Corrosion control of reinforced concrete structures in construction industry: A review

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Abstract. Corrosion of steel reinforcement is one of the main deterioration phenomena which affect the durability of reinforced concrete structures. Together with the structural damages, corrosion will also increase the cost associated with it. Therefore, protection of reinforcing steel in concrete structures from corrosion is an inevitable need. Various protection techniques are in practice to mitigate corrosion of reinforcing steel in the concrete structure such as use of patch repairing, protective coating, impressed current method, and sacrificial anodes. Among these, electrochemical protection technique using sacrificial anodes can be suggested as a very effective tool for corrosion mitigation. Sacrificial anode cathodic protection system is a less popular corrosion control technique because of lack of awareness about the benefits of this method and the wide usage of other corrosion control practices. This paper provides a critical review on the common techniques in construction sites used for corrosion control of reinforced concrete structures. An overview of the benefits of sacrificial anode cathodic protection system, its working and installation is also provided in this paper.

1. Introduction
Corrosion of reinforcement in concrete is one of the most common deterioration mechanisms found in reinforced concrete structures which affect the durability as well as the structural capacity of the structure. Extensive research had been conducted over past few years to control the corrosion and to achieve the designed service life for the reinforced concrete structure [1, 2, 3, 4]. When the oxygen and moisture around gets penetrated into the concrete, the reinforcing steel (herein, rebar) gets corroded and corrosion products will be formed. The corrosion products occupy a larger volume than the original steel reinforcement which induces internal pressure around the rebar and tensile stresses get developed in the concrete which affects the performance the structure [1]. Corrosion induced damages include cracking, spalling, delamination of concrete and cross-sectional reduction of the reinforcing steel. It can cause aesthetic damages, reduction in the load bearing capacity of the structure, and can even lead to fatal consequences, such as structural failure [5, 6].

Along with the structural impacts, corrosion can also affect the economy of country. Steel corrosion in structures causes considerable losses to society due to maintenance and repair needs [6]. A significant percentage of concrete structures are structurally deficient due to corrosion and is subjected to repair and rehabilitation to regain the functional and structural performance [7]. This cost of repair and rehabilitation directly contributes to the cost of corrosion. Additionally, indirect cost which includes loss of productivity, traffic delays etc. is approximated around 10 times that of direct cost of corrosion. The direct and indirect cost of corrosion together is over three times worlds GDP [8]. Thus, the impacts of corrosion can be defined in both structural terms and economic terms.
Accordingly, study of corrosion, its mitigation and monitoring are significant concerned to reinforced concrete structures. This paper provides a brief overview of current knowledge about the traditional and cathodic techniques used for corrosion control of reinforced concrete structure. This paper also discusses the working of sacrificial anode protection system, its components, working and installation.

2. Corrosion control measures

2.1. Traditional practices for corrosion control

2.1.1. Patch Repair: Patch repairing is a conventional and the most commonly adopted practice to rehabilitate the corroded structural elements. To repair the physically damaged reinforced concrete area, damaged concrete cover need to be first removed. The corroded steel surface will then be cleaned and made rust free. Further, the repair mortar with adequate viscosity and bond strength will be applied as cover to protect the steel rebars from further corrosion [9].

It has been widely reported in literatures that the localised patch repairs are more preferred in construction sites due to its low cost and temporary aesthetic relief [1, 9]. However, patch repairs are rarely successful where chlorides are present in sufficient concentration in vicinity of repaired concrete. The chloride concentration in the patched repair area will be lower than that in the existing concrete around the patch. Under such conditions, treatment of the symptoms merely serves to send the corrosion cell into areas adjacent to those that have been repaired. This causes the formation of incipient anode as shown in Figure 1 and active corrosion could thus promptly start [1]. This unfavourable consequence is known as a ring or halo damage around the patch.

![Figure 1. Formation of incipient anodes after patch repair (adapted from [1])](image)

The formation of incipient anode around the patch repair will result in progressing corrosion of the rebars. Further, more stresses got induced the repair mortar and thus cracking occurred [9, 10]. The continued expansion of corroded steel will raise the internal pressure near the rebar and this induces cracking in the initial concrete or in the patched section depending upon the condition and geometry of patches. Thus, probability of occurrence of corrosion is still prominent even after patch repairing [1]. Consequently, other corrosion protection techniques must be undergone following patch repair; eventually making patch repairing the most expensive aspect of any rehabilitation process, unless adopted in a chloride free corrosive environment.

