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Review on Cathodic Protection of Embedded Steel Bars in Concrete by Sacrificial Anodes

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Abstract - *Corrosion of the reinforcement in concrete structures had been realized to be a serious problem world-wide in the 60s and 70s and the amount of damages still increased considerably in the 80s, extensive research programs had been initiated to understand the mechanisms of reinforcement corrosion and to become able to assess, repair and maintain those structures appropriately. In INDIA, though the research has gained little popularity in this area. This literature review is aimed for studying latest trends of the work being carried out world over in cathodic protection of steel bars in concrete in prevention and protection of corrosion. Also, this review is carried out for identifying research gaps in cathodic protection methods using sacrificial anodes.*

***Key Words*: Corrosion, Cathodic Protection(CP), Steel Rebars, Sacrificial Anodes, Concrete Structures**

1. INTRODUCTION

1.1 Rebar Corrosion in Concrete

Infrastructure development, that is going on today, all over the world, is like never before. Reinforced cement concrete is the most versatile and potentially one of the most durable materials that a designer can choose for almost any type of structure. It is because RCC can be mould into almost any desired shape; it is weather resistant, strong and durable under the normal exposure conditions.

Today the major problem currently confronting the construction industry all over the globe is 'deterioration of RCC structures'. The phenomenon is so pervasive that it has created almost a crisis-like situation and has put the engineering fraternity on red alert. A number of factors are responsible for early distress in RCC structure. However, all over the world 'Rebar Corrosion in concrete' is seen as major cause of distress of structures and thus an issue of major concern in the sustainable infrastructure development.

Worldwide, it is now confirmed that, even after specific national building code requirement of durability are followed, there is always a high risk of premature rebar corrosion in concrete. Even when, code specification for concrete cover and concrete quality are observed, rebar corrosion in concrete occurs, causing loss of serviceability and safety of RCC structures. The scale and extent of the problem is severe.

Zumdahl [30] defined Corrosion as it is a spontaneous process of returning metals to their natural state by oxidation reduction reactions. Corrosion of metals results in a loss of both structural integrity and attractive appearance, 'Rebar corrosion in concrete' is attributed to 'differential concentration cells caused by non-homogeneity of the concrete and its environment'. The main sources of cell potentials are differences in pH, oxygen and chloride content, commented Hausmann [31]. This difference in potential can result in electrochemical corrosion cells forming between areas on the reinforcement where the protective film has been destroyed and the remainder of the surface where the film is still intact. Such cells create minute electric currents which flow through the reinforcement in one direction and return through the concrete by electrolytic conduction.

Following are some facts about corrosion of steel, in general.

- Internationally, 1 tonne of steel turns into rust every 90 seconds.
- The energy required to make 1 tonne of steel is approximately equal to the energy an average family consumes over three months.
- To make one tonne of steel, around 2.9 tonnes of CO_2 equivalent of Green House Gases are pumped into the atmosphere.
- Of every tonne of steel from the world's production, approximately 40% is required to replace rusted steel.

1.2 Cost of Corrosion

Nearly 3% of national GDP of almost every country is spent on repairs due to corrosion. For a developing nation like India, this amount is very high. GDP of India in 2010 is estimated to be between $1000 trillion to $1300 trillion. If cost of corrosion is considered to be a moderate 3% of GDP, a huge $30 trillion to $40 trillion is spent on corrosion, that is, INR 1400000Cr to 1850000Cr.

"The cost of corrosion in US is estimated to be around $364 billion as of 2004. This does not include the indirect cost and other consequential damages. If this is taken into account, it would go up several times from the present level of 3.1% of GDP", said Houston-based NACE International president George Hays [34] during his presentation at the NACE International India Section conclave in Mumbai on November 15th, 2004. "As for the cost of corrosion in India alone, it is estimated to touch Rs. 36,000 crore," said Mr. Hays, "We can only be proud that we have enough money to lose like this! Yet another fact is that we are not in bad company as the cost of corrosion in US is much over $360 billion."

