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Corrosion Behavior of Reinforcement Bars with Various Surface Treatments in Chloride-Contaminated Concrete

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Abstract- This work explores the corrosion behavior of reinforcing bars in concrete environments polluted by chloride, analyzing the impact of various surface treatments. The corrosion-resistant nature of reinforcement bars is critical to the longevity of infrastructure in severe settings, particularly those subjected to seawater or de-icing agents. Enhancing this resistance are surface treatments like as galvanization, corrosion inhibitors, and epoxy coatings. Epoxy coatings protect steel from direct contact to corrosive factors by acting as strong barriers against chloride penetration. Applying a protective zinc layer that corrodes sacrificially to prolong the steel's life is known as galvanization. Corrosion inhibitors, on the other hand, reduce the rate of corrosion whether they are added externally or blended into concrete mixtures. This study examines the effectiveness of various treatments using field investigations, electrochemical analysis, and accelerated corrosion tests. It takes into account variables including concrete quality, coating type and thickness, and weather conditions. By optimizing surface treatments for reinforcing bars, the study's findings hope to increase the overall lifetime and durability of concrete buildings in settings high in chloride.

Keywords- Corrosion behavior, Reinforcementbars, Surfacetreatments, chloride Concrete.

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INTRODUCTION

In chloride-contaminated environments, such as maritime settings or places exposed to de-icing chemicals, the corrosion behavior of reinforcing bars has a considerable impact on the longevity of concrete buildings. This is especially true in conditions where chloride is present. Over the course of time, chloride ions are able to permeate concrete, eventually reaching the reinforcing bars and beginning the corrosion processes that might undermine the structural integrity of the building. Several surface treatments have been devised and applied to reinforcement bars in order to reduce the danger of corrosion that is commonly encountered. The purpose of these treatments, which include galvanization, corrosion inhibitors, and epoxy coatings, is to increase the resistance of reinforcing bars against corrosion that is caused by chloride (Garcia et al. 2021).

The use of epoxy coatings results in the formation of a protective barrier that stops chloride ions from accessing the surface of the steel, hence lowering the likelihood that corrosion will begin. The process of galvanization includes applying a layer of zinc to the steel. This layer serves as a sacrificial protection, allowing the zinc to corrode more quickly than the steel itself, so delaying the corrosion of the steel itself. It is possible to limit the electrochemical processes that contribute to corrosion by using corrosion inhibitors, which can be integrated into concrete mixes or coated externally. In order to improve the durability and lifetime of concrete buildings in chloride-rich settings, it is essential to have a solid understanding of the efficiency of various surface treatments. This research explores the corrosion behavior of reinforcement bars that have been treated to a variety of surface treatments. The investigation is carried out by accelerated corrosion tests, electrochemical analysis, and outdoor field surveys. The purpose of this research is to improve surface treatments and contribute to the construction of infrastructure that is more resilient. This will be accomplished by assessing aspects such as the kind and thickness of coatings, environmental conditions, and the quality with which concrete is produced. As a result of its adaptability, longevity, and structural strength, reinforced concrete has become an extremely common material in contemporary building settings. Nevertheless, corrosion of the steel reinforcement bars (rebars) implanted inside the concrete matrix is one of the most significant issues that reinforced concrete constructions must contend with. When chloride ions break through the concrete cover and make their way to the reinforcing steel, they set off an electrochemical reaction that ultimately results in the creation of rust, expansion, and spalling of the concrete cover. This is the mechanism that causes corrosion. Not only does this corrosion phenomena affect the structural integrity of the concrete, but it also shortens the concrete's service life, which results in expensive repairs and maintenance.

In locations where concrete is exposed to chloride-containing chemicals, such as saltwater, deicing salts, or industrial pollutants, chloride-induced corrosion is more widespread. This type of corrosion can be caused by chloride. Structures along the coast, bridges, parking garages, and other types of infrastructure in cold regions are particularly susceptible to chloride ingress, which can then lead to the corrosion of rebars. Therefore, it is vital to implement corrosion prevention methods that are efficient in order to guarantee the long-term durability and performance of reinforced concrete buildings in environments that are polluted by chloride chemicals (Almusallam et al. 2020).

Numerous approaches and surface treatments have been devised and used in order to reduce the amount of corrosion that occurs in reinforcing bars that are embedded in chloride-rich concrete. The purpose of these surface treatments is to strengthen the protective barrier that exists between the reinforcing steel and the harsh environmental agents, which will ultimately result in the reinforced concrete buildings having a longer service life. Epoxy coatings, galvanization, and corrosion inhibitors are examples of surface treatments that are often utilized.

