
ENHANCING CORROSION RESISTANCE IN REINFORCED CONCRETE STRUCTURES: A COMPREHENSIVE ANALYSIS OF CATHODIC PROTECTION AND SACRIFICIAL ANODE TECHNIQUES

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ABSTRACT

Cathodic Protection is an established technique utilised to extend the service life of structures, reducing the frequency of repairs required. This method is increasingly being adopted worldwide. Metal bars can be provided with corrosion resistance through the application of the effective and easily maintainable Cathodic Protection technique. Within this review, a comprehensive analysis was conducted on more than 15 studies, focusing on the evaluation and presentation of Cathodic Protection techniques for reinforced concrete components. The optimal performance of the sacrificial anodes is determined by the pH level of the activation mortar. The corrosion of zinc-based anodes is prevented by maintaining a high pH level. The observed decrease in electrical current flowing through the anodes suggests that the metal has undergone passivation, leading to a reduction in the rate of ongoing corrosion. Galvanic anodes are considered appropriate in situations where the corrosion rate is relatively low, specifically less than 10 mA/m². Passivation may not be performed during the operational phase of the steel. The anode's influence length is determined by the electrical resistance of either the substrate concrete or the repaired concrete. The cathodic protection efficiency of the anode decreases in direct proportion to the increase in electrical resistivity of the concrete. The implementation of sacrificial anodes improves the corrosion protection effectiveness of concrete containing inhibitor admixture by promoting the formation and maintenance of a passive barrier within the reinforced structure of the concrete. The utilisation of sacrificial anode-based repair methodologies has the potential to replace the iterative process of fixing prior repairs.

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

1. INTRODUCTION

The phenomenon of corrosion occurring in the steel reinforcement of reinforced concrete structures is a widespread problem that significantly impacts the durability and lifespan of infrastructure on a global scale. The adverse impacts of corrosion, caused by environmental factors like the infiltration of moisture and exposure to chloride, require the implementation of efficient prevention methods in order to guarantee the long-lasting durability and safety of concrete components. Within the realm of corrosion mitigation techniques, sacrificial anodes have emerged as a viable solution, presenting an innovative approach to cathodic protection.

The principle of sacrificial anode cathodic protection entails the application of highly reactive metals, such as zinc or magnesium, in conjunction with the steel reinforcement to establish a galvanic cell. During this electrochemical process, the sacrificial anode undergoes sacrificial corrosion, resulting in the release of electrons that are then directed towards the steel reinforcement, effectively inhibiting its corrosion. The utilisation of this methodology offers numerous benefits, such as ease of implementation, minimal upkeep demands, and cost-efficiency in comparison to conventional corrosion prevention techniques like coatings or impressed current systems.

However, notwithstanding its potential benefits, the effectiveness of sacrificial anodes in mitigating corrosion in reinforced concrete elements continues to be subject to rigorous scrutiny. The objective of this study is to conduct a thorough analysis of the application of sacrificial anodes for the purpose of corrosion prevention in reinforced concrete structures. By conducting a comprehensive analysis of current literature, conducting experiments, and making observations in the field, this study aims to clarify the mechanisms behind sacrificial anode-based cathodic protection and evaluate its practical usefulness in various environmental conditions and structural configurations.

The key aspects to be addressed in this critical study encompass an investigation into the corrosion mechanisms in reinforced concrete, the principles governing sacrificial anode cathodic protection, the experimental methodology employed for performance evaluation, a critical analysis of its effectiveness, a discussion of the challenges and limitations encountered, and recommendations for future research and practical implementation strategies. Through a comprehensive analysis of sacrificial anodes' application in corrosion prevention for reinforced concrete elements, this research endeavour seeks to enhance corrosion mitigation strategies and advocate for sustainable infrastructure development practices.

2. CORROSION MECHANISM

Carbonation Induced Corrosion

The biochemical interaction between the hydroxycalcium and hydrocalcium silicate present in the material and the carbon dioxide present in the atmosphere is commonly referred to as carbonation or neutralisation. When designing a concrete structure, it is customary to specify the concrete cover for the rebar (the thickness of the layer that encases the rebar within the element). The minimum concrete cover is typically determined by building regulations in the design industry. Premature failure resulting from corrosion can occur if the reinforcement is positioned too close to the surface. The measurement of the depth of the concrete cover can be determined by utilising a cover indicator. However, the strength of sparkling concrete can be compromised if there is sufficient presence of air and water, leading to potential corrosion of the structural brace.