In the UK, total construction industry expenditure was about £56 billion in 2000. It is expected to be in the tune of £200 billion in 2010; some 40% of this amount is spent on repairs and rehabilitation due to corrosion.

1.3 Corrosion Control

Emerging trends today to combat corrosion can be broadly classified into the following categories. More or less, each of the following idea is based on one or the other principle mentioned above.

1. Additives in Concrete
2. Concrete Coatings
3. Rebar Coatings
4. Sealants
5. Metallurgy of Rebars
6. Sacrificial Anode Cathodic Protection
7. Impressed Current Cathodic Protection (ICCP)
8. Electrochemical Realkalization (ERA)
9. Electrochemical Chloride Removal (ECR)
10. Galvanic Protection (GP)
11. Discrete Galvanic Anodes (DGA)
12. Application of Nanotechnology

Among the various corrosion control methods available, cathodic protection (CP) is a major technique adopted to control the corrosion of steel embedded in concrete worldwide.

2. LITERATURE REVIEW

This literature review is focused on various aspects of corrosion and cathodic protection of reinforced concrete structures using different anodes including prestressed, corroded and marine structures with magnesium, zinc anodes with conducting coatings, including current density and miscellaneous aspects involving environmental influences, passivation, giving attention to cathodic protection and prevention. Special attention is given for sacrificial zinc anodes and zinc wired rebars.

Corrosion and cathodic protection of reinforced concrete structures

Steven F. Daily [16] has studied corrosion of steel in concrete and observed that there are two major situations in which corrosion of reinforcing steel can occur. These include:

1. Carbonation, and 2. Chloride contamination

Corrosion and Cathodic Protection Theory

Bushman [38] reviews the corrosion process and observes that, nature has endowed each metallic substance with a certain natural energy level or potential.

When two metals having different energy levels or potentials are coupled together, current will flow. The direction of positive current flow will be from the metal with the more negative potential through the soil to that which is more positive. Corrosion will occur at the point where positive current leaves the metal surface.

Cathodic Protection Fundamentals

Cathodic protection (CP) is the only technology that has proven to stop corrosion in existing reinforced concrete structures, regardless of the chloride content in the concrete.

CP is a widely used and effective method of corrosion control. In theory it is defined as the reduction or elimination of corrosion by making the metal a cathode via an impressed direct current (DC), or by connecting it to a sacrificial or galvanic anode. Cathodic areas in an electrochemical cell do not corrode. By definition, if all the anode sites were forced to function as current-receiving cathodes, then the entire metallic structure would be a cathode and corrosion would be eliminated.

A sacrificial or galvanic anode system for reinforced concrete uses a more reactive metal (anode) such as zinc or aluminum-zinc-indium (Al-Zn-In), to create a current flow. Sacrificial anode systems are based on the principle of dissimilar metal corrosion and the relative position of different metals in the galvanic series. The direct current is generated by the potential difference between the anode and reinforcing steel when connected. The sacrificial anode will corrode during the process and is consumed.

Corrosion control of steel-reinforced concrete

D.D.L. Chung [18] reviewed the methods viz. steel surface treatment, the use of admixtures in concrete, surface coating on concrete, and cathodic protection and materials for corrosion control of steel-reinforced concrete. His paper is a review of the methods and materials for corrosion control of steel-reinforced concrete.

Selection guidelines for using cathodic protection

Rod Callon et al. [1] have provided guidelines to owners and design engineers for proper selection of cathodic protection systems to overcome corrosion problems on reinforced and prestressed concrete structures. They have observed that when cathodic protection is selected as a rehabilitation method for a concrete structure, there are many choices that can influence the type, effectiveness, durability and cost of the system. If the structure is complex in design and exposed to a dynamic environment, proper selection of the system components is important to suitable performance and longevity of the system. They have also observed that while making selection of anode the parameters, such as anode life, protection current densities, zoning, current distribution and maintenance have to be considered.

