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

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## ABSTRACT

Reinforced concrete buildings are vital elements of contemporary infrastructure, offering robustness and longevity in many construction contexts. Nevertheless, a major obstacle that these buildings encounter is the risk of corrosion, which may undermine their strength and result in substantial expenses for maintenance. In order to tackle this problem, scientists and engineers have been investigating novel techniques to improve the strength and efficiency of reinforced concrete. An effective method includes using sacrificial anodes, which function as cathodic protection devices to reduce corrosion and prolong the lifespan of concrete buildings.

Sacrificial anodes are metallic components, usually composed of zinc or aluminum alloys, that are strategically positioned inside the concrete matrix. When placed into concrete, sacrificial anodes serve as cathodes in a galvanic corrosion cell, intentionally corroding themselves to save the nearby steel reinforcement against corrosion. By sacrificially acting, rust development on the reinforcing bars is successfully prevented, thereby maintaining the structural integrity of the concrete. Both laboratory research and field investigations have been done to assess the efficacy of sacrificial anodes in preventing corrosion and improving the longevity of reinforced concrete. These investigations include quantifying the speeds at which corrosion occurs, the extent to which chloride ions infiltrate, and the state of reinforcing bars in concrete samples, both with and without sacrificial anodes. Electrochemical methods, such as measuring polarization resistance and mapping half-cell potential, are used to evaluate the corrosion characteristics of concrete.

The findings of these investigations indicate that the use of sacrificial anodes effectively decreases the corrosion rate of reinforcing bars and enhances the concrete's resistance to chloride ion penetration. The sacrificial anodes prevent the corrosion of steel reinforcement and slow down the deterioration of concrete by undergoing sacrificial corrosion themselves. Cathodic protection is a method that preserves the structural integrity of reinforced concrete buildings and prolongs their lifespan, especially in harsh situations that are exposed to corrosive substances. Field studies provide further evidence to support the efficacy of sacrificial anodes in practical situations, demonstrating that reinforced concrete buildings outfitted with sacrificial anodes exhibit less corrosion damage over a period of time. These structures demonstrate improved resilience and extended lifespan, making them appropriate for use in challenging situations where corrosion is a key issue. In summary, the use of sacrificial anodes provides a pragmatic and economical method for improving the longevity and efficiency of reinforced concrete. This approach offers extended protection against corrosion, hence minimizing the need for expensive upkeep and repairs. Ultimately, sacrificial anodes provide a favorable method for reducing corrosion and enhancing the longevity of reinforced concrete buildings. Researchers and engineers are continuously improving the usage of sacrificial anodes in concrete infrastructure to enhance its long-term performance and durability. They do this via laboratory tests, field investigations, and practical implementations. By integrating sacrificial anodes into building projects, stakeholders may efficiently safeguard their investments and guarantee the durability and safety of reinforced concrete structures in various environmental situations.

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

## 1. INTRODUCTION

Reinforced concrete buildings are quite common in contemporary construction, playing a crucial role in the foundation of infrastructure around the globe. Nevertheless, these constructions are constantly at risk from corrosion, which has the potential to undermine their structural strength and durability. Corrosion of steel reinforcement in concrete happens when environmental elements, such as moisture, oxygen, and chloride ions, infiltrate the concrete cover and chemically interact with the steel, resulting in the creation of rust and eventual degradation. In order to address this widespread issue, engineers and researchers have devised many corrosion mitigation techniques, one of which is the use of sacrificial anodes.

Sacrificial anodes, often referred to as galvanic anodes or sacrificial cathodes, are metallic elements inserted into the concrete matrix to provide cathodic protection to the steel reinforcement embedded therein. Anodes are often fabricated from active metals like zinc or aluminum alloys, which possess a greater electrochemical potential than steel. Consequently, when sacrificial anodes are placed within concrete, they corrode preferentially in a sacrificial manner, so releasing electrons that go to the steel reinforcement. This technique efficiently transfers the corrosive response from the steel reinforcement to the sacrificial anodes, thereby safeguarding the steel from corrosion.