Chloride Induced Corrosion

High quantities of chlorides may expedite the corrosion of embedded rebar. Steel reinforcements may experience both localised corrosion, known as pitting corrosion, and generalised corrosion due to chloride anions. In order to prevent the usage of admixtures containing chlorides, it is advisable to only use potable water or fresh, untreated water while manufacturing mortar. Furthermore, it is important to ensure that the commonly used and widely available aggregates are devoid of chlorides.

Historically, calcium chloride was often used into concrete as an addition to expedite the concrete's curing process. Moreover, there was a mistaken belief that it might prevent freezing. Nevertheless, once the detrimental consequences of chlorides were uncovered, this strategy fell out of favour. Whenever possible, you should avoid it.

The primary cause of the early failure of prestressed concrete bridge decks, roads, and parking areas is unquestionably the use of deicing salts on road surfaces, which are designed to lower the freezing point of water. The problem has been mitigated by the use of cathodic protection (CP) and epoxy-coated reinforcing bars. Fiber-reinforced polymer (FRP) rebars are known for their reduced vulnerability to chlorides. Concrete mixtures that have been adequately blended and given sufficient time to harden are highly impervious to the detrimental impacts of de-icers.

In the 1960s and 1970s, magnesite, a chloride-rich carbonate mineral, was often used as a material for floor toppings. Primarily, this functioned as a layer that evened out surfaces and reduced noise.

It is now known that the chlorides present in magnesite react with moisture to produce a moderate hydrochloric acid solution. Over the course of many decades, the solution gradually erodes the embedded rebars. This phenomenon was more often noticed in areas that were regularly exposed to moisture or in situations with high levels of humidity.

3. PROBLEM STATEMENT

An essential process of degradation Steel undergoes corrosion in concrete-reinforced structures. According to Schmidt (2009), the worldwide cost of corrosion is estimated to be \$2 trillion, which is equivalent to around 3 to 4% of the gross domestic product (GDP) of industrialised countries.

Corrosion reduction is crucial due of the exorbitant expenses associated with corrosion. Concrete design often satisfies both the durability and strength criteria. In Reinforced Concrete (RC) projects, ensuring proper rebar coverage and using a meticulously designed concrete mix are effective in preventing early corrosion. Early onset of rebar corrosion in construction might be attributed to substandard materials and inadequate workmanship.

Metals need the simultaneous presence of moisture and oxygen in order to undergo corrosion. The presence of carbonate or chloride ions at the level of rebars increases the rate of corrosion. Managing the propagation of corrosion using conventional methods becomes difficult after it has begun.

In order to halt the propagation of corrosion, it is necessary to remove the concrete that has been contaminated with chloride or carbonate from the rebar location and substitute it with fresh concrete. However, if contaminated concrete is replaced incorrectly, it may exacerbate the corrosion activity at the location.

Comprehending the functioning of the CP system and the basic principles of the various protection criteria is essential for evaluating the performance of the CP system on reinforced concrete structures. The study investigates the various anodes used globally and their functioning in different settings.

Both laboratory and field experiments are offered. Field studies aim to evaluate the operational effectiveness of CP systems in real-world conditions, whereas laboratory research seeks to understand the underlying principles of CP approaches.

4. OBJECTIVES

The objectives of this research are:-

- Investigate the processes by which corrosion occurs in reinforced concrete buildings.
- Assess the efficacy of sacrificial anodes in mitigating the corrosion of steel reinforcement.
- Examine the impact of environmental conditions on the effectiveness of sacrificial anodes.
- Examine the long-term resilience of sacrificial anodes.
- Compare the efficacy of sacrificial anodes with various techniques of corrosion prevention.
- Identify the most effective ways for placing sacrificial anodes in reinforced concrete components.
- Assess the economic viability of installing sacrificial anode systems.
- Investigate the compatibility between sacrificial anodes and various concrete compositions.
- Examine the extended-term upkeep needs of sacrificial anode systems
- Recommend strategies to enhance the efficiency of sacrificial anode-based corrosion prevention in reinforced concrete structures.

