improve adhesion and reduce porosity. The use of cathodic protection system to reduce rebar corrosion to its barest minimum has gained currency. Attention should be directed at corrosion reduction practices at the design and planning stages as well as modification concrete mixes with modified agricultural wastes/products and polymers.

**Key words:** Rebar, concrete, steel, green corrosion inhibitors, agricultural industries.

## 1. Introduction

Agricultural, marine and other facilities are often built of reinforced concretes in order to withstand various inclement environments as well as heavy traffics of various animals and moving equipment. In the past, corrosion of reinforcement bar (rebar) in concrete mainly focused on bare steel. However it has been established that in the high alkaline concrete environment which is free of aggressive ions, such as  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{CO}_3^{2-}$  including uric acids, manures and fertilizer chemicals etc, a layer of tenacious oxide passive film forms on the surface of bare rebar which can protect the steel from corrosion [1]. This passive film is only a few nanometres in thickness and it may be compromised at flaws in the film, where the substrate is exposed to aggressive ions when present or gained access into the concrete in one manner or the other. The concentration of these aggressive ions must attain a threshold limit to cause corrosion of the rebar. Studies have shown that corrosion of steel in concrete containing chloride will gradually change from pitting corrosion to uniform corrosion, and the initial accelerated corrosion rate, later decreases as a result of re-passivation of the steel during favourable environmental conditions.

Later, a second generation of rebar materials made of scaled steels, which are supposed to simplify descaling procedures and save costs, were employed. It was established that the passivity of the scaled rebar can be maintained in the alkaline environment in the concrete as well as showing better resistance to chlorides, sulphates and agricultural chemicals attack



depending on post treatment of the rolled steel [2]. While the water cooled steel carries a loosely held oxide scale, with attendant appreciable number of flaws through which any chloride or aggressive anions in the steel environment will cause a high degree of corrosion damage, the air cooled counterpart has a more adherent and compact oxide layer. Hence, the air cooled steel gives a better performance.

This review describes the occurrence; methods of protection and monitoring rebar corrosion throughout the service life of reinforced structures with background information on the problem of reinforced corrosion. Further various additives into concrete mixes to improve the physical properties of concretes such as strength and porosity which will translate into better protection for the reinforcing steel bar against corrosion are well documented [3-7].

## 2. Reinforcement bar corrosion

The occurrence of corrosion implies the ingress of an electrolyte such as water contaminated with ions must be present on the metallic surface. The contaminated water which may be a thin layer of moisture must wet the rebar in the concrete. Once corrosion commences, its rate of progression is determined by revelation of anodic and cathodic sites as well as physical and chemical properties of the water in addition to the integrity of the concrete. This further determines the oxygen content in the concrete as well as its extent of carbonation. It has been established that, unprotected steel in the atmosphere quickly develops brown oxide which will continue to grow unless some means are provided to prevent its growth. According to Pourbaix [8], with reference to the E/pH diagram, Fig.1, the provision of an alkaline

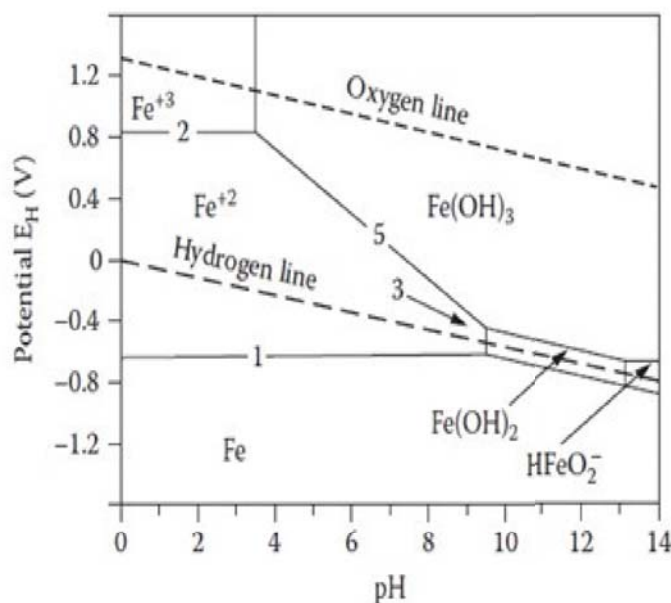


Fig.1.Pourbaix diagram of Fe-H<sub>2</sub>O system [8]

environment having a pH value in the range of 9.5 to 13 will provide such a deterrent to the occurrence of corrosion. An environment of this nature is provided by wet concretes in the

absence of aggressive anions. In the pH regime in concretes which may be between 12 and 13, passive films form on steel. This, in the absence of aggressive ions will reduce the rate of corrosion drastically. However, due to some extraneous environmental factors, corrosion of reinforcement bar still occurs. Rust has a larger volume than the parent steel which translates to stress being generated within the concrete and the result can lead to cracking, rust-staining and later spalling of the concrete cover to expose the steel bar, Fig.2, for further accelerated