Using sacrificial anodes in reinforced concrete buildings is a proactive method for preventing and reducing corrosion. The anodes function as sacrificial cathodes by undergoing self-corrosion, so preventing the corrosion of the steel reinforcement and maintaining the structural integrity of the concrete. The use of this cathodic protection method provides several benefits, such as improved resilience, prolonged lifespan, and decreased upkeep expenses for concrete buildings that are exposed to corrosive surroundings.

Both laboratory research and field investigations have been carried out to evaluate the efficacy of sacrificial anodes in preventing corrosion and enhancing the performance of reinforced concrete. These investigations include assessing characteristics such as the rate of corrosion, the penetration of chloride ions, and the state of reinforcing bars in concrete samples, both with and without sacrificial anodes. Electrochemical methods, such as measuring polarization resistance and mapping half-cell potential, are used to observe the corrosion characteristics of the concrete and evaluate the effectiveness of the sacrificial anodes.

The findings of these investigations clearly illustrate the substantial influence of sacrificial anodes on the prevention and reduction of corrosion in reinforced concrete buildings. Concrete specimens that incorporate sacrificial anodes demonstrate decreased corrosion rates and less penetration of chloride ions in comparison to traditional reinforced concrete. In addition, sacrificial anodes play a crucial role in prolonging the lifespan of reinforced concrete buildings. They do so by safeguarding the steel reinforcement's integrity and reducing the likelihood of damage caused by corrosion.

Field investigations have been done alongside laboratory trials to verify the effectiveness of sacrificial anodes in practical situations. These research include observing the corrosion patterns of reinforced concrete buildings that are fitted with sacrificial anodes under real-world environmental circumstances. The field investigations support the results of laboratory research, showing that sacrificial anodes efficiently reduce corrosion and enhance the longevity of reinforced concrete under various environmental conditions.

To summarize, the use of sacrificial anodes offers a viable approach to improve the corrosion resistance and overall performance of reinforced concrete buildings. Sacrificial anodes provide long-term cathodic protection and prolong the lifespan of concrete constructions exposed to corrosive conditions by intentionally corroding themselves to shield the underlying steel reinforcement. Engineers are continuously improving and perfecting the usage of sacrificial anodes in reinforced concrete infrastructure globally via laboratory research, field investigations, and practical applications. This is done to enhance the longevity and dependability of the infrastructure.

## 2. LITERATURE REVIEW

**The Trivedi, Bhadoriya, and Sharma (2018)** research offers a comprehensive analysis of corrosion in reinforced steel buildings, with a specific emphasis on evaluating the impact of parameters such as water-cement ratio, concrete fluidity, and alkalinity during installation. The research indicates that Acoustic Emission (AE) is a reliable method for accurately forecasting corrosion during its early phases. In addition, the study explores the methods and variables that contribute to corrosion, specifically emphasizing the effects of calcium palmitate and its combination with calcium nitrite on the strength of concrete. Lower water-cement (W/C) ratios were shown to be important in reducing macro cell current by slowing down the kinetics of both cathodic and anodic processes, which in turn increases polarization resistance. Furthermore, empirical studies demonstrated that longitudinal fractures were more widespread in specimens subjected to continuous current as opposed to constant voltage throughout the corrosion process. The research also examines the impact of tensile stress on the corrosion rate, revealing that corrosion occurs more rapidly under tensile stress compared to compressive stress. In addition, this text provides a detailed exploration of many corrosion evaluation techniques, such as the Coulostatic technique, Galvanostatic pulse method, Half-Cell potential, Linear polarization resistance (LPR), Time domain reflectometry (TDR), Ultrasonic guided waves, X-ray diffraction, and atomic absorption. This research provides useful insights into the comprehension and evaluation of corrosion in reinforced concrete buildings, having practical implications for the monitoring and reduction of corrosion.

