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Prevention of Corrosion of Steel Reinforcement in Concrete

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Abstract. Premature failure of reinforced concrete structures occurs primarily due to early corrosion of steel reinforcement. These reinforcements are prevented from corrosion by the formation of a passive oxide film in the high pH environment of concrete. However, pH decreases in actual conditions due to the ingress of harmful ions like carbon dioxide, sulphur dioxide, chloride, etc., leading to localized corrosion. In view of the intensity of the problem, serious efforts have been made to prevent corrosion of reinforcement. These have led to the development of varying types of prevention techniques/measures including coatings, electrochemical techniques like cathodic and anodic protection, inhibitors, control of concrete mix and reinforcement with superior corrosion resistance. These preventive techniques have inherent advantages and disadvantages with respect to the type of structure and the surrounding environment.

INTRODUCTION

From many years, humans have taken advantage of ductile materials with high tensile strength in the reinforcement of brittle materials with high compressive strength. The ductile reinforcement transfers tensile loads in the structure, allowing the brittle material to crack without causing failure of the structure. Throughout the last two centuries, concrete has been developed into a construction material with ever increasing potential to support compressive forces. As the compressive capacity of concrete has increased and with it demands to support longer and larger and taller structures, stronger, more ductile and more tensile reinforcement has been required.

Reinforced concrete (RC) is nowadays present in a large part of the infrastructure all over the world. The high compressive strength of concrete combined with the tensile properties of steel makes it a competitive and versatile material suitable for a multitude of applications. Existing structures made of RC include, for instance, bridges, tunnels, harbours, dams or off-shore platforms, as well as a wide range of buildings. It is precisely due to this broad variety of applications that reinforced concrete structures are often exposed to extremely severe conditions, e.g., marine environment, freeze-thaw cycles, carbon dioxide, chemical and biological attack, etc.

Corrosion, due to chlorides present in sea water and in most of the de-icing salts used to remove ice and snow from the roads, is today regarded as one of the biggest problems affecting the durability of RC structures [1]. Corrosion of reinforcing steel is avoided in the first place because it entails the appearance of surface cracks and rust stains giving a bad aesthetic impression. However, if corrosion proceeds, it may lead to a serious loss of the local cross-sectional area of the reinforcing bars and a reduction of the bond between the concrete and the steel, both of which affect the structural behaviour of the RC element and which may eventually compromise the stability and safety of the structure. During the last century a number of structural failures have occurred the causes of which have been mainly attributed to corrosion problems [2].

Over the past 30 years, a number of approaches have been established and followed by asset owners and managing agent contractors. All aim to stop on-going deterioration and extend the service life of the structures.

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Techniques previously employed can be broadly categorized in the following four approaches:
1. Conventional
2. Surface treatments
3. Electrochemical treatments
4. Design solutions