2.1 Different alloy anodes

Magnesium alloy anodes

G.T. Parthiban et al. [2] have carried out a study with a view to analyse the use of magnesium alloy anode for the cathodic protection of steel embedded in concrete. They observed that the magnesium anode was found to shift the potential of the steel to more negative potentials initially, at all distances and later towards less negative potentials. The chloride concentration was found to decrease at all the locations with increase in time. The mechanism of cathodic protection with the sacrificial anode could be correlated to the removal of corrosive ions such as chloride from the vicinity of steel. They studies indicated that longer durations are required for the cathodic protection to stabilize.

Aluminium alloy anodes

S.M.A. Shibli et al. [7] have studied the development of high performance aluminium alloy sacrificial anodes reinforced with metal oxides. Metal composites of alumina and zinc oxide were incorporated into Al+5% Zn alloy and the reinforced alloys were used as efficient sacrificial anodes for cathodic protection of steel objects. They have observed high and steady negative potential, very low polarization and substantial reduction in self-corrosion of the anodes during prolonged galvanic exposure tests. They observed that alloying with 5 wt.% of zinc is optimum to fabricate aluminium alloy sacrificial anodes. These authors concluded that with Al–Zn alloy sacrificial anodes the metallurgical characteristics of the anodes were significantly improved when the anodes were reinforced with ZnO. The reinforcement of the Al+5% Zn alloy anode with 0.5% ZnO increased the efficiency from just 58% to as high as 83%.

Anode materials

I.Gurappa [10] studied the selection of appropriate materials for cathodic protection. He studied both sacrificial anodes and impressed current cathodic protection (ICCP) systems however he has not drawn any conclusion about their usage. He suggested to use the expert system for efficient cathodic protection. He has also suggested that, though expert systems have been made to select the appropriate material for a selective environment and are available commercially, however, for newer applications, the materials have to be tested in the laboratory as well as in the field.

2.2 Prestressed & already corroded structures

Cathodic Protection for prestressed concrete structures

K. Ishii et al. [17] conducted a series of experiments using cathodic protection system on prestressed concrete structures in order to establish the reliable cathodic protection systems. They have indicated some experimental results on susceptibility of prestressing steel to hydrogen embrittlement and mechanical behavior of pretentioned beams subjected to current supply. The authors concluded that:

1. With slow strain rate tensile test(SSRT), susceptibility of the prestressing wire to hydrogen embrittlement tended to increase at a more negative potential (≤ -1000 mV, V.S. SCE);

2. There was no influential change regarding mechanical behavior of pretensioned beams with and without current supply;

3. Cathodic protection had a useful effect on the migration of chloride ions; and

4. Cathodic protection had an effect on preventing steel corrosion.

Corroded structures

K. Wang, concrete et al. [8] have studied the potential use of zinc in the repair of corroded reinforced concrete. They have observed that current practice for conventional patch repair of replacing the deteriorated concrete with a highly impermeable chloride-free concrete mortar, leads to an increase in the driving voltage of the corrosion cell because of differences in chloride ion concentration, moisture, and electrical conductivity between the repair patch and the old concrete. This increase in driving potential causes accelerated corrosion of the reinforcing bar (rebar) adjacent to the patch. As a result such localized repairs may cause the onset of corrosion in other locations, increasing the problem instead of solving it. They also observed that not only the concrete cover thickness but also the variety of cross-section of concrete cover has a great influence on the corrosion of reinforcing steel.

Throwing power of anodes

Luca Bertolini and Elena Redaelli [5] have studied the throwing power of cathodic prevention applied by means of sacrificial anodes to partially submerged marine reinforced concrete piles. This paper deals with the determination of current and potential distribution in reinforced concrete elements partially submerged in seawater aimed at predicting the throwing power of cathodic prevention applied by means of sacrificial anodes. This paper presents the results of the numerical simulations. Authors also observed that, not only cathodic prevention has a higher throwing power compared to cathodic protection.