5. LITERATURE REVIEW

The researchers gathered data on the use of steel rebar to avoid corrosion in reinforced concrete (RC) from chosen indexed journals over a period of two decades. This was done to get insights into the global scenario in this sector. This chapter provides an overview of the results.

Hobgen et. al (1957) It was emphasised that ZN functions as both an anode and a shield for iron upon contact, thereby avoiding corrosion. When dealing with corrosion problems, it is necessary to consider the potential values provided in the galvanic series, but only under specified assumptions. In practical situations, the presence of surface coatings causes major changes to these values. Furthermore, the usage of metals in high concentrations in a solution of their ions is never justified. Under appropriate circumstances, the sequence of two metals in a series may be altered. However, alkali would corrode the outer layer of a material, which often acts as a protective barrier, as it did with aluminium. Thus, in this particular situation, it is only essential to provide the minimum amount of electric current required for protection. Additional factors that have an impact on the distribution and prerequisites at the time of submitting the application are also influential. Despite a significant voltage differential, the flow of electric current to the outside of the structure fluctuates considerably. Coating the metal-electrolyte contact with a substance that has a high electrical resistance will decrease the amount of current required for protection. Furthermore, it enhances the dispersion of electric current at the surface. Sacrificial anodes are often fabricated using magnesium, zinc, and aluminium. When the resistance of the electrolyte is not very low, it is preferable to use mg since it has a driving voltage that is three times better than ZN.

Sergi and Page (1992) investigated ZN sacrificial anodes that were contained inside a specially built mortar. The mortar was filled with an electrolyte solution that was excessively saturated with LiOH. Through experimental analysis, it was shown that in sections of repaired concrete that were originally polluted with substantial levels of chloride, sufficient cathodic protection (CP) could be applied to the steel. The reinforcement was maintained in a polarised state for a minimum duration of 2 years. The electric current densities measured were sufficiently enough to cause a significant migration of chlorides from the surrounding material into the repair. By substituting the tainted concrete with fresh concrete, the process of corrosion may be accelerated in a specific area. Corrosion leads to the establishment of a condition of equilibrium between the anodic and cathodic processes. The point at which the oxidation and reduction curves overlap indicates the point when the overall rates of oxidation and reduction are equal. The selection of cathodic shielding as a protective strategy for the structure is contingent upon factors such as the presence of alkali on the metal surface, the desired electric current density, and the distribution of electric current. Over time, alkali accumulates on the surface of the cathode. The outcome of this depends on the specific metal being protected, which may either be beneficial or detrimental. The formation of the relatively insoluble hydroxide coating takes place in the presence of iron and steel when the pH of the electrolyte next to the cathode increases. This helps reduce corrosion.

Scannel and Sohahngpurwala conducted a study in 1993. The cathodic protection (CP) system is an established method used to avoid corrosion in metallic structures that are exposed to corrosive conditions. This includes underground pipes, maritime constructions, water storage tanks, and several other facilities. RC constructions are now being equipped with cathodic shielding as a consequence. Research has shown that cathodic protection (CP) is an

effective strategy for preventing the spread of corrosion in reinforced concrete (RC) structures. Cathodic protection (CP) is a technique used to prevent corrosion in metals. The metals that need protection are formed as the cathode of an electrochemical cell. It is applicable in scenarios when a metal is immersed in a solution containing an aqueous electrolyte. The anode must be made of metal and in direct contact with the electrolyte, while preventing any formation of a building. The cathode is the area that experiences no corrosion, whereas the anode is the area that undergoes corrosion. Cathodic protection (CP) is used in many sectors, such as underground and maritime construction, water storage tank manufacturing, gas pipeline installation, and other facilities that are exposed to corrosive conditions. In their study, Ahmad et al. (2000) found that reinforced concrete buildings often undergo repairs that fail to target the underlying cause of the problem. These repairs have limited use if corrosion is not effectively prevented with adequate safeguards. Three essential elements are necessary for the initiation of steel corrosion in reinforced concrete (RC) constructions. The factors include the concrete's resistance to moisture, air permeability, and the presence of harmful substances such as sodium chloride or ambient carbon dioxide. The anodic response refers to the reaction that occurs at the anode during an electrochemical process. The cathodic reaction may be represented as follows: $2\text{Fe} \rightarrow 2\text{Fe}^{2+} + 4\text{e}^-$ and $\text{O}_2 + 2\text{H}_2\text{O} + 4\text{e}^- \rightarrow 4\text{OH}^-$. Rust is the cumulative result of the following chemical reactions: The chemical equation is $2\text{Fe} + 2\text{H}_2\text{O} + \text{O}_2$.