Figure 1 provides a comprehensive, but non-exhaustive, summary of the various techniques and how these fit under the above approaches.
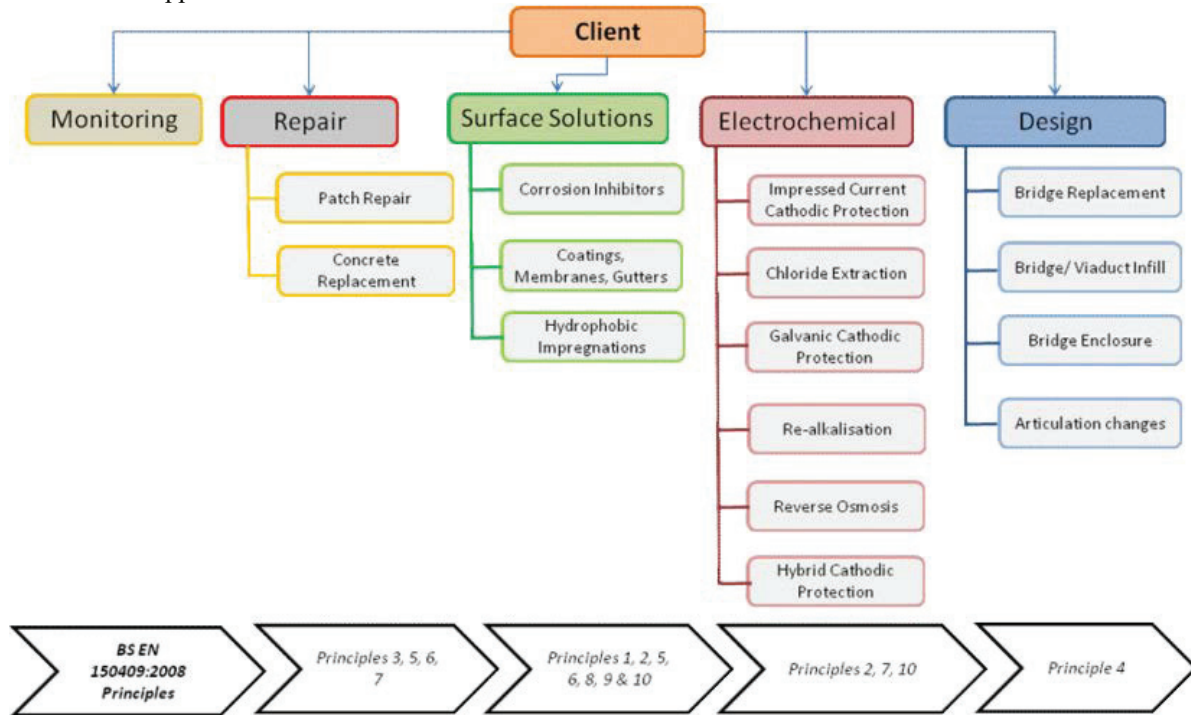

FIGURE 1 Categorization of corrosion management techniques based on the nature of the works

RELATED WORKS

VYogeshIyer Murthy et al. (2017) the performance of pure magnesium anode is evaluated systematically by subjecting bare reinforcements and reinforcements tied with anode in extreme chloride ion atmosphere. It is concluded that pure Magnesium being electro-chemically active compared to reinforcements, acts as anode, while reinforcements are rendered cathode. Hence, reinforcements are protected from corrosion. Further, the weight loss in anode supplements the conclusion drawn. The weight loss for bar reinforcements is reported to be drastic during the initial 12 days while that of reinforcements tied with pure Magnesium is found to be negligible even up to 80 days. Five distinct zones of corrosion are identified in bare reinforcement. Zone V is identified as corrosion free zone, which in due course of time is expected to be prone to rusting and later corrosion. From the results, it is well-established that pure Magnesium anodes are effective means of cathodic protection of steel reinforcements. Shakir A. Salih et al.(2011) examined the effect of combining repair and substrate materials with different physical properties on the corrosion of embedded steel. The experimental program includes casting, curing, and testing five different mixes of repair and substrate materials. All tests are conducted at early and later ages after one year of severe exposure conditions. The physical properties such as water absorption and porosity of each repair and substrate materials have been examined to quantify the range of these properties. The electrochemical compatibility of the materials was measured using linear polarization resistance measurements using Gecor instrument in later age. Results indicate that minimizing the porosity differences between the repair and substrate materials reduces the corrosion currents measured in both the repair and substrate materials. B. Elsener, M. Büchle et al.(1999) showed

that experiments in solution were useful for the characterization of the efficiency of the inhibitor and the determination of influencing parameters. However, experiments in mortar were required to confirm the obtained results. A. W. Otunyo et al.(2018) investigated the effectiveness of resin/exudates in corrosion prevention of reinforcement in reinforced concrete cubes. The reinforced concrete cubes of dimension (150mm x 150mm x 150mm) were coated with dacryodesedulis resin paste of various thicknesses: 150um, 250um, and 300um. The reinforced concrete cubes were exposed to a corrosive environment for 60days after 28 days of curing. in order to stimulate accelerated corrosion of the reinforcing steel. Another test was carried out with steel reinforcement cubes, whose steel reinforcement were not coated with dacryodesedulis resin but also exposed to the same corrosive environment. for the same 60 days after 28 days curing.