2.3 Zinc anodes

Sacrificial zinc anode

Risque L. Benedict et al. [28] developed a sacrificial zinc anode CP system for prestressed concrete cylinder pipelines which experienced many corrosion failures within the first 10 years of service. The use of zinc sacrificial anodes for the CP installation was selected as the most practical way to prevent corrosion, while minimizing embrittlement damage to the high strength prestressd wires. The trial installation of CP on a 4.25 km test section of the Cedar Creek line had already prevented about five projected corrosion failures in the initial 2-year period. Without CP, the Cedar Creek pipe line would likely have required major repairs or abandonment by the year 2010. CP was expected to extend the useful life of both the Cedar Creek and Richland Chambers lines many decades

Zinc wired rebar

X.G. Zhang and J. Hwang [13] have studied a novel method for corrosion protection of rebar in concrete wherein they used a zinc wire attached to rebar along its length and accelerated laboratory tests were conducted to evaluate the corrosion performance of zinc wired rebar. They found that a rebar is galvanically protected by physically attaching a zinc wire along the length of the rebar. The wire acts as a sacrificial anode when the rebar embedded in concrete is exposed to corrosive environments. They also investigated the effect of concrete mix, cover thickness and steel surface area on the self and galvanic corrosion of zinc wire and on the extent of galvanic protection for the steel.

It was observed by authors that the potential of all the wired rebar samples during the entire test period was below -0.85 V_{cse}, at least 0.15 V lower than the potential of the plain steel rebar which was above -0.7 V_{cse} indicating that the attached zinc wire effectively protected the steel from corroding inside the concrete. The authors have also checked other numerous aspects including self corrosion vs galvanic corrosion, effect of W/C ratio, concrete cover thickness, extent of Protection etc. They have observed that a zinc wire can be used to galvanically protect a steel rebar from corrosion and the protection area is limited to certain rebar sizes depending on the concrete conditions also the consumption of zinc wire consists of self and galvanic corrosion.

Sacrificial metallized zinc

R. Brousseau et al. [26] have observed that removing salt-contaminated concrete, patching, and applying waterproofing membranes are treatments used to rehabilitate corrosion-damaged infrastructure. There are concerns about the effectiveness of only using such an approach to mitigate reinforcement corrosion when the concrete is salt-contaminated. Sacrificial cathodic protection (CP) using metallized zinc coatings is regarded as a possible rehabilitation alternative. They measured results on the Yves Prevost, on Highway Montreal, Canada. The performance of metallized zinc as a sacrificial anode for the CP of reinforced concrete showed promising results. But for drier environments where the amount of reinforcing and resistivity of the concrete is relatively high, there is concern that pure zinc might not provide adequate levels of CP required.

Conducting coatings

K. Darowicki et al. [6] have studied the use of conducting coatings as anodes in cathodic protection. They have carried out the calculations of electrochemical parameters of conducting coatings on the basis of impedance measurements. The results were subjected to statistical analysis and the scatter level of the experimental results was obtained. They have also observed that good protective properties are obtained by metal spraying with zinc, as opposed to aluminium coatings, application of which does not yield the expected effects. Also cathodic protection system installation costs are greatly reduced. They have carried out electric and electrochemical measurements of specially prepared conducting coatings to evaluate their suitability as anodes in cathodic protection of reinforced concrete structures. The most important aim was choice of optimum contents of the conducting component in the epoxy coating, to ensure optimal anode working parameters. They have also observed that electric and electrochemical properties of coatings depend on the content of graphite. Coatings containing greater quantities of graphite (over 50%) cannot be used for protection of concrete, in spite of good electric properties.

Zinc/aluminium alloy coatings

Z. Panossian et al. [15] have assessed the cathodic protection afforded by various zinc/aluminium alloy coatings those have been used instead of zinc. They have observed that although these coatings present some advantages over zinc, they are not able to cathodically protect steel substrates in all types of natural atmospheres. In this present work they have discussed the cathodic protection provided by aluminium and zinc/aluminium alloy coatings in comparison with traditional zinc coatings based on experimental results obtained in their study. Their work was aimed at to study behaviour of several types of coatings in atmospheres representing a wide range of corrosivities and contamination conditions. The work was focused on ascertaining the ability of this wide range of coatings to afford cathodic protection to the steel base in a wide range of natural atmospheres. This study shows that zinc alone or alloyed with very small amounts is effective and efficient in protecting steel.