The oxidation process refers to the anodic reaction. It represents the liberation of electrons and the decay of iron. It gains advantages from the breakdown of the passive layer. This reaction is used to assess the rate at which reinforcing steel undergoes corrosion. The kind of anodizing process that occurs is determined by the pH level of the electrolytes at the interface, the concentration of impurities, the presence of oxygen in the surrounding environment, and the electrical potential at the steel's edge.

Kumar et. al (2001) The study has examined the performance of coated bars in relation to sacrificial anodes. Reinforcing corrosion causes steel to decrease in cross-sectional area, leading to failure under the intended load owing to a lesser cross-sectional area than what was originally anticipated for the design. Reinforcing corrosion sometimes leads to the formation of cracks on the surface of concrete projects. There are several strategies to mitigate corrosion in steel. Cathodic protection is the most effective method for preventing corrosion in steel. To prevent this, one may avoid it by using the appropriate concrete grading, curing, and compacting techniques. Applying a protective layer on steel bars is really a temporary measure, since it undermines the connection between steel and concrete.

Bashi et. al (2003) The user emphasised that the resistivity of the surroundings, pH level, moisture content, and oxygen availability all influence the pace of corrosion. The resistivity of a medium is influenced by many factors, including the concentration of dissolved salts, which are naturally present in the medium, as well as the moisture content.

Corrosion intensifies when the level of moisture in the air increases, mostly due to the higher solubility of salts. As the level of resistance increases, there is a noticeable reduction in the rate of corrosion. pH is a crucial factor that affects the process of rusting. The rate of degradation increases according to the acidity of the medium. Moreover, it increases in tandem with the increase in oxygen levels. Cathodic protection disrupts the flow of energy from the metal's surface to the electrolytes by supplying a more powerful electric current of opposite polarity from an external source. The Sacrificial Anode (CP) is sometimes referred to as the electrolytic technique. The implemented variation refers to the difference in biological potential between the structure and the second metal. The potential fluctuation is dictated by the relative placement of the metal in the galvanic series.

The anode is made from a metal that has a more negative potential than the structure it is meant to protect. The cathodic polarisation of the structure relies on the decomposition of the anodic metal to generate electrons. The structure and the sacrificial anode must undergo spontaneous anodization. It is feasible to promptly attach the anode to the structure. The structure undergoes cathodic polarisation when a positive electric current is supplied from the anode to it by the power source. Electrical connection is required between the anode and the structure. The magnitude of the applied potential is not critical; it just has to be sufficient to provide an appropriate electric current density over all parts of the protected structure.

Marine applications need a voltage of less than 6 volts, but high-resistance soil requires a voltage of more than 50 volts. Electrons with a negative charge are more strongly attracted to the difference in electric potential than the ions from the structure that has to be protected. The resistivity of the electrolyte, the composition of the anode, and its size all have an impact on the performance of the anode.

Liu et. al (2009) They have stressed that by preventing the need to remove the contaminated concrete, (CP) is the most affordable technique for chloride-affected structures. (CP) is seen to be the best option to stop corrosion if the environmental factors that encourage it continue to present throughout the structure's lifetime. When the necessary

protection criteria are met at representative sites on the structure, it offers the structure enough corrosion protection. The protective requirements are chosen based on actual experiences, electrochemical considerations, and the surrounding local environment. It is difficult and pointless to define a specific protective potential for cathodic protection. The goal of (CP) is to deliver enough electric current to reduce corrosion in the steel rebar. When choosing the electric current to be applied, it is important to take into account the variations in the surrounding concrete's moisture content, ion concentration, aeration, and electrolyte resistivity. The steel cathode's electric current density and the electric current distribution path are the two most important considerations in the design of the CP system. Factors including corrosion product, concrete age, reference electrode position, concrete constitutions, and fissures can all have an impact on the half-cell potential measurements.