PREVENTING REINFORCEMENT CORROSION

Researchers from different disciplines have tried to develop different preventive methods based on the experience related to their field For example, metallurgists or materials scientists developed corrosion resistant rebars and metallic coatings, chemical engineers or chemists developed organic coatings, whereas civil engineers developed better understanding of concrete control. Therefore, thorough analysis is needed of various preventive methods, their advantages and disadvantages.

Since corrosion is an electrochemical process, it involve a cathode, an anode and a suitable environment The corrosion takes place at the anode and simultaneous reduction of hydrogen or hydrogen evolution takes place at the cathode (in the case of an acid solution) or hydrolysis of water giving rise to hydroxide ions (in the case of a highly alkaline solution). The rates of both the anodic and the cathodic process are always equal. The environment (electrolytic solution) provides a way for electron as well as metal-ion transfer. The rate of corrosion can be restricted by the absence of any of these three, or by regulating them.

The corrosion of reinforcement can be prevented by
(i) Use of corrosion resistant steel rebars,
(ii) Use of a protective coating on the rebar,
(iii) Use of an electrochemical technique, and
(iv) Control of concrete mix.

Corrosion Resistant Rebars

In recent years, efforts have been made to develop corrosion resistant rebars to prevent reinforcement corrosion (Table 1). These developments have been based on (i) alloy additions and/or (ii) micro structural control.

A.   Low-Alloy Steel Rebars
Alloying elements like Cu, Cr, Ni, W, P, etc. are added for this purpose. Chromium has been the common choice by most of the researchers; however, other alloys have also been added along with chromium. This is due to the fact that Cr makes the iron oxide denser and adherent. These steels still rust, but under highly alkaline conditions the rust formed becomes adherent and protective so that corrosion becomes less rapid than with ordinary steels.

B.   High-Alloy Steel Rebars
These rebars belong to the stainless steel category where alloy additions are made in excess of 12%. Both ferritic as well as austenitic stainless steels have been used for reinforcement purposes. Cochrane 1521 observed that only austenitic stainless steel (Type 304) was wholly serviceable in the high chloride concentration (3.2% chloride ion equivalent to 5% by weight of cement) whereas ferritic stainless steels (Types 405 and 430) were affected by the same chloride concentrations. McDonald et al. have shown that the use of austenitic stainless steel for the reinforcement of concrete bridges would add between 6% to 16% cost to the structure. It is reported that stainless steel rebars, besides showing superior corrosion resistance properties, show only negligible reduction in tensile strength and yield strength when exposed for two hours at 600°C. Non-magnetic steels having superior corrosion resistance have also been developed for use in various concrete structures, such as magnetic floating high-speed railways, nuclear fusion facilities and marine structures and appliances where non-magnetic properties are required in addition to corrosion resistance.

TABLE 1. Corrosion Resistant Reinforcement

Rebar Quality	Alloying Elements	Addition
Microalloyed steel	Microalloy	**
Low-alloy steel	Cr	2%
	Cr + Cu	0.75% min.
	Cr + Cu + P	1.62% max.**
	Cu + W	3.5%
	Ni	1.0-5.5%Ni;
	Ni + W	0.001-0.5%W
		12%
High-alloy steel	Cr	Ferritic
	Stainless steel	Austenitic
	Al + Cr + Cu/Ni + Ti/Nb/Mo/V/W/Cb/B (Non-magnetic steel)	20.0-37.3% Al 5.50 -10.0% Cr 0.1-5.5% Cu/Ni 0.01-0.5% Microalloy

C.   Inhibited Cement-Slurry Coating

Due to the failure of epoxy-coated reinforcing steel in marine substructure service, interest has recently been revived in macro-cell corrosion studies. The steel reinforcement embedded in concrete is surrounded by an alkaline medium; a coating based on cement is expected to be more compatible. A cement coating is a passivating type of coating and may have higher tolerance towards defects. Because of the surrounding concrete, which is again alkaline, the galvanic effect is likely to be pronounced. Various passivating treatments for reinforcement have been suggested, such as pickling in hydrochloric acid followed by treatment with phosphoric acid and treatment with a hydrolysable silicate or hydrated silica. Simple preliminary coating of steel with a dense mortar is recommended to counteract acid fumes

