

EVALUATION OF CATHODIC PROTECTION AND SURFACE TREATMENT TECHNIQUES OF REINFORCED CONCRETE STRUCTURES: A REVIEW

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ABSTRACT:

Corrosion of steel reinforcement is one of the main causes of damage in reinforced concrete structures, especially in environments exposed to chlorides or carbonation. Two commonly used protection methods are cathodic protection of reinforcement and surface treatments for concrete. However, these methods are usually studied separately. Research on cathodic protection mainly focuses on electrochemical performance, while studies on surface treatments focus on reducing the penetration of water, chlorides, and gases. As a result, there is limited research directly comparing their long-term durability within a unified framework. This study presents a structured qualitative review that compares cathodic protection and surface treatments based on their protection mechanisms, long-term performance, spatial effectiveness, and sustainability aspects. The results show that surface treatments mainly act as preventive systems by limiting the entry of harmful substances, while cathodic protection actively controls ongoing corrosion by modifying the electrochemical conditions at the steel surface. The effectiveness of each method depends on the level of structural deterioration, environmental exposure, and maintenance requirements. The findings highlight the need for standardized evaluation approaches that consider both transport and electrochemical factors to improve decision-making in corrosion protection of reinforced concrete structures.

KEYWORDS:

reinforced concrete corrosion, cathodic protection, surface treatment, durability, service-life extension, sustainability, life-cycle assessment

1 INTRODUCTION

Reinforced concrete structures are widely used in modern infrastructure due to their strength, durability, and economic advantages. However, long-term exposure to aggressive environmental conditions such as moisture, chlorides, carbonation, chemical attack, and freeze-thaw cycles can significantly reduce their service life by initiating deterioration processes, particularly the corrosion of steel reinforcement. Corrosion not only weakens the structural integrity of concrete elements but also increases maintenance and rehabilitation costs, making durability protection an important aspect of structural engineering [1].

Numerous protection and restoration strategies have been developed to address these issues and enhance the performance and longevity of reinforced concrete structures. Cathodic protection systems, sealers, and protective coatings are some of the most used techniques. Cathodic protection, one of the numerous corrosion mitigation strategies, is well known for being an efficient electrochemical approach for preventing corrosion in steel reinforcement. Cathodic protection moves the steel potential to a region where corrosion reactions are inhibited by applying an external current or by employing sacrificial anodes. Cathodic protection systems can considerably lower the corrosion current density and increase the service life of reinforced concrete structures contaminated with chloride [2]. In addition to external protection systems, the internal characteristics of concrete also play a major role in durability performance [3].

By acting as physical barriers, protective coatings and sealers limit permeability and slow deterioration processes by preventing water, chlorides, oxygen, and other dangerous substances from penetrating concrete. A number of variables, including as coating composition, surface preparation, exposure to the environment, and substrate compatibility, affect how effective they are. The potential of several coating systems, including polymeric, organic, and inorganic materials, to increase long-term durability and corrosion resistance has been researched [3].

Properties such as porosity, pore size distribution, curing conditions, and cement composition directly influence water absorption, permeability, and resistance to aggressive agents. Proper curing and optimized concrete mixtures contribute to a refined pore structure and improved durability, while recycled aggregates and supplementary cementitious materials continue to be investigated as sustainable alternatives in concrete production.

This study focuses on the evaluation of protective approaches for reinforced concrete durability, with particular attention to coatings, sealers, and cathodic protection systems. The research also considers the influence of concrete microstructure and material properties on long-term performance and corrosion resistance.

2 BACKGROUND AND METHODS

2.1 THEORETICAL BACKGROUND

Protective measures are essential for extending the service life and durability of reinforced concrete structures exposed to aggressive environmental conditions. One widely adopted approach is the application of coatings and sealers to concrete surfaces. Different coating systems, including polymeric, organic, and inorganic coatings, have been investigated, and their effectiveness largely depends on proper selection according to service conditions and substrate characteristics. In addition, adequate surface preparation and compatibility between the coating properties and the exposure environment are critical for achieving reliable long-term protection of concrete infrastructure [3].