Liu and Shi (2009). Cathodic safeguarding for concrete with reinforcement has become a well-developed technique that may effectively prevent thaw-induced rust and lengthen the useful life of concrete reinforced buildings exposed to the maritime environments and freezing purposes. By giving engineers more options, technological advancements have increased the appeal of CP. This is exemplified by developments in new electronic equipment that make it easier to monitor and regulate the operational system. This study of cathodic suppression on buildings made of concrete covers anode substances, anode evaluation, anode lifespan forecasting, CP monitoring of performance, chemically spraying galvanized anode installations and substitution, and related numeric techniques. The creation of best practices for choosing, implementing, maintaining, and replacing CP systems will be aided by such knowledge. (CP) has advanced to the point where soon there may not be any revolutionary adjustments. However, it is envisaged that existing materials, equipment, and characterisation techniques will continue to be improved upon gradually and continuously. To lower the likelihood of machine-driven harm and hence boost structure presentation, it could be conceivable to develop unique self-healing conductive painting anodes. Near chance the large electric electric current needs of CP structures, new metal anode materials that are less sensitive to the acidity generated by electrochemical aging may be developed areas where the electric resistance of the concrete is more. Further study is additionally required to improve the electric characteristics of building materials, intersection components in order to permit conductive circuits in dry regions. This can be done by utilizing innovative additives such carbon fibers. Even though technology advancements of this kind are expected, economic factors must also be taken into account. Until the advantages and dependability of new technologies are established or shown, user approval can be a barrier to implementation. The creation of improved monitoring systems for universal applications, which would have the ability to assess outside influences on CP performance and correct/adjust system parameters accordingly, is highly desirable but technically complex. Many electric current ly installed thermally sprayed Zn anode CP systems may soon approach or beyond their intended life. Thus, they could perform inadequately or poorly, necessitating the replacement of the old anodes.

6. METHODOLOGY

The electric current study critically analysed research papers that examined various aspects of cathodic protection (CP) for reinforced concrete elements. These papers covered topics such as sacrificial anode cathodic protection, impressed electric current cathodic protection, long-term performance of sacrificial anodes in repair works, the effectiveness of anodes in neutralising the incipient anode effect, and the use of sacrificial anodes for corrosion prevention.

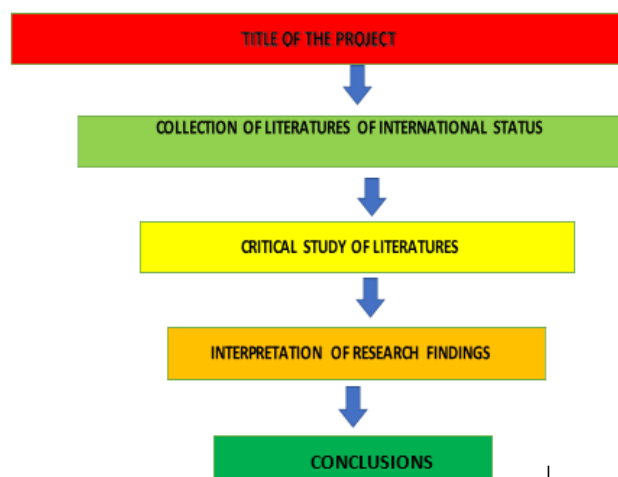


Figure.1 shows the methodology flow chart depicting various activities in the project work.

7. SPECIMEN PREPARATION FOR CORROSION PREVENTION

Concrete specimens measuring 150 mm by 200 mm by 1500 mm were fabricated with two separate anodes to assess the effectiveness of different cathodic preventative anodes. Steel rebar with a diameter of 10 mm was used for reinforcement, and all sides of the specimen were completely coated to a depth of 25 mm. The water-to-cement ratio in the concrete mixture is 0.55. A higher water-to-cement ratio is used to facilitate the rapid penetration of chlorine compounds and oxygen to the level of the rebar, hence expediting the corrosion process on the surface of the rebars. Figure 3.2 presents a detailed schematic illustration illustrating the internal structure of the prism.