Electrochemical investigations of conductive coatings

J. Orlikowski et al. [21] presented results of electrochemical measurements of conductive coatings, based on the mixing of pigmentary graphite in a polymer matrix, in this work. Electrochemical parameters are determined for the investigated coatings during long-term anodic polarization on reinforced concrete. Based on impedance measurements the electrochemical parameters of conducting coatings are calculated. It is shown that the investigated coatings can be used in cathodic protection of reinforced concrete. The investigations show that the optimum graphite contents in coatings used for protection of concrete should be in the range from 40% to 45%. The aim of the work was to perform electrochemical measurements on specially prepared conductive coatings in order to evaluate their suitability as anodes in cathodic protection of reinforced concrete structures.

The results show that conducting coatings can fulfill the role of anodes in cathodic protection of reinforced concrete structures. Improvement of electric and electrochemical properties can be obtained by changing the coating binder. However, many technological problems need to be solved connected with, e.g., the ageing process of coatings and the state of the coating electric connection.

Current density

G.K. Glass and N.R. Buenfield [11] have studied the current density required to protect steel in atmospherically exposed concrete structures. They have observed that the current required to cathodically protect steel in atmospherically exposed concrete is strongly dependent on the corrosion rate. At modest corrosion rates, typical design current densities would not achieve the level of cathodic polarisation required by commonly accepted protection criteria. However a cathodic current effectively lowers the unprotected corrosion rate by removing chloride ions and increasing the pH at the cathode. They have suggested that the prevention of further corrosion and the achievement of an adequate level of polarisation by a cathodic protection system is strongly dependent on these protective effects. They have aimed their study to examine the current densities predicted by mixed potential theory for a predetermined level of cathodic polarisation and the implication of this on the mechanism of the protection provided in practice.

They have concluded that the cathodic protection of steel in concrete is strongly dependent on the protective effects of the current which promote steel passivity. This results from the removal of chloride ions and an increase in the pH at the steel interface. These effects make the achievement of the commonly applied 100mV potential decay criterion less demanding and, in their absence, the protection current density required to arrest modest corrosion rates would be significantly higher than currently used values.

Development of a galvanic sensor system

Zin-Taek Parka et al. [23] studied the results of corrosion behavior of reinforcing steel which showed a consistence among the data obtained by open-circuit potential monitoring, linear polarization resistance (LPR) and electrochemical impedance spectroscopy (EIS) measurements. Steel/copper sensor showed a good correlation in concrete environment between sensor output and corrosion rate of steel bar. Through the relationship between the steel/copper sensor output and the corrosion rate of reinforcing steel, the real corrosion damage of the reinforcing steel can be detected. Consequently, this confirms that the galvanic sensor system is a good method for detection of corrosion in reinforced concrete.

2.4 Miscellaneous

Environmental influence on anodes

Oladis Troconis de Rincon et al. [3] have studied environmental influence on the performance of point anodes in reinforced concrete. Their work reports the most recent laboratory results from zinc-based point anodes performance in two different humidity environments (~95% and~77%) in reinforced concrete small beams, with and without chloride contamination. The commercially available point zinc-based anodes were used to determine the polarization performance of these anodes along the reinforcing steel. Half cell potentials, current distribution, and polarization decay due to the anode interconnection with the reinforcing steel bar (rebar) were measured. A detailed discussion of the system efficiency at both humidities is included in this report.

These authors have observed that an investigation or research is needed to define an effective distance between anodes so that the system could be used effectively in large structures.

According to these authors the point anodes tested did not reach the galvanic potentials needed to protect the embedded rebar for the relative humidity of ~77%. However the anodes were found to be efficient when relative humidity in the environment is high i.e. more than 90%.