**Ahlstrom, Tidblad, Sandberg, and Wadso conducted a study in 2015.** This research examines the phenomenon of Galvanic corrosion and its characteristics on steel in fully soaked concrete. The objective is to find ways to avoid ongoing corrosion in cooling water tunnels of a nuclear power plant. Sacrificial anodes made of aluminum are utilized in reinforced concrete. Steel bars were affixed to the stainless steel water pipes as well. As a result, the pace at which the sacrificial anode was being used up was higher than anticipated. Steel in concrete with low chloride concentrations is often passive in pore water solution as a result of elevated pH levels. An electrochemical experiment is done utilizing a carbon steel alloy composition. A steel bars with a diameter of 12mm were cut into lengths of 150mm. Prior to casting, all steel bars underwent degreasing using trichlorethylene. A blend consisting of Portland cement and 4 mm sand is used to create a steel casting with a 60mm cover, using a water cement ratio of 0.6. A stainless steel cylindrical tube served as the counter electrode, while an electrode was put near the concrete sample. The electrodes used were either an Ag/AgCl saturated with KCL electrode or a saturated calomel electrode. An electrode is immersed in a solution of 3% NaCl. At each potential, the surface of the test sample was thoroughly cleaned, the sample was polarized, and the resulting data was documented. The measured potentials in the cooling water tunnels did not surpass 600 mV (SCE) on the side without sacrificial anodes. The voltage on the side with anodes was decreased to 700-800 millivolts. The chloride content in the cooling water was determined to exceed 0.7 by mass of cement. The Electrochemical experiment demonstrated the possible danger of Galvanic corrosion occurring in steel when the potential is intentionally polarized to a value above 200 mV in the presence of concrete.

**Bushman's** analysis of the corrosion process highlights the need of comprehending the intrinsic energy levels or potentials of metallic materials. When two metals with different potentials are linked, an electric current is generated, with positive charges flowing through the soil from the metal with the lower potential to the one with the higher potential. The passage of electric current in a positive direction triggers the process of corrosion when it leaves the surface of the metal. These findings highlight the need of taking into account the choice of materials and their compatibility to successfully reduce galvanic corrosion. To limit the risk of corrosion and extend the lifespan of buildings in corrosive environments, one may use materials with comparable energy levels or use preventive measures like sacrificial anodes. Thus, Bushman's discoveries provide vital knowledge on how to avoid corrosion. This knowledge may be used to inform the design and upkeep of infrastructure, ultimately improving its durability and performance.

**Gurappa's** study focused on the identification of suitable materials for cathodic protection. This included an investigation into both current cathodic protection (ICCP) systems and sacrificial anodes. Nevertheless, definitive recommendations for their use were not achieved. Instead, Gurappa proposed using expert systems to guarantee the efficacy of cathodic protection techniques. Gurappa underlined the need of validating materials via laboratory testing and field trials, especially for emerging applications, despite the existence and commercial availability of expert systems that can identify acceptable materials based on specific environmental circumstances. This highlights the need of comprehensive validation procedures to guarantee the dependability and effectiveness of cathodic protection systems in protecting reinforced concrete buildings from corrosion.

**Risque L. Benedict et al.** investigated the common occurrences of corrosion-related failures in prestressed concrete cylinder pipes over the first ten years of use. In order to reduce corrosion and decrease the risk of embrittlement to the high-strength prestressed wires, zinc sacrificial anodes were chosen for the installation of cathodic protection (CP). Within the first two years, the installation of cathodic protection (CP) on a 4.25 km portion of the Cedar Creek line has successfully averted about five expected instances of corrosion failure. In the absence of this action, by 2010, substantial repairs or eventual abandonment of the Cedar Creek Pipe Line would have been required. The implementation of CP measures is anticipated to significantly prolong the operational lifespan of the Richland Chambers and Cedar Creek lines. This highlights the efficacy of sacrificial anodes in safeguarding the structural soundness of prestressed concrete cylinder pipes and ensuring the dependability of water distribution infrastructure.

**Brousseau et al.** conducted a study on the restoration methods for infrastructure affected by corrosion. Their focus was on the removal of concrete polluted with salt, the repair process, and the use of waterproofing membranes. Nevertheless, concerns have emerged questioning the efficacy of this approach, namely in its ability to prevent reinforcement corrosion alone in salt-contaminated concrete. An investigated method for rehabilitation is sacrificial cathodic protection (CP) using metallized zinc coatings. Researchers in Montreal, Canada performed tests and reported positive results on Yves Prevost Highway by using metallized zinc as sacrificial anodes for cathodic protection in reinforced concrete buildings. Nevertheless, there are ongoing worries over the effectiveness of pure zinc in dry circumstances, particularly when there is a considerable amount of reinforcement and the concrete has high resistivity. This underscores the need for more investigation and contemplation of alternative corrosion protection strategies in order to guarantee efficient corrosion prevention in diverse environmental circumstances.