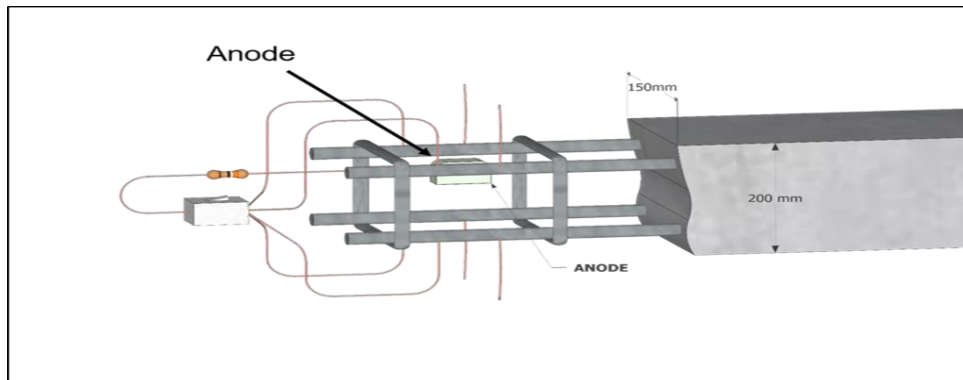


Figure 2 Three, dimensional schematic diagram of the column specimen showing the connections from the rebars.

The specimen contains an anode that is not electrically connected to the rebars. The example uses insulated tin-coated copper wires for external electrical connections. All four rebars have wires cut off at one end, which are connected to a wire cut from the anode through a switch (Figure 3.2). This makes it possible to monitor polarized and depolarized potentials on the specimen while the anode is externally linked and disconnected. Between them is attached a 10 resistor. Calculating the electric current delivered by the anode can be done using the potential drop across the resistor.

According to Chess & Broomfield (2014), anodes do not accurately represent the rebars' inherent corrosion potential. The measurements represent the rebar-anode system's actual potential. As a result, rather than using ASTM C876, as is the case for systems without sacrificial anodes, the performance evaluation of a (CP) system adheres to the standards from BS 12696. The picture depicts the various steps required in conducting corrosion prevention tests on cast prism specimens.