Reinforced concrete structures are increasingly affected by steel reinforcement corrosion due to prolonged exposure to aggressive environments. Chloride ions originating from seawater, de-icing salts, or contaminated concrete mixtures, often combined with carbonation effects, are among the primary causes of corrosion. To mitigate this deterioration, cathodic protection has been widely used as an electrochemical rehabilitation technique. The method operates by shifting the steel concrete interface potential toward more negative values, thereby suppressing anodic reactions and significantly reducing corrosion rates [4]. Under normal conditions, reinforcing steel remains in a passive state because of the highly alkaline pore solution within concrete. However, when chlorides or carbonation destroy this passive layer, corrosion initiates, compromising structural durability [5].

Cathodic protection systems function by forcing the reinforcing steel to act as the cathode in an electrochemical system. This can be achieved either through sacrificial anodes, which naturally generate protective current, or through impressed current systems that use inert anodes connected to an external direct-current power supply. Impressed current cathodic protection is more commonly applied to reinforced concrete structures because the high electrical resistance of concrete requires controlled and relatively high protection currents. Despite their effectiveness, impressed current systems depend on a continuous external power supply, which has encouraged research into low-energy and renewable alternatives [6].

The effectiveness of cathodic protection is commonly evaluated using standardized protection criteria. Laurens and Francois [7] examined these criteria in reinforced concrete structures and demonstrated that polarization and depolarization responses can vary considerably depending on electrode location. Their experimental and numerical investigations showed that the criteria defined in standards such as EN ISO 12696 may not always provide a fully reliable assessment of cathodic protection performance in reinforced concrete structures. The study emphasized the importance of understanding spatial potential variations when evaluating protection efficiency [7].

In addition to performance assessment, proper system selection is essential for ensuring effective and durable corrosion control. Callon et al. [8] presented guidelines for selecting cathodic protection systems for reinforced and prestressed concrete structures, highlighting that the choice of system directly influences performance, durability, and overall cost. Factors such as structural complexity, environmental exposure, required

service life, concrete resistivity, current density requirements, and maintenance capabilities must all be considered during design [8].

Sealers and coatings also play an important role in protecting concrete bridge structures against environmental and chemical deterioration. Safiuddin and Soudki [9] reviewed the use of penetrating and surface sealers to reduce the ingress of water, chlorides, sulphates, and other harmful substances into concrete. These materials improve moisture vapor transmission and facilitate drying, thereby lowering the risk of reinforcement corrosion. Surface coatings provide an additional protective barrier against aggressive chemicals and environmental exposure [9].

The study by Anwar [10] examines how both the type of cement and curing method influence concrete's pore structure, which is critical for durability and resistance to degradation. The durability of reinforced concrete is strongly influenced by its pore structure, which governs the transport of water and aggressive agents such as chlorides and carbon dioxide. Numerous protection and restoration strategies have been developed to address these issues and enhance the performance and longevity of reinforced concrete structures. Cathodic protection systems, sealers, and protective coatings are some of the most used techniques. The performance of surface protection methods depends not only on the applied material but also on the underlying concrete pore structure, which determines the rate of corrosion initiation in reinforced concrete structures. [10].

2.2 METHODOLOGY

This study applies a systematic qualitative review methodology to evaluate the protection of reinforced concrete structures using cathodic protection systems and surface treatments, with emphasis on durability performance, sustainability, and life-cycle implications. Instead of conducting experimental investigations, the research synthesizes and critically analyses existing peer-reviewed literature.

A comprehensive literature search was performed using major scientific databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar. Keywords included reinforced concrete corrosion, cathodic protection, surface treatment, durability, service-life extension, sustainability, life-cycle assessment.

The review is structured thematically. First, the mechanisms of corrosion initiation development in reinforced concrete are examined. Second, the electrochemical principles, performance characteristics, and durability impact of cathodic protection systems are analysed. Third, surface treatment technologies and their effectiveness in limiting moisture and chloride penetration are evaluated. The comparative evaluation of durability performance, service-life implications, and sustainability aspects is presented in Sections 4.3 and 4.4.

The study addresses two key research questions:

Q1: How do the electrochemical mechanisms of cathodic protection compare with the transport-based barrier mechanisms of surface treatments in controlling reinforcement corrosion?

Q2: How do this fundamentally different mitigation strategies differ in terms of long-term durability performance, spatial effectiveness, and service-life extension under aggressive environmental exposure?