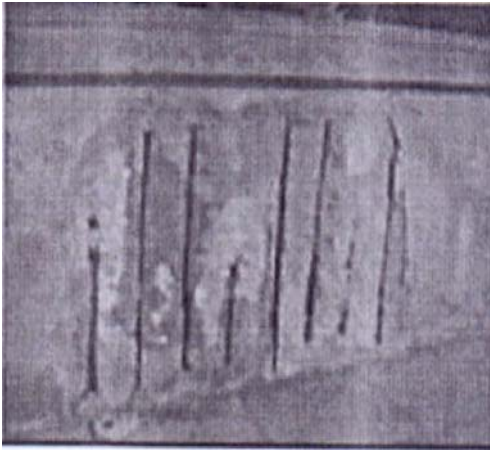


Fig. 2. Spalled reinforced concrete wall showing exposed reinforcement bar

corrosion. The rate of this will depend on the constituents in its immediate environment and oxygen. The occurrences of such phenomena mostly arise from loss of alkalinity in concrete in the environment adjacent to the rebar which is further dependent on the integrity of the concrete. In addition, the presence of high concentration of aggressive ions such as chlorides has been implicated as corrosion accelerators.

### 2.1 Loss of Alkalinity

Loss of concrete alkalinity is a major cause of rebar corrosion. This may arise as results of reactions with acid-forming gases (such as  $\text{CO}_2$  and  $\text{SO}_2$ ) in the atmosphere and subsequent leaching away of  $\text{Ca}(\text{OH})_2$ , a product of the hydration reactions of cement in the form of calcium bi-carbonate which is very soluble. Such carbonation reactions have been described in the literature [9] and may involve some step reactions culminating in the formation of  $\text{Ca}(\text{HCO}_3)_2$  which is very soluble. With the leaching phenomenon, a rapid and dangerous fall in the pH from about 12 to 8 will occur. However, if the concrete is of good integrity, the carbonation reactions take place only on the surface.

$\text{SO}_2$  in the atmosphere can react with  $\text{Ca}(\text{OH})_2$  in concrete directly in a similar manner to carbon dioxide culminating in the formation of hydrated calcium sulphate,  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ , which can then react with tri-calcium aluminate in the concrete to form calcium sulpho-aluminate hydrate. This complex has a volume which is about twice that of its precursor, calcium aluminate. The bulky nature of this product induces stress within the component parts of the concrete leading to cracks formation and consequent spalling and erosion of the concrete.

Other contaminants like chlorides and organic acids do cause deterioration of concretes based on similar reactions as exemplified by  $\text{CO}_2$  and  $\text{SO}_2$ . However, the extents to which these occur

are functions of the integrity of the concrete and on the conditions of exposure. For long term exposure as in the cases of bridges, provisions are often made for an acceptable degree of carbonation in the concrete bearing in mind factors such as porosity, permeability and degree of exposure. However, to provide the steel with an effectively permanent protective alkaline environment, the designer must ensure that the thickness of the concrete cover to the reinforcing steel closest to the surface is sufficiently greater than the depth of atmospheric penetration.

Usually, if not all cases, reinforced concrete structures are built to guidelines given in Standard Codes of Practice in which cases, very long maintenance-free lives are accommodated. However, it has been observed severally that concretes at times may not give the desired, almost indefinite, protection to the steel reinforcement. Such occurrences have been observed when:

(a) Errors of construction/supervision suggest that adequate concrete cover was not achieved for the reinforcement.

(b) The concrete may contain high concentrations of extraneous ions, such as chloride, either present in high quantity in the materials from which the concrete is made or rapid setting of the concrete was accelerated by addition of extra chloride.

(c) The concrete may be exposed to sea water as in the cases of bridges, thus additional precautions should be taken.

In these situations, it is desirable to know the extent of the impact of corrosion on the steel reinforcement.

However, chemical admixtures are often added to modern structural concretes such as blast furnace slags, fly ash or silica which may be derived from waste agricultural products such as rice husks, corn cobs etc. The most commonly employed admixtures are plasticizers which improve workability of concretes [10] with subsequent reduction in porosity within the finer structure induced by this additive. In general a concrete with higher strength and improved durability will be achieved.