2.1.2. Coatings on steel rebars: Applications of anti-corrosion coatings on steel surface can also prevent reinforcement corrosion in concrete structures [11]. Fusion Bonded Epoxy (FBE) and Cement Polymer Composite (CPC) are the commonly used anti-corrosion coatings for reinforcing steel.
Fusion Bonded Epoxy or FBE coatings are factory coated thermoset polymer coating that are applied on the rebars at a higher temperature about 180 to 250°C and it gets solidifies faster by chemical cross linking [12]. Soon after hardening, the epoxy coating becomes brittle. When FBE coated rebars are prone to bending operations in the construction site, cracks are formed on rebar coating. Similarly, practices like dragging, stacking and long-time exposure of rebars are common in construction sites. Such poor construction practices damage the FBE coatings and can lead to the pitting corrosion of rebars when they are embedded inside the concrete [13].

Cement Polymer Composite or CPC coating is a barrier type of organic coating which forms a complex cementitious protective film by reacting with the metal surface [13]. The CPC coatings can passivate the steel rebars exposed to corrosive environment and thereby delay the corrosion process [14]. These coating formulations consist of thermoplastic resins as the base material, either ordinary cement or fly ash as the extender adhesive component and titanium dioxide and/or zinc phosphate as the main pigments [13, 14, 15, 16].

Due to elasticity and flexibility of the coating, CPC coated rebars can be cut and bend without cracking. Therefore, poor handing of the rebars on site will not damage the coating on CPC coated rebars. However, many literatures have reported the failure of CPC coated rebar systems [13, 16, 17]. The main reason behind the failure of CPC coated rebars is the inadequate surface preparation techniques adopted in the construction sites prior to the application of the coating [13, 17, 18].

The magnified photograph in Figure 2 adapted from Kamde and Pillai (2020) shows the CPC coated rusted rebars of a pier caging. It is evident from the figure that, CPC coating is applied on inadequately surface prepared steel rebars [13]. If the rebar surface is not sufficiently surface prepared; the rust layer between steel and coating can entrap the moisture [18]. This moisture can act as a conducting medium for ionic transfer, resulting in premature corrosion initiation. Therefore, surface preparation or rust removal is an inevitable step prior to the application of CPC coating [13, 16, 18].

Kamde and Pillai (2020) reported that the application of CPC coating on inadequately surface prepared rebars can reduce the average service life to about 50% of expected design life [13]. Literature recommend compulsory sandblasting prior to the application of CPC coating to provide good adherence to the CPC coating and ensure sufficient resistance to ionic transfer which attributes to its resistance against corrosion [16, 19]. However, sand blasting rebar surface are not practiced at construction sites, due to constraints such as time, cost and poor quality control.

2.2. Cathodic protection systems
Due to poor quality control prevailing in the construction site, the use of traditional corrosion control techniques can affect the entire performance of the control mechanism which can lead to adverse
corrosion conditions [1, 13, 16, 19]. This reflects the importance of cathodic protection systems for reinforced concrete structures. Cathodic protection (CP) is the most modern and effective method to control corrosion of reinforcing steel in concrete structures.

In cathodic protection, a metal surface is resisted from corrosion by making it the cathode of an electrochemical cell [20]. CP systems protect wide range of structure in various environments. The current circulation between anode and a cathode through an electrolyte produces protection effects [21]. This process has more endurance than conventional corrosion control strategies.

There are two types of cathodic protection systems; they are galvanic cathodic protection system also known as sacrificial anode cathodic protection (SACP) and impressed current cathodic protection (ICCP) [21].

2.2.1. Impressed current cathodic protections system: In the impressed current cathodic protection (ICCP) system an anode is introduced into an atmospherically exposed reinforced concrete structure and corrosion can be controlled by passing direct electrical current to the reinforcing steel [21, 22, 23, 24]. ICCP requires a permanent installation of low voltage controlled electrical framework that transfers direct current to the steel which converts the metal into the cathode, thus assuring corrosion mitigation. The anode can be installed on the surface of structure or can be drilled into the small holes of the structure [21]. This electrochemical treatment provides protection that can effectively be monitored & controlled in long haul. Impressed current anodes can be materials such as conductive coating, mixed metal oxide/titanium based mesh in cementitious overlay, and conductive overlay incorporating carbon fibres [23]. Durability of ICCP is to a great extend determined by the choice of anode. This is because the damaging reasons are moved from the steel to the installed anode.