Relevance to reinforced concrete structures exposed to carbonation or chloride conditions was taken into consideration when choosing the literature. Corrosion potential shifts, chloride diffusion decrease, resistivity changes, service-life extension predictions, and maintenance requirements are some of the key performance indicators that were taken from the analysed research. The comparative evaluation was structured using four analytical dimensions: protection mechanism, spatial effectiveness, long-term durability performance, and sustainability considerations.

3 RESULTS AND DISCUSSION

3.1 RESULTS

3.1.1 Cathodic Protection

When cathodic protection is applied to steel reinforcement in concrete, the porous nature of concrete restricts the movement of ions and molecules involved in electrochemical reactions and ionic conduction. In particular, the region adjacent to the steel cathode tends to become enriched in hydroxyl (OH⁻), sodium (Na⁺), and potassium (K⁺) ions, while being depleted of chloride ions (Cl⁻) and oxygen (O₂). The concrete surrounding the cathodic protection anode becomes progressively more acidic and exhibits an increased concentration of chloride ions [11].

Owing to the slow diffusion of ions within concrete, these favourable conditions persist even after interruption of the cathodic protection current, providing continued protection until the concentration gradients are gradually dissipated. This phenomenon enables the use of intermittent cathodic protection in certain applications and supports the application of high current densities over limited periods to achieve longer-lasting protective effects, such as those associated with electrochemical re-alkalization or chloride extraction [11].

Two basic types of cathodic protection systems are commonly used: impressed current cathodic protection (ICCP) and galvanic (sacrificial) cathodic protection (GCP). Typical anode materials include activated titanium coated with mixed metal oxides or conductive coatings. Activated titanium anodes are commonly installed as meshes embedded in cementitious overlays on the concrete surface, or as fine mesh strips placed in boreholes or slots cut into the concrete, which are subsequently filled with cementitious grout. Conductive polymer coatings filled with carbon particles may be applied directly to the concrete surface and usually protected with a conventional topcoat [4].

Primary anodes, typically metal wires, distribute the current to the anode material and must be closely spaced to minimize potential drops. Effective system performance requires durable bonding of cementitious overlays or conductive coatings to the concrete surface, which depends on adequate surface preparation and proper application and curing. In impressed current cathodic protection systems, the anodes and power source are connected using electrically isolated copper cables with sufficient cross-sectional area to limit voltage losses. Power for impressed current cathodic protection systems is

commonly supplied from the electrical grid or from renewable sources such as solar or wind energy, typically supported by battery backup systems [4].

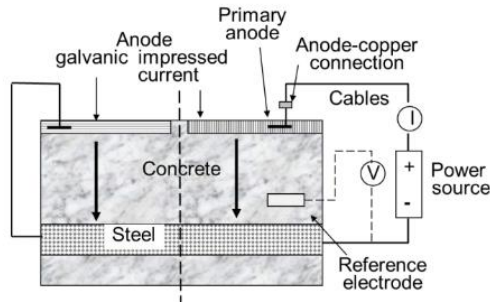


Figure 1: Key elements of impressed current (right) and galvanic (left) cathodic protection systems [4]

Impressed current cathodic protection (ICCP) systems are employed in situations where the electrolyte resistivity is high and sacrificial anode systems are unable to deliver sufficient protective current in a cost-effective manner. These systems are widely used for atmospherically exposed reinforced concrete structures, particularly those affected by chloride ingress, and are most appropriate for large structures with severe corrosion damage, long design lives, or limited accessibility. Impressed current cathodic protection systems utilise inert or minimally consumable anodes in combination with an external direct current power source, typically supplied via an AC-to-DC rectifier, to impose a controlled current onto the steel reinforcement [12].

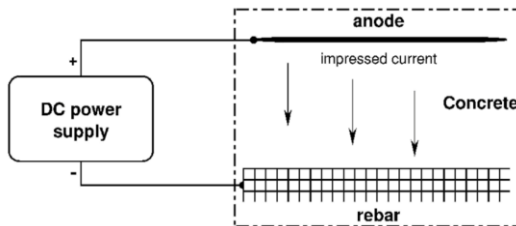


Figure 2: Impressed Current Cathodic Protection [12]

An ICCP anode must be durable and resistant to acidic conditions generated during operation, while remaining compatible with the surrounding concrete. It should also ensure good electrical conductivity at the anode–concrete interface, allowing efficient current flow from the anode to the reinforcing steel [13]. Unlike sacrificial anode systems, impressed current cathodic protection installations can deliver higher driving voltages and adjustable current outputs, allowing effective operation in high-resistivity environments and enabling the system to accommodate variations in corrosion activity and protection demand over time [12].