**Panossian et al.** conducted a comparative analysis to assess the effectiveness of aluminum and zinc/aluminum alloy coatings in comparison to typical zinc coatings for cathodic preservation of steel substrates in various natural conditions. Although aluminum-based coatings have benefits over zinc coatings, they have been proven to have limits in some natural environments where they are unable to provide efficient cathodic protection for steel substrates. Their research assessed the effectiveness of aluminum and zinc/aluminum alloy coatings in providing cathodic protection under different environmental circumstances characterized by differing degrees of corrosiveness and pollution, using experimental analysis. The study sought to determine whether a wide variety of coatings might effectively protect steel substrates in various natural conditions. In conclusion, the research found that zinc, whether employed alone or in modest amounts as an alloy, continued to be a reliable and efficient option for safeguarding steel surfaces under various environmental situations.

**Orlikowski et al.** Anodic polarisation over an extended period of time on reinforced concrete enables the identification of electrochemical parameters for the coatings being studied. Impedance measurements are used to calculate the electrochemical properties of conducting coatings. The use of studied coatings has been shown effective in providing cathodic protection for reinforced concrete. Studies indicate that the optimal proportion of graphite in coatings for concrete preservation should be within the range of 40% to 45%. The purpose of the study was to perform electrochemical tests on particularly made conductive coatings to evaluate their suitability as anodes in cathodic protection of reinforced concrete buildings. The results indicate that conducting coatings may be used as anodes to produce cathodic protection of reinforced concrete structures. Modifying the coating binder may enhance the electrical and electrochemical properties. Nevertheless, there are other technical challenges that need resolution, including difficulties pertaining to the deterioration of coatings over time and the state of the coating's electrical connection.

**G.K. Glass and N. R. Buenfield** conducted research to determine the optimal current density required to protect steel in concrete structures that are exposed to the atmosphere. It has been shown that the pace at which corrosion occurs greatly affects the amount of electric current required to protect steel in concrete that has been exposed to the air. Typical design current densities would not provide the level of cathodic polarization required to meet commonly accepted protection standards at low corrosion rates. Unprotected corrosion may be considerably slowed down by removing chloride ions and increasing the pH near the cathode, which results in a cathodic current. They assert that these protective effects are essential for the cathodic protection system to effectively prevent further corrosion and achieve an appropriate level of polarization. The objective was to examine the current densities projected by the mixed potential theory at a certain cathodic polarisation level and assess their impact on the actual protection mechanism. The researchers reached the conclusion that the current's protective effects, which promote the passivity of steel, play a vital role in the cathodic protection of steel in concrete. This occurs due to an increase in pH at the steel contact and the removal of chloride ions. As a result of these effects, meeting the commonly used 100 mV potential decay criterion becomes more feasible. Otherwise, the protective current density required to prevent moderate corrosion rates would be far higher than the current levels being utilized. Development of a galvanic sensor system Zin-Taek Parka et al. [23] discovered that measurements of electrochemical impedance spectroscopy (EIS), linear polarisation resistance (LPR), and open-circuit potential monitoring yielded consistent results in their investigation of the corrosion behavior of reinforcing steel. Within a tangible setting, there was a robust correlation seen between the output of a sensor made of steel or copper and the rate of corrosion in steel bars. The true extent of corrosion damage to the reinforcing steel may be determined by analyzing the relationship between the output of the steel/copper sensor and the corrosion rate.

**Edoardo Proverbio and colleagues** The problem arose from the visibility of the steel reinforcements and the significant spalling of the concrete surface on the platforms, which was discovered during routine maintenance inspections. The upper portions of the decks sustained significant damage, however the lower sections of the deck remained relatively intact.