ICCP systems only focus on the steel reinforcement and are well known to result in side effects for the bulk matrix or the steel-cement paste interface, for example in alkali aggregate reaction and bond strength degradation; together with the risks of hydrogen embrittlement for protected steel in prestressed concrete [25, 26]. ICCP systems are very costly and difficult to get installed where no external power source is available and for sites with high cost traffic management is required [22, 25]. Literatures suggest the use of ICCP systems only for large structural systems subjected to significant corrosion problems, where life expectancy is expected to be more than 25 years [25].

2.2.2. Sacrificial anode cathodic protection system: Sacrificial anode cathodic protection is a corrosion control system where a less noble material that acts as a sacrificial anode is connected to the reinforcing steel in the structures to be protected [25, 27, 28, 29]. Many researchers recommend the use of sacrificial anodes as prevention mechanism for the structures anticipating corrosion and as a protection mechanism for the structures experiencing significant corrosion [12, 20, 23].

The advantage of SACP over ICCP is that there is no external power source required in the case of SACP, which can reduce the start-up cost and maintenance cost. System voltages and current output are lower compared to ICCP systems leading to low risk of cathodic interference in the adjacent structures [25]. Data exchange, document handover and knowledge transfer is much less required in the case of SACP systems making it easier to design and install [25]. For highly confidential buildings which does not promote frequent visits for maintenance, sacrificial anode cathodic systems are be found to be more suitable cathodic system.

3. Components of a sacrificial anode

Sacrificial anode cathodic protection (SACP) is a type of cathodic protection where a more reactive metal that acts as a sacrificial anode is connected by metallic conductors to the structure to be protected [27]. Corrosion occurs on the anode which sacrifices itself in order to offer protection from corrosion to the structure. In reinforced concrete structures, the metal which is used to protect the rebars act as anode and the steel rebars that has to be protected behaves as a cathode [20, 25]. A sacrificial anode consists of an anodic metal or a metal alloy and an encapsulating mortar as shown in Figure 3.
3.1. **Anodic metal**
Sacrificial anode cathodic protection or SACP system is a corrosion protection system solely based on the reactivity of metals. In an electrochemical series the metals with more negative potential has more reactivity than the metals with less negative potential [27]. The common metals used for this type of corrosion protection are magnesium, aluminium, and zinc [30]. The anode takes up the function of the previously corroding rebar and prevents corrosion from starting both in the patch area and its surroundings.

3.2. **Encapsulating mortar**
The encapsulating mortar covers the anodic metal and is designed to provide a low resistance environment around the anode and improve the performance of the anode. The two main feature of the encapsulating mortar is its high alkalinity and high porosity [31, 32, 33].

3.2.1. **High alkalinity:** The anodic metal is encased in a highly alkaline mortar disk in the sacrificial anode. The encased mortar has a reservoir of excess alkali to maintain high alkalinity around the sacrificial metal. In order to promote the anodic dissolution and to provide the steel galvanic protection against pitting, highly concentrated alkali electrolyte should be maintained around the anodic metal. The high alkaline mortar has increased moisture content that hinders the formation of a passive film on the metal and allows the anode to stay in an active condition [33].

However, the alkaline environment could induce alkali–silica reaction (ASR) in concrete; if alkalis are mobile and concrete contains vulnerable aggregates. The silica content in aggregates can react with the alkalis such as sodium and potassium hydroxide to form alkali-silica gels. These gels absorb water and induce expansive forces that are capable of initiating cracks in aggregates and surrounding cement matrix which weakens the structure. Therefore, literatures suggest the usage of lithium hydroxide instead of other alkalis in the encapsulating mortar to avoid the formation of these gels [32, 33]. It is assumed that the lithium hydroxide form a non-expansive lithium silicate which reduces the risks of local expansion and cracking [34].

In addition, if the lithium hydroxide in the mortar is distributed properly, it is capable of supplying enough current densities which provide required cathodic protection to steel rebars in concrete structures with moderate level of chloride contamination. Thus, the addition of lithium hydroxide in the making of encasing mortar gives it the purposes of stimulating active dissolution of zinc, reducing the possibility of ASR in appropriate cases and supplying enough current densities for the proper working of SACP system [34].