Passivation of steel in concrete induced by CP

G. K. Glass et al. [22] have carried out an experimental work that examines the applicability of mixed potential theory to predict the corrosion rate of steel in concrete using the negative potential shift induced by a known cathodic current density. The set of results obtained correlate well with the polarisation resistance method of corrosion rate determination. This effect provides a theoretical basis for an improved cathodic protection criterion for atmospherically exposed reinforced concrete.

Cathodic protection and cathodic prevention

Pietro Pedeferri [25] illustrates the development of CP technique, the principles on which it is based, the criteria for prevention and for protection and some aspects regarding operating conditions, current distribution, hydrogen embrittlement risk, anodic system and monitoring. In order to ensure that protection or prevention conditions are reached and overprotection ones are avoided, and more generally to determine the performance of the CP systems, permanent monitoring systems have to be installed. These systems are based mainly on potential measurements of the reinforced steel with respect to reference electrodes.

Incorrect Cathodic Protection Connection Leads to Rebar Corrosion

Edoardo Proverbio et al. [27] reported a case history of a oil loading wharf. The problem was, during routine maintenance surveys, the concrete deck of the platforms showed severe spalling and the steel reinforcements were exposed. The attacks were very heavy on the upper surface of the decks; the bottom of the deck was generally in good condition. This fact was a little uncommon because the bottom of the deck was more exposed to marine spray, a more aggressive environment. The steel piles and their coatings were also in good condition.

After conducting numerous field tests they found that the corrosion attacks were not due to the permeability of the concrete, the usual cause of rebar corrosion in concrete. They concluded that the return power of the CP system intended for the steel piles was incorrectly connected to the rebar of the concrete deck and not to the steel piles. The problems did not occur at the beginning of the structure's lifetime, when the concrete was in perfect condition and the rebar probably electrically connected to each other, and no corrosion problems were observed. Over time, any electrical connection between some of the rebar weakened or broke, and stray currents started to flow between the rebar, causing the formation of anodic areas, and, thus, of corrosion attacks. These attacks became so strong as to cause the spalling of concrete large areas on the upper surface of the deck.

The authors also caution that all the technological details during the design and construction of CP systems must be understood and carefully kept in mind to avoid corrosion.

Corrosion Control of Muncipal Infrastructure using Cathodic Protection

R. A. Gummow [39] has observed that since its introduction in 1824, Cathodic Protection (CP) technology has developed to become a fundamental tool for preventing corrosion on municipal infrastructure. Potable water storage tanks and piping, prestressed concrete cylinder pipe, reinforced concrete structures, bridges, parking structures, underground fuel tanks, and effluent treatment clarifiers now benefit from this technology. In Cathodic Protection (CP) for municipal infrastructure purpose both the impressed current and sacrificial anodes (magnesium and zinc) are used. He has also observed that to a limited extent, cathodic protection has also been applied to other components of the municipal infrastructure such as hydraulic elevator cylinders, car and truck hoists in service stations, potable water treatment facilities, and swimming poolfilters.

3. CONCLUSIONS

After the extensive literature survey/review and elaborate discussions with field experts, the following gaps in research are worked out for carrying out further research activity.

- An investigation or research is needed to define an effective distance between sacrificial anodes i.e. placement of anodes, so that the system could be used effectively in large structures.
- Though expert systems available commercially to select the appropriate material for a selective environment, however for newer applications, the materials have to be tested in the laboratory as well as in the field. An investigation or research is required in this context.
- Also throwing power of sacrificial anodes in context with placement of anodes along with the various parameters viz. cathode/anode area ratio, anode life, anode efficiency, side and shift of changes in current are not studied to the extent that is desired.
- Further data about total anode requirement for a give structure as well as current attenuation in sacrificial anode cathodic protection system have not been studied satisfactorily.
- Also combined current attenuation in sacrificial anode cathodic protection system has not yet been studied specifically and there is a great scope of investigation and research in this field.

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