Sacrificial anode cathodic protection (SACP) systems use reactive metals as auxiliary anodes that are directly electrically connected to the steel reinforcement requiring protection. These systems operate on a galvanic principle and therefore do not rely on an external power source, which reduces the risk of interference with nearby structures and simplifies system design. Although the protection current can be monitored, it cannot be

actively controlled, meaning that any increase in current demand, such as that caused by coating degradation or structural changes, may require the installation of additional sacrificial anodes [1].

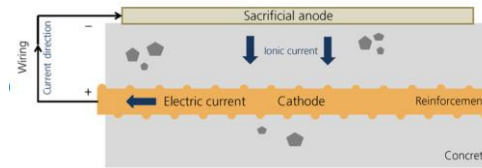


Figure 3: Sacrificial Anode Cathodic Protection [6]

Compared with impressed current cathodic protection (ICCP), sacrificial anode cathodic protection systems generally have a shorter service life because the anode material is progressively consumed during operation. Despite their relatively low driving voltage, which may limit effectiveness in some reinforced concrete applications due to the high electrical resistivity of concrete cover, sacrificial anode cathodic protection systems are considered safer for prestressed concrete structures. Because sacrificial anode systems work at lower driving voltages and hence lessen the risk of excessive hydrogen evolution, they are typically regarded as safer for pre-stressed concrete buildings. Excessive polarization in impressed current systems may encourage pre-stressing steel to become hydrogen embrittled, which could jeopardize structural integrity [14]. These metals are frequently alloyed, such as aluminium-zinc-indium alloys, to enhance dissolution behaviour and long-term performance [1] [15].

Long-term field investigations demonstrate that cathodic protection operates by fundamentally altering the electrochemical equilibrium at the steel-concrete interface. In alkaline concrete, reinforcement is normally protected by a passive oxide film; however, chloride ingress or carbonation destabilizes this passivity and initiates anodic iron dissolution. Cathodic protection counteracts this process by externally supplying electrons, shifting the steel potential toward more negative values and suppressing anodic reactions. Sustained polarization promotes hydroxyl ion generation at the steel surface, increasing local alkalinity and enabling repassivation, while the imposed electric field influences ionic redistribution, reducing chloride concentration at the reinforcement level [4].

In impressed current systems, inert anodes facilitate oxidation reactions that may induce localized acidification near the anode region, whereas galvanic systems rely on the controlled dissolution of sacrificial metals such as zinc to provide protective current. Long-term durability therefore depends on appropriate current density control, monitoring of depolarization behaviour, and mitigation of secondary chemical gradients, including alkali accumulation near the steel or hydrogen evolution under excessive polarization [4].

Cathodic protection is an active electrochemical corrosion control method that suppresses anodic reactions at the reinforcement surface by shifting the steel potential toward a more negative state. This method is particularly effective for reinforced concrete structures already affected by chloride-induced corrosion, especially in aggressive environments such as marine structures, bridges, and parking garages. Cathodic protection systems generally provide long-term service-life extension, often ranging from 20 to 40 years when properly maintained. However, their operation requires continuous monitoring, electrical

control, and a moderate to high energy supply, particularly in impressed current systems [16]. From a durability perspective, this spatial variability underscores the importance of performance-based monitoring and highlights a key distinction between active electrochemical systems and passive surface treatments [7].

3.1.2 Surface Treatment

Recent research highlights that surface coatings enhance the long-term durability of concrete primarily by significantly reducing the diffusion of water and harmful species into the substrate. Coatings with lower diffusion coefficients than the concrete matrix act as effective barriers against moisture, chlorides, CO₂, and other aggressive agents, thereby limiting the main drivers of reinforcement corrosion and physical degradation such as freeze-thaw damage. Nano-modified and multifunctional treatments that combine hydrophobicity with pore-blocking or enhanced mechanical properties have shown particularly strong reductions in water absorption, especially for concrete with high water-to-cement ratios [17].