## 2.2 Chloride ingress in concretes

Chlorides can enter concretes by various mechanisms which include capillary absorption, wick action, diffusion and permeation depending on exposure conditions. Conventionally, durability of concretes can usually be addressed by the selection, at design stages, a combination of thickness and depth of concrete cover, which is adequate to eliminate high chloride concentration over and above the threshold limit at the depth of the reinforcement within the design life of the structure. Chlorides have been established to be injurious to steels and other metals of construction at a level of about 0.35% to 1% by weight of cement especially in moist conditions which can allow the flow of corrosion currents. Such corrosion damages arise as a result of the disruptive actions of chlorides on the passive oxide layers of steel which are converted from the stable, gamma variety to soluble, iron chloride. Thus, from thermodynamics point of view, the region of passivity of iron on the E/pH diagram [8] will be reduced while expanding the active zone. Hence kinetically, all forms of corrosion, ranging from pitting to general will occur on the steel's surface depending on the resistivity of the environment and the integrity of the concrete. However, as indicated earlier, the addition of extra cementitious materials, such as slags, ashes derived from waste agricultural materials which contain substantial quantities of silica often induce improved durability as a result of pore refinement in concretes. In addition, adequate incorporation of these secondary materials often achieves high degrees of resistance to chloride ingress and sulphate attacks.

### 2.3 Agricultural Wastes and Chemicals in Concretes

Various agricultural chemicals are aggressive towards concretes. These range from uric acid which are wastes encountered in urine. Such acids neutralise the alkaline environment provided by cement thereby causing sharp decline in the alkalinity and further convert the components of the concrete to their soluble salts. Consequently, erosion of the concrete will expose the rebar to inclement outside environment with its attendant accelerated corrosion and further erosion of the structure. Thus, in agricultural environments, reinforcements require additional attention in terms of managing corrosion right from the design stages.

### 3. Management, protection and monitoring of rebar corrosion

It has been considered adequate that, epoxy coated reinforcing bars as corrosion resistant alternatives to bare carbon steel bars are adequate for on-shore reinforced structures as well as marine sub-structures. Several case studies [9] on the durability and deterioration of both bare and epoxy coated C-steel bars within 30 years period found the applicability and corrosion resistance superiority of the epoxy coated counterpart. In addition, the methods for predicting the end functional service life for structures reinforced with bare and coated bars have shown that the epoxy coated bars can give three times years of maintenance free service life over and above those of bare C-steel bars. Epoxy coating, a relatively modern development, provides barrier for reinforcing steels which will be exposed to significant moisture and chlorides on bridge decks as well as marine sub-structures. The coating provides an additional barrier that is resistant to corrosive anions and significantly increases the service life of the reinforced structure. However, minor setbacks to the use of this procedure have been encountered in extremely harsh environments where corrosion of coated rebar occurred at cracked regions in concretes and at some coating defects due to damages during construction. These notwithstanding, epoxy coated rebar still proved to be a cost effective alternative to C-steel rebar in reducing maintenance costs over a long service period. In addition to the aforementioned improvements, epoxy coatings also act as insulators to electronic movements which contribute to electrochemical corrosion.

Another highly favoured management tool is the use of stainless steel rebar with proven resistance to chloride ions. Although stainless steels are far more expensive than mild steels, however, they do not corrode over the design life of structures which has been taken to be 125 years in the case of highway bridges. From this consideration, downtime for maintenance and costs implications are drastically reduced which make the use of stainless steel very attractive despite the initial costs of implementation of this option. There are several types of stainless steel; however, types 315 and 316 are favoured over others as a result of their resistances to corrosion on experimental exposure to stagnant and flowing sea water over a period of 12.5 years. On the other hand, carbon steel exhibited corrosion and loss of strength.

Other management tools include the use of prediction models which can be safely divided into damage prediction and corrosion rate prediction models. The former is predicated on some and combinations of the following methods in determining the conditions of reinforced concretes (i) visual inspections of surface and under carriage of concrete structures; (ii) delamination survey with the use of steel hammer or rod in sounding the structure. In this case, the resultant sound can be interpreted as the presence or absence of delamination; (iii) depth of cover measurement with the use of pachometer which measures concrete thickness variation by means

of magnetic flux. Although a destructive analogue of holes drilling to make direct measurements have been employed as well, however, the former is preferred for obvious reasons; (iv) determination of chloride content with the aid of ion specific probes. Such probes convert voltage measurements from a solution of 3 grams of concrete powder taken at a specific depth, into percent chloride by weight of concrete; (v) Others include potential mapping as per ASTM C876 standard; petrographic analysis; determination of rebar cross section loss; rebound tests using a spring driven hammer and penetration test which involves driving a small rod into the concrete while the distance of penetration indicates the compressive strength of the concrete. Thus, models developed along these routes do not take into consideration the time and other environmental-dependant corrosion damages to the rebar which influence the integrity of the concrete in service. The corrosion rate dependent models have been developed by various researchers, however, the most popular is that developed by Weyers *et al.*[11] called “diffusion spalling model”. This model used Fick’s law to calculate the length of rebar corrosion initiation period. To this period, it was stipulated that 4-5 years are added for the corrosion products of the steel to build up to an extent that will cause extensive damage to the concrete in order to warrant damage control management.