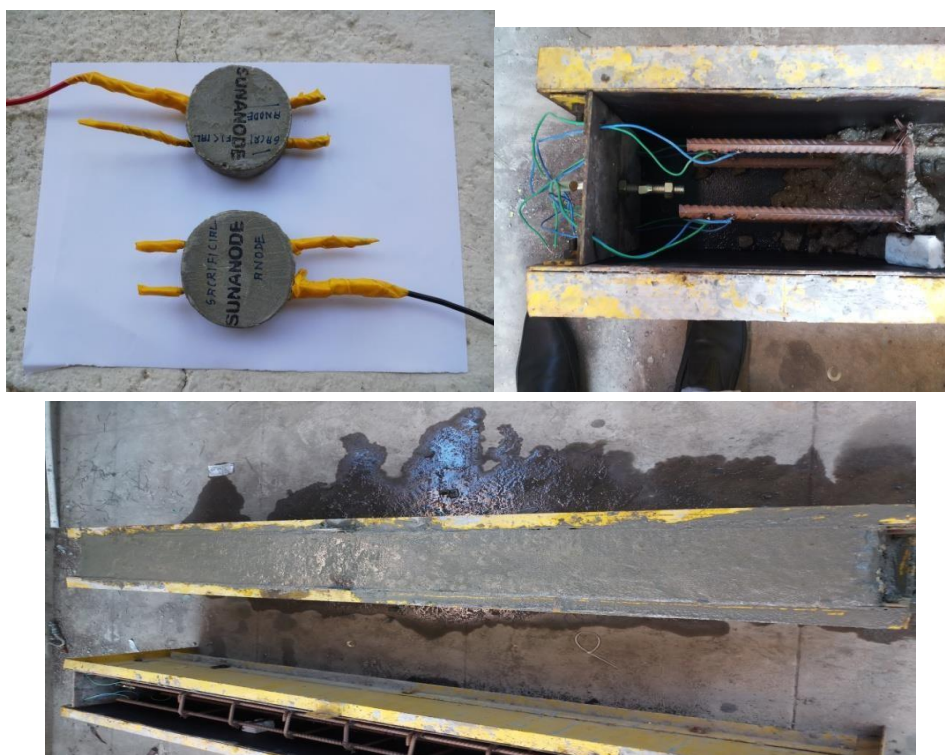


Figure: 3 Various stages involved in casting of prism specimen corrosion prevention studies

The depolarization test described in BS 12696 (2012) is used to detect the potential in the ON condition before detaching the anode from the system in order to determine the influence length up to which the anode can protect and to evaluate the efficacy of the anodes placed. We measure the depolarized potential after 24 hours and the instant-off potential. Calculations are made to determine whether the anode can provide protection based on the shift in potential measurements (depolarization accomplished). The specimens that underwent the soaking and drying cycle as well as the following potential measurements are shown in Figure.

In order to protect against corrosion, sacrificial anodes must be installed in corrosion-damaged reinforced concrete structures by drilling a hole at the installation locations of the anodes and filling it in with a mortar made of regular Portland cement without the addition of any chemical or mineral admixtures.

8. RESULTS

Several studies, including more than fifteen, have examined various aspects of cathodic protection (CP) for reinforced asphalt elements. These studies have investigated topics such as sacrificial anode cathodic safety, the use of electric current for cathodic protection, the long-term effectiveness of sacrificial anodes in repair operations, the avoidance of the anode effect through the use of anodes, self-sacrificing anodes for rust prevention, and the achievement of cathodic safeguarding in concrete with corrosion inhibitors.

The key findings from the analysis are as follows:

Sacrificial ZN anodes, surrounded in a specially formulated mortar containing a pore electrolyte saturated with additional (LIOH), effectively provide cathodic protection for the steel in areas of repaired concrete that were originally contaminated with high levels of chloride. (CP) excels in novel structures rather than in dismantling unities. When the chloride concentration around the rebars reached levels of about 3% in the adhesive form, no corrosion was seen in the blocks that were protected with cathodic current densities equal to or more than 1.6 mA/m², even after more than five years of experimentation.

Cathodic protection is a very effective method for delaying the onset of corrosion and extending the lifespan of reinforced concrete structures that are susceptible to chloride penetration.

To maintain the fall in exposure to four hours between 110 and 150 mV, which is the threshold for providing cathodic protection, it is sufficient to have protective electric current densities in the range of 1 to 2 mA/m² on the steel surface.

Field study has shown that attempting to repair patches without fully removing concrete that is contaminated may lead to the formation of a halo effect. This effect may create a localised corrosion cell, which in turn causes corrosion to occur. Furthermore, research has shown that the application of cathodic protection (CP) to these repairs may effectively prevent the initiation of corrosion.

9. CONCLUSION

An exhaustive analysis yielded a few outcomes:

The optimal pH level of the activation mortar is essential for the sacrificial anodes to function at their highest efficiency. In order to prevent corrosion of the ZN-based anodes, it is preferable to maintain a high pH. Over time, the capacity of the anodes to generate electric current declines, indicating the passivation of the steel. Therefore, the use of a sacrificial anode leads to a reduction in the rate of ongoing corrosion. Galvanic anodes are suitable when the corrosion rate is relatively low (less than ten milliamperes per square metre). During the steel's use, it is not permissible to passivate it. In order to prevent cathodic breakdown in RC structures, it is advisable to use galvanic anodes.

There has been no comprehensive analysis conducted to determine the specific relationship between the electrical resistivity of repair concrete and the extent to which sacrificial anodes are effective. Conducting study on the relationship between concrete resistance and the variation in length is essential. Studies have shown that sacrificial anodes are more efficient than cathodic protection at preventing corrosion. Nevertheless, there are no established criteria for determining the specific number and arrangement of anodes to be used in the field for the purpose of cathodic protection.

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