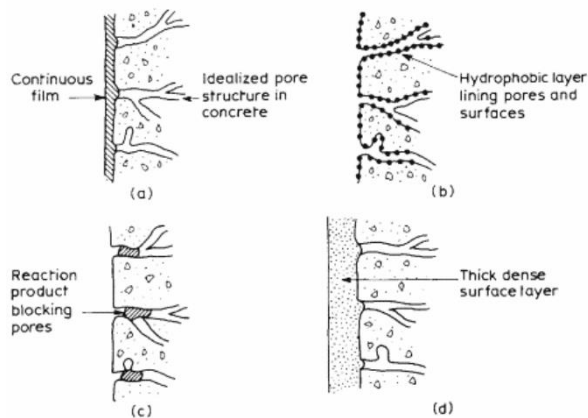


Figure 4:Types of Surface Treatments of Concrete Structures [18]

Surface treatments enhance reinforced concrete durability by limiting the transport of aggressive agents rather than altering corrosion electrochemistry. Penetrating sealers modify the near-surface pore structure to create hydrophobic conditions that reduce water and chloride ingress while preserving vapor permeability. In contrast, film-forming coatings establish a continuous external barrier that restricts the diffusion of moisture, chlorides, and carbon dioxide. These mechanisms delay corrosion initiation by reducing chloride accumulation and carbonation depth, and by improving freeze-thaw resistance. However, their effectiveness depends on maintaining an appropriate balance between impermeability and breathability. Excessive vapor restriction may lead to internal moisture retention and durability concerns. Surface treatments function primarily as preventive, transport-control strategies rather than active corrosion mitigation systems [9].

The mechanisms in table 1 below show that rather than altering electrochemical corrosion processes, surface treatments mainly preserve concrete by regulating the movement of aggressive chemicals. While hydrophobic treatments decrease capillary absorption without obstructing vapour flow, film-forming systems and thick, dense coatings serve as

external diffusion barriers. To reduce permeability, reaction-based devices partially densify the near-surface pore structure. The long-term performance of sealers and coatings depends not only on intrinsic material properties but also on environmental exposure, substrate condition, and application quality.

Table 1: Representation of different surface treatments of concrete structures [18]

Surface Treatment Mechanism	Principle of Action	Depth of Influence	Moisture/Vapour Behaviour	Main Durability Contribution	Key Limitations	Typical Systems
Continuous film	Forms a continuous external layer that acts as a physical barrier to water, chlorides, and gases	Surface layer only	Low to moderate vapour permeability (depends on material)	Reduces chloride ingress, carbonation, and water penetration	Sensitive to cracking, UV degradation, and adhesion failure	Epoxy, acrylic, polyurethane coatings
Hydrophobic layer lining pores and surfaces	Lines internal capillary pores with hydrophobic compounds without blocking pore structure	Shallow penetration (typically 1–3 mm)	High vapour permeability ("breathable")	Reduces capillary suction and water absorption while allowing drying	Limited effectiveness in cracked or highly permeable concrete	Silane, siloxane treatments
Reaction product blocking pores	Chemical reaction within pore structure produces solids that partially block capillary pores	Near-surface penetration	Moderate vapour transmission	Decreases permeability and slows chloride diffusion	Penetration depth may be limited; performance depends on substrate condition	Silicate-based densifiers, reactive sealers
Thick dense surface layer	Creates a dense, high-build coating layer that physically isolates concrete from environment	Surface only (thicker than continuous films)	Low to negligible vapour permeability	Strong resistance to aggressive environments and chemical attack	Risk of moisture entrapment; high dependence on adhesion quality	High-build polymer or resin coatings

Surface treatment systems function as preventive protection methods by reducing the ingress of water, chlorides, carbon dioxide, and other aggressive agents into concrete [19]. Common surface treatments include coatings, sealers, and hydrophobic impregnations, which improve durability by reducing permeability and delaying corrosion initiation. Surface treatments generally require lower operational energy and simpler application procedures compared to cathodic protection systems. However, their effectiveness gradually decreases due to environmental exposure, ultraviolet radiation, abrasion, and aging, making periodic inspection and reapplication necessary [20].