Prior to discussion on damage control management, it is pertinent to mention methods for corrosion monitoring techniques for rebar corrosion in order to forestall end of service life maintenance. These include detection by electrode potential measurements with reference to copper/copper sulphate standard electrode which provides information on passivity if the potential is 0.2V, whereas, it indicates corrosive activities if the potential is 0.35V and above; detection by constant anodic current polarization method; monitoring by electrical resistance probe which can continuously, on daily bases, give corrosion figures that can be converted to corrosion rates. Others are monitoring by polarization resistance probe method and monitoring by alternating current (AC) impedance which may still in its infancy for use on steel in concretes. It has the advantage of being independent of the resistivity of the concrete. However, using some of this electrochemical corrosion inspection/monitoring techniques, a recent study [12] on a reinforced concrete bridge in Sweden showed that it was in good condition. This was confirmed to be true during visual inspection which revealed little or no corrosion of the steel after the reinforced bridge was loaded to failure.

Other corrosion and environment-induced concrete damage monitoring methods, such as imaging techniques have been advocated by various researchers [13,14], however, evaluation of relevant and promising processing technologies are still ongoing.

### **3.1 Damage Control Management- Repair and Rehabilitation Strategies**

It may be understandable that epoxy coated reinforcements (ECR) and stainless steel reinforcements (SSR) may not require rehabilitation within the current knowledge of their service lives, some of the drawbacks witnessed in the use of ECR have been mentioned in which epoxy coating defects and disbondment have been sources of concern to the integrity of reinforced concrete. It is common knowledge that, C-steel reinforcements require rehabilitation and maintenance within 12-20 years of construction. While there are yet to be established guidelines for repair/rehab for ECR and Stainless steel reinforcements (SSR), a general approach can be described as follows:

- (1) For cracking which is not induced by corrosion, rehabilitation can be effected by injection of epoxy coatings into the cracks and flooding same with corrosion inhibitors.
- (2) For corrosion induced cracking and spalling, recoat the steel with epoxy coating after thorough cleaning and application of anti-rust [15]. Apply corrosion inhibitors on all surfaces and in case of delamination, add corrosion inhibitors to repair mortar.

There are various types of inhibitors [16], some synthetic [17] while others are naturally occurring and can be extracted from several plants such as pawpaw leaves [18] and the dried skin of onions which has no food nor commercial value but its extracts performed well as corrosion inhibitors [17] cannabis extract [20], argan extract [21], onion extracts [22], *coriandrum sativum* leaves extract [23], *veronica amygdalina* [24,25], *Jatropha curcas* [26], *curcuma longa* [27], rice husk [28, 29], *treculiaafricana* [30], *atropa belladonna* [31] and many more. These are eco-friendly and sustainable. They are referred to as “Green corrosion inhibitors” and are currently being investigated by several researchers in order to gain further insights into their potency. However as mentioned by Oki [32] elsewhere, the biodegradability of green inhibitors puts them at a disadvantage because microbes will feed on them and their dosages will be continuously replenished in order to maintain a reasonable level of corrosion control which may imply higher costs. In addition microbial induced corrosion may become very important in such an environment after a protracted period of time. However for the biodegradable inhibitors to be viable they must be mixed with other eco-friendly inorganic inhibitors/organic chemicals.

Another important rehabilitation strategy is the use of cathodic protection. Although this can be incorporated at the design stage, it is also useful in arresting the advancement of rebar corrosion in on-going reinforced structures. When applied at later stages of commencement of chloride induced corrosion, the alternate anodic reaction will be the oxidation of chloride leading to formation and elimination of chlorine as gas from the environment of the concrete with limited moisture content [33].

There is a web based tool described by Broomfield [34] in which the technique selects repair options and analyze life cycle costing of corrosion damaged rebar concrete structures. From such considerations, it was concluded that from quantitative analyses of good quality survey data, the costs and advantages of different repair options can be obtained objectively.

### Conclusions

For reinforced agricultural facilities, it is best to incorporate, at the design stage, corrosion prevention gadgets such as means of monitoring corrosion of rebar and cathodic protection, use of inhibitors in concrete, as well as planned maintenance schedule. Prediction models are veritable tools in the management of rebar corrosion. However, management of reinforcement bar corrosion and its attendant damage to concretes should commence at design stages wherein all relevant and necessary corrosion prevention methods and monitoring techniques are incorporated.

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