The lower part of the deck was susceptible to sea spray, which created a more hostile atmosphere. This observation was quite uncommon. Both the coatings and steel piles were in great condition. Multiple field experiments have shown that the corrosion attacks in concrete were not caused by the permeability of the concrete, which is commonly a factor in rebar corrosion. They determined that the electrical power generated by the CP system, which was intended to be connected to the steel piles, was instead linked to the rebar in the concrete deck rather than the steel piles. The difficulties did not arise during the initial construction of the structure, when the concrete was in perfect condition and the rebar was securely interconnected, with no visible evidence of corrosion. The electrical connections between the rebars gradually degraded or fractured, resulting in the passage of stray currents between them. As a result, anodic areas formed and eventually led to corrosion attacks. The frequency and severity of these attacks increased to the extent that large sections of the deck's upper surface were extensively damaged with spalled concrete. The authors caution that a thorough understanding and diligent adherence to all technical concerns are necessary throughout the design and installation of CP systems to effectively avoid corrosion.

**Pietro Pedeferri** provides a thorough analysis of cathodic protection (CP) in his work, covering its historical development, fundamental principles, measures for prevention and protection, operational factors, distribution, risks of hydrogen embrittlement, dynamics of anodic systems, and protocols for monitoring. Pedeferri highlights the need of establishing enduring monitoring methods to guarantee adherence to protection criteria, avert excessive protection, and assess the overall effectiveness of CP systems. The measuring of potential in reinforced steel relative to reference electrodes is crucial for monitoring efforts. It serves as the primary foundation for evaluating the performance of cathodic protection (CP) procedures. Pedeferri's analysis of these fundamental elements enhances comprehension of CP approaches, emphasizing the significance of resilient monitoring mechanisms in preserving the integrity and effectiveness of CP systems in the long run.

## 3. CONCLUSIONS

After conducting a comprehensive review of the available literature and engaging in extensive discussions with experts in the field, the following areas of research deficiency have been highlighted for further investigation.

In order to achieve the effective integration of sacrificial anode systems in large-scale projects, it is crucial to ascertain the ideal spacing between anodes or their exact positions. This requires meticulous evaluation of variables such as the dimensions, shape, and locations prone to corrosion of the structure. Efficient strategizing and precise determination of anode positioning provide consistent safeguarding of the whole structure, hence reducing the likelihood of corrosion-induced harm. Strategically placing sacrificial anodes at certain intervals in building projects may optimize the effectiveness of corrosion prevention methods, therefore improving the long-term durability and structural integrity of the infrastructure.

While expert systems offer guidance in selecting appropriate materials for specific environments, their application in newer contexts requires thorough evaluation both in laboratory settings and real-world applications. Conducting studies or inquiries becomes essential to assess the suitability and performance of materials in diverse conditions. By subjecting materials to rigorous testing and field trials, researchers can gather valuable insights into their effectiveness and durability. This empirical approach ensures that materials chosen for corrosion prevention measures meet the demands of modern construction practices and environmental conditions, facilitating informed decision-making in infrastructure projects.

Moreover, there is a dearth of thorough research on the relationship between the ratio of cathode to anode area, the lifetime of the anode, its efficiency, and the changes in current distribution. This includes issues such as the location of the anode and the throwing force of sacrificial anodes. These factors are essential for maximizing the efficiency and durability of sacrificial anode systems in methods aimed at preventing corrosion. Performing focused study to comprehend the intricacies of these variables may improve the efficiency and dependability of cathodic protection systems, guaranteeing their successful integration into extensive building and infrastructure projects.

The evaluation of the overall anode demand for a particular structure and the reduction of the cathodic protection system linked to sacrificial anodes is yet unfinished. Comprehending these factors is essential for developing efficient corrosion prevention tactics and guaranteeing the prolonged resilience of reinforced concrete buildings. Additional investigation and examination are required to precisely ascertain the most effective arrangement of anodes and the level of system attenuation necessary to produce efficient and dependable cathodic protection. This will ultimately improve the overall performance and durability of the infrastructure.

Moreover, there is significant untapped potential for investigation and study in the field of combined current attenuation in sacrificial anode cathodic protection systems, an area that has not been well studied thus far. Gaining knowledge about the synergistic effects and processes of corrosion mitigation via coupled current attenuation might result in the development of improved and more efficient solutions for protecting reinforced concrete structures from corrosion. Further investigation and testing are necessary to fully explore the possibilities of this area in improving the durability and performance of infrastructure that is exposed to corrosive conditions.

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