Protective Coatings

The use of coatings for corrosion protection of structures has already been presented in detail by Giudice et al. Coated steel reinforcements have been widely used in many areas, like moderate-to-severe exposures, such as marine and coastal construction, industrial plants, water treatment and chemical processing facilities, power generation facilities, and bridges and highways. Coated reinforcements are also used in less severe applications in building and construction fore cast-in-place and precast elements. Different types of coatings suitable and unsuitable for rebar are included in Table 2.

A.   Metallic Coatings

The development of metallic coatings was based on their role as regards corrosion in combination with the parent metal (mild steel, in general). In view of this, two broad types of coatings have been developed. These are (i) passive film-forming coatings, e.g. Si-based coatings, Cr-based coatings, and (ii) sacrificial coatings, e.g. galvanizing. The first option is based on a passive Film formation and its adherence to the rebar. It may lead to localized attack, if broken during service, transportation, fabrication, etc. It should be noted that the parent metal acts as an anode compared to the cathodic passive film. However, in the second option, corrosion prevention is based on a sacrificial anode compared to the cathodic underlying parent metal, and, therefore, even if the coating is broken due to the above-mentioned reasons, the metal remains protected.

B.   Organic Coatings

Organic coatings include epoxy coatings, polyvinyl chloride, polypropylene, phenolic nitrite, polyurethane, etc. All these coatings act as a barrier to the aggressive ions, moisture and oxygen and remain cathodic with respect to the steel. Of these, epoxy coatings have been most popular.

TABLE 2. Different Types of Coatings for Steel Rebar

System	Disadvantages
Coatings not suitable	
Red lead	Deterioration in alkaline medium
Coal tar enamel	Brittle, subject to cold flow, sticky
Asphalt	Subject to cold flow
Phenolic	Deterioration in alkaline medium
Urethane	Hard, brittle, intolerant to poor surface preparation
Neoprene	Poor bond
Vinyl	No concrete to vinyl bond
Aluminum	No electrical insulation effect, rapid corrosion in presenceof chloride
Coatings suitable	
Zinc/cadmium	Sacrificial, rapid corrosion in the presence of chloride; noelectrical insulating effect
Nickel/copper	Not suitable for chloride exposure, no electrical insulatingeffect, galvanic corrosion
Epoxy	Hard and brittle. In many formulations will not bend orstretch Many formulations have poor bond. Only powderepoxy suitable.
Chlorinated rubber	May bond to both concrete and steel

Cathodic Protection

Cathodic protection is currently becoming one of the most useful methods in corrosion protection because it controls the electrochemical corrosion process itself.

In this method, the structure to be protected is made into a cathode by supplying an electric current from an external d.c. source. The cathodic protection method may be broadly classified into two categories: (i) sacrificial anode cathodic protection and (ii) impressed current method. Pithouse has studied both types of cathodic protection systems on concrete repair work and found that the current systems have been the most successful. He found that the distributed mesh systems are the latest development and have proved to be very effective.

One of the main criteria for effective cathodic protection is that the applied current should be uniformly distributed to the steel to be protected. A highly non-uniform current distribution may not only leave some of the reinforcement unprotected; it may also cause the formation of macrocells between protected and unprotected steel, as well as the danger of hydrogen evolution in the high current zones.

A.   Sacrificial Anode Cathodic Protection

This preventive method is based on the use of a sacrificial anode which is consumed during corrosion and the reinforcement remains unaffected. The standard electrode potential of the sacrificial anode must be lower than the standard electrode potential of the reinforcement so that during galvanic corrosion, the reinforcement acts as the cathode and remains unattacked. Zinc as the sacrificial anode is the unanimous choice for cathodic protection. This may be present in the form of a coating or separately, being electrically connected with the reinforcement.