Surface preparation is particularly critical, as inadequate removal of contaminants or carbonated layers can compromise adhesion and reduce service life. Film thickness, coverage uniformity, and surface profile directly affect resistance to carbonation and chloride diffusion, while defects such as pinholes may create localized pathways for aggressive agents. Although surface treatments can substantially improve concrete resistivity and delay corrosion initiation, their performance gradually degrades over time due to environmental aging and mechanical wear, often requiring reapplication to maintain

protective effectiveness. Consequently, these systems should be considered maintenance-dependent preventive strategies rather than permanent corrosion control solutions [9].

3.1.3 Case Studies

Cheaitani et al. [21] did a research on Australian Bridge on corrosion protection of Mission River Bridge in Australia, which is exposed to a harsh marine environment. Due to constant exposure to saltwater, humidity, and biological activity, the structure experienced severe corrosion, particularly in tidal and splash zones. To address this issue, impressed current cathodic protection (ICCP) systems were implemented across different parts of the bridge. The case study highlights that cathodic protection can effectively control ongoing corrosion and significantly extend service life. However, it also demonstrates that such systems require careful design, continuous monitoring, and adaptation to varying environmental conditions. Furthermore, different protection strategies had to be applied to specific zones of the structure, reflecting the complexity of real-world conditions. This example emphasizes that corrosion mitigation solutions must be tailored to both environmental exposure and structural characteristics [21].

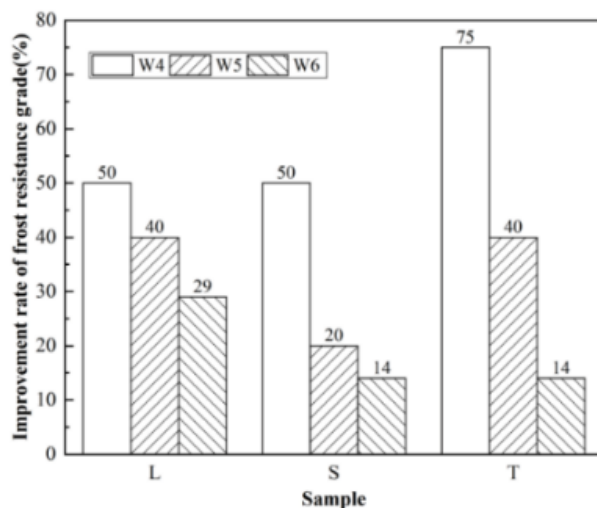


Figure 5: Increase in the frost resistance grade of concrete because of surface treatment [22]

Protective coatings were prepared and applied to concrete cube specimens 100 mm x 100 mm x 100 mm to evaluate their corrosion resistance and mechanical performance. Different formulations were developed by varying the type and concentration of additives, followed by controlled application and curing prior to testing. The coated samples were then subjected to a comprehensive series of laboratory tests to evaluate both mechanical and corrosion properties. Mechanical performance was assessed through adhesion strength and durability tests, while corrosion resistance was investigated using electrochemical techniques such as electrochemical impedance spectroscopy (EIS) and polarization measurements. Figure 5 below illustrates the influence of surface treatment systems on freeze-thaw durability performance, demonstrating how permeability

reduction contributes to improved frost resistance under aggressive environmental exposure.

Microscopic analyses, including scanning electron microscopy (SEM), were performed to examine the surface morphology, coating uniformity, and the presence of defects such as pores and cracks. The experimental results showed that coatings with optimized compositions exhibited improved adhesion, reduced surface defects, and enhanced barrier properties. The presence of additives contributed to a more uniform and compact microstructure, limiting the penetration of water and aggressive ions and thereby significantly improving corrosion resistance [22].

3.2 DISCUSSION

This review shows that the mechanism and range of applications of surface treatments and cathodic protection are fundamentally different. While cathodic protection offers active electrochemical control that can decrease ongoing corrosion, surface treatments generally serve as preventive systems by preventing the infiltration of hostile chemicals. As a result, the degree of exposure and the stage of structural degeneration have a significant impact on their efficacy. Performance requirements, durability goals, and long-term management issues should all be taken into account when choosing a method because neither is inherently better.