3.2.2. **High porosity:** Another important feature of the mortar around anodic metal is its high porosity. The highly porous encapsulating mortar is designed by the manufactures to accommodate the corroded anodic metal products. Literature confirms that the porous cover around the sacrificial metal ensures no stresses and expansive forces to build up around the metal core. However, details regarding the composition of the porous mortar are not available. Sergi (2011) studied a 10-year-old sacrificial 'zinc' anode which was embedded inside a reinforced concrete beam [31]. Upon autopsying the used sacrificial anode, the zinc corrosion products can be seen present in pores away from zinc-mortar interface of the mortar used for encasing. This agrees with the assertion that the zinc corrosion products...
products remain soluble because of the exceeding pH of pore solution due to saturated solution of lithium hydroxide in the encasing mortar, and can travel through the pores before the occurring of super saturation and precipitation. Therefore, literature suggest to design the encapsulating mortar porous enough to accommodate the corrosion products and its movements; to ensure no stresses of any kind arise around metal core to initiate cracks [31, 32].

4. Installation of anodes

Based on the design concept of Schweitzer’s cathodic protection for buried pipeline [35], the sacrificial anode cathodic system for reinforced concrete members can be designed. Ahmad et al. adapted them to determine the required weight of sacrificial anode to protect the steel for a remaining expected life of concrete by calculating the practical energy content or the charge required for electrolytic deposition of unit mass of anode [36].

The following equation given by Ahmad et al. (2000) can be used to determine the total weight of anode in kilograms required to protect the rebars from corrosion [36].

\[
\text{Total weight of anode required} = \frac{n \times \eta \times 8760 \times \text{GEW} \times I_{req}}{26805.56}
\]

where, ‘\(n\)’ is the remaining expected life of the structure, ‘\(\eta\)’ is the anodic efficiency of the metal, ‘\(\text{GEW}\)’ is the gram equivalent weight of the metal and ‘\(I_{req}\)’ is the total current required.

The shape and geometrical dimensions of each anode can be designed depending on the size of reinforced system it is to be installed. Further, the spacing between the anodes is calculated based on the throwing or critical length of the sacrificial anode [25, 35]. The throwing power of the sacrificial anode is a possible limitation, which is the height up to which corrosion control can be accomplished [37]. Thus, the required number of anodes can be calculated depending on the size and spacing of anodes.

Sergi (2011) installed sacrificial anodes within the repaired area of a beam around the perimeter of patch repair as shown in Figure 4 [31]. The anodes were designed for a minimum service life of 10 years and the embedded anodes were removed from the beam after the designed service life of anode to analyse its performance. The efficient functioning of sacrificial anodes was evident from the analysis of the recovered anodes. The anodes displayed electrolyte continuity, uniform metal consumption and coherent encasing mortar even after its designed protection period [31]. This allows further prolonged corrosion protection by the recovered anodes.

![Figure 4. Installation of anodes within the repaired area of a beam (adapted from [31])](image)

Small galvanic anodes or point anodes are available commercially for casting in patch repairs, for the intended purpose of delaying the halo damage effect [28, 37]. However, in order to ensure potential corrosion control, many researchers have proposed guidelines regarding the installation of sacrificial anodes in patch repair areas to ensure potential corrosion control [9, 31, 38]. They include: (i) sacrificial anode should always be embedded in the substrate concrete area rather than in the patch
area; (ii) the length of patch repair should be greater than the corroded length in order to guarantee the load capacity of the patched region; (iii) complete removal of contaminated concrete all around the steel rebars must be ensured for a sustainable repair.

5. Conclusions

Many reinforced concrete infrastructures all over the world are facing severe deterioration due to corrosion of rebars. This paper discusses the problems related to conventional corrosion control practices and emphasizes the benefits of sacrificial anode cathodic protection system, its components, working and installation.

So far, many traditional mitigation and protection techniques have been investigated and applied to the structures such as patch repairing, fusion bonded epoxy coating, cement polymer composite coating and surface sealers. Poor handling of conventional corrosion control techniques can lead to adverse corrosion conditions. Cathodic protection can be suggested as an effective technique compared to others. Sacrificial anode cathodic protection is the best suitable corrosion control technique available now. A more reactive metal or its alloy is used as a sacrificial anode and is connected by metallic conductors to the reinforcing steel of the structural element to be protected.

A sacrificial anode is made of a metal or a metal alloy which is encapsulated in a highly porous-highly alkaline mortar. The high alkalinity of the mortar is maintained by the addition of lithium hydroxide for the purpose of stimulating active dissolution of zinc, reducing the possibility of ASR in appropriate cases and supplying enough current densities for the proper working of SACP system. To accommodate the corroded anodic metal products in the mortar, high porosity should be a necessary feature of the encapsulating mortar. The sacrificial anodes can be used as a prevention mechanism for the structures anticipating corrosion and as a protection mechanism for the structures experiencing significant corrosion.

6. References

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