B.   Impressed Current Cathodic Protection

This system is more flexible but more complex than a galvanic anode system. The basic principle is the same for both systems, except that the impressed current system energizes the anode by means of an external electrical energy source. The DC current is passed into the electrolyte by means of an internal electrode like a lead-silver alloy or platinum. A number of studies have been directed towards this method. McArthur has shown through modeling that the cathodic area is initially made very alkaline immediately after switch-on, and the anodic area becomes acidic in nature. This acidic area spreads out from the anodic electrode toward the cathodic area. It is found that this alkalinity is produced at the cathodically impressed rebar as the impressed current uses up the dissolved oxygen requires the

hydroxyl ions to carry the ionic current, and produces hydrogen. For cathodic protection to work effectively there must be a way for oxygen to diffuse to the cathodic area, so that it takes part in the cathodic reaction. The anodic area becomes acidic and the alkaline OH" ions are moved away from the rebar as a requirement for continuous current flow.
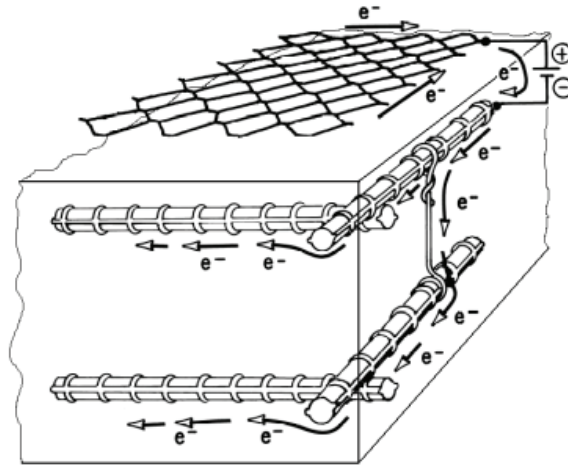

FIGURE 2 Cathodic protection systems for steel reinforcement in concrete

ANALYSIS DISCUSSION

In recent years, efforts have been made to develop reinforcement steel with better corrosion resistance. These corrosion resistant rebars do not require any special care during transportation, storage, fabrication, placement or even construction. Moreover, they do not require any skilled labour and capital investment, design changes, etc.

Cathodic protection applied to steel in concrete is normally considered effective if the 100 mV decay criterion is fulfilled, i.e. if a decay of at least 100 mV is achieved during a certain period (usually 4 or 24 h). This criterion, which was developed empirically, has shown to be effective in practical applications, and is also recommended by standards. Recently, it has been suggested that the achievement of a decay of 100 mV should imply that a near passive state has been induced on the protected steel. The 100 mV decay criterion has shown to be applicable to cathodic prevention as well. Tests with very low cathodic current densities applied to passive steel in chloride contaminated concrete showed that this criterion is also reliable in evaluating the effectiveness of this technique. In fact, current densities able to achieve 4-h decay higher than 100 mV were sufficient to maintain passivity on steel bars even when chloride content up to 3% by weight of cement was reached near the steel surface. In proposed method for Prevention of corrosion of steel reinforcement in concrete is giving better result than previous research.

CONCLUSIONS

From the above discussion, it is evident that a good concrete cover in terms of quality of ingredients, mix proportion, water-cement ratio, etc., has no substitute for the prevention of reinforcement corrosion. Corrosion takes place only when a path exists for the ingress of chloride, sulphur dioxide, oxygen, etc., in the concrete cover.

Steel reinforcement can also be prevented through cathodic protection. As mentioned above, a zinc-based sacrificial anode cathodic protection system is considered a better choice than the impressed-current cathodic protection method due to practical difficulties involved with the latter. These include non-uniform distribution of current due to the complex non-homogeneous nature of concrete, electrical connections to all embedded rebars, large capital investment, and suitable provision in the structural design a large number of studies are also directed towards concrete additives like corrosion inhibitor and fly ash which have been found useful in preventing

reinforcement corrosion. It can be concluded that the upmost care should be taken during concrete-mix preparation and construction the choice of other protection methods will depend upon the type of structure to be protected, life expectancy, and nature of environment and cost of application.

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