This lack of consistency limits the development of clear, performance-based guidelines for selecting corrosion protection strategies [23]. The findings of this review therefore highlight the need for standardized evaluation methods that integrate these key factors within a single durability framework. Developing such approaches would support more reliable and transparent decision-making in corrosion mitigation practice.

Table 2: Comparison between surface treatment and surface protection

Performance Criteria	Cathodic Protection	Surface Treatments
Protection Principle	Electrochemical suppression of corrosion	Restriction of moisture and chloride ingress
Corrosion Stage Suitability	Effective after corrosion initiation	Most effective before corrosion initiation
Service-Life Extension	Typically 20–40 years	Typically 5–15 years
Maintenance Requirements	Continuous monitoring and electrical control	Periodic inspection and reapplication
Chloride Resistance	Active chloride redistribution	Reduction of chloride diffusion
Energy Requirement	Requires electrical energy	Minimal operational energy
Environmental Impact	Long-term durability benefits but energy consumption	Lower initial impact but repeated material use
Typical Applications	Marine structures, bridges, parking garages	Preventive protection for exposed concrete

Examining the fragmented character of previous studies makes the observed research gap on the absence of integrated comparative evaluations very clear. The analysis conducted in this review demonstrates that the existing literature evaluates cathodic protection and surface treatments using different performance criteria and assessment approaches, which makes direct comparison challenging. Through the structured comparison

presented in this study, it became evident that there is no unified framework that simultaneously considers electrochemical control, transport limitation, long-term durability, and maintenance requirements.

The life-cycle performance of corrosion protection systems is a critical factor in their selection and application. Cathodic protection systems, particularly impressed current systems, are characterized by high initial costs and continuous energy requirements, as they rely on a constant external power supply to function effectively. Surface treatment systems typically require lower initial investment but demand periodic reapplication and maintenance use to degradation over time. While cathodic protection is more suitable for long-term corrosion control in aggressive environments, surface treatments are often considered a more economical short-to medium-term solution [24].

In addition to the identified research gap, practical constraints must be recognized. The effectiveness of surface treatments and cathodic protection is largely reliant on appropriate design, high-quality installation, and ongoing maintenance. Variability in concrete quality, exposure to the environment, craftsmanship, and monitoring procedures can all have a big impact on durability results in real-world settings. There is still a dearth of long-term field data that directly compares the two approaches under comparable exposure circumstances. This emphasises how crucial it is to conduct a site-specific assessment before choosing a corrosion mitigation strategy and bolsters the demand for comprehensive assessment instruments that integrate technical performance with realistic feasibility factors.

4 CONCLUSION

Cathodic protection systems and surface treatment methods are the two main corrosion prevention options for reinforced concrete structures that were analysed and contrasted in this study. Reinforcement corrosion is a major durability issue, particularly in structures exposed to carbonation and chlorides. As a result, choosing the right protection technique is crucial to increasing service life and lowering maintenance expenses.

The results show that surface treatments and cathodic protection use essentially distinct protective mechanisms. By preventing water, carbon dioxide, chlorides, and other hostile chemicals from penetrating concrete, surface treatments essentially serve as preventive barrier systems. Cathodic protection, on the other hand, is effective even after corrosion initiation has taken place because it actively suppresses corrosion by altering the electrochemical conditions at the steel surface and decreasing anodic dissolution.

Significant variations in durability performance and spatial efficacy were also brought to light by the comparative research. Because of current distribution and concrete resistivity, cathodic protection may show localized variations in protection efficiency, whereas surface treatments offer more uniform surface coverage but are only effective near the surface and are susceptible to adhesion failure and coating flaws. Because their efficacy

is highly dependent on structural condition, environmental exposure, degradation stage, and maintenance method, neither option can be deemed generally preferable.

The absence of established evaluation frameworks that may directly compare electrochemical protection techniques with transport-based surface protection systems is a noteworthy result of this analysis. Current research frequently evaluates these approaches using various performance metrics, which restricts integrated durability evaluation and decision-making.

Standardised evaluation methods that integrate electrochemical behaviour, transport mechanisms, spatial performance, and life-cycle factors should be the goal of future study. In the practice of reinforced concrete, such integrated frameworks would facilitate more dependable corrosion mitigation techniques and enhance decision-making.

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