On the surface of rebars, epoxy coatings are put in order to establish a barrier that prevents chloride from entering the structure and to give mechanical protection against abrasion and other forms of physical damage. The process of galvanization includes applying a zinc coating on rebars, which then corrodes through a process called sacrificial corrosion in order to protect the steel underneath from such corrosion. On the other hand, corrosion inhibitors are chemicals that are either added to the concrete mix or sprayed directly to rebars. Their purpose is to limit the rate of corrosion by either passivating the steel surface or blocking the electrochemical processes that are involved in corrosion.

In spite of the fact that these surface treatments are widely used, the question of whether or not they are successful in real-world situations, particularly in chloride-contaminated concrete, is still being researched and debated. The selection and performance of surface treatments for corrosion protection are influenced by a variety of factors, including coating adherence, compatibility with concrete, long-term durability, and cost-effectiveness. The purpose of this study paper is to provide a contribution to the knowledge of the corrosion behavior of reinforcing bars that have been subjected to a variety of surface treatments in situations that present chloride contamination in concrete. The purpose of this study is to evaluate the effectiveness of surface treatments in reducing corrosion and increasing the service life of reinforced concrete buildings. This will be accomplished via the use of accelerated corrosion tests, electrochemical measurements, and in-depth analysis. The insights that were gathered from this research may be used to guide future improvements in this essential field of civil engineering and to assist the selection of appropriate corrosion prevention systems.

REVIEW OF LITERATURE

Garcia et al. (2021) focused on the development and characterization of eco-friendly corrosion inhibitors derived from natural compounds for sustainable reinforcement protection. Their study explored the use of plant extracts, bio-based polymers, and green corrosion inhibitors in mitigating chloride-induced corrosion in concrete structures. Garcia et al. emphasized the environmental benefits, biodegradability, and low toxicity profiles of these inhibitors, highlighting their potential to align with global sustainability goals while effectively safeguarding reinforcement bars against corrosion.

Almusallam et al. (2020) conducted a comprehensive investigation into advanced surface treatment technologies for corrosion protection in reinforced concrete structures. Their research aimed to address the challenges associated with traditional methods, such as chloride-induced corrosion, adhesion issues, and long-term sustainability concerns. The study reviewed existing literature on epoxy coatings, galvanization, and corrosion inhibitors while highlighting the limitations and areas for improvement. Almusallam et al. delved into innovative solutions, including nano-coatings for enhanced barrier properties, self-healing materials for autonomous crack repair, and smart coatings with corrosion-sensing capabilities. These advancements were seen as promising strategies to improve durability, reduce maintenance requirements, and ensure the long-term performance of corrosion protection systems. The study concluded by proposing future directions for optimizing these technologies and integrating them into practical applications to address the evolving challenges in corrosion prevention in reinforced concrete infrastructure.

Wang and Li (2020) investigated the synergistic effects of incorporating nanomaterials, such as graphene oxide and carbon nanotubes, into concrete matrices to enhance corrosion resistance. Their research focused on the mechanisms of nanoparticle dispersion, interfacial bonding, and barrier formation within the concrete matrix, resulting in improved mechanical properties and durability. Wang and Li's findings underscored the potential of nanomaterial-modified concrete as a high-performance solution for combating corrosion in aggressive environments.

Jones and Patel (2019) contributed to the literature by investigating the effectiveness of novel hybrid coatings in enhancing the durability of reinforced concrete exposed to chloride-rich environments. Their research involved synthesizing hybrid materials combining organic and inorganic compounds to create robust protective layers with superior adhesion, corrosion resistance, and self-healing properties. Jones and Patel's study showcased promising results in terms of reduced chloride ingress, improved mechanical properties, and prolonged service life, positioning hybrid coatings as a viable alternative to conventional surface treatments.

Smith et al. (2018) conducted an extensive review of corrosion mechanisms and mitigation strategies in reinforced concrete structures, focusing on the impact of environmental factors such as moisture, temperature variations, and aggressive chemical agents on corrosion rates. Their study delved into the electrochemical processes underlying corrosion initiation and propagation, emphasizing the role of chloride ions in accelerating corrosion in marine and coastal environments. Smith et al. critically evaluated traditional corrosion protection methods, including surface coatings, cathodic protection systems, and concrete admixtures, while highlighting the need for advanced, multifaceted approaches to combat corrosion challenges effectively.

METHODOLOGY

- **Material-**

Table 1 displays the molecular makeup of the HPB235 reinforcement that was employed. Prior to being impregnated in epoxy resin, the working electrode in this investigation had one end soldered to a Cu wire. The working electrode, which included the Cu-wire contact region, was then impregnated in debubbled epoxy resin following profile polishing (#1200 SiC) and cleaning in an ultrasonic bath. This left only a partial Cu wire with a plastic cover for connecting electrode clips; the working surface's diameter and area were 8 mm and 0.502 cm2, respectively. Prior to the measurements, the working electrode surface was ground using #220 to #4000 SiC papers (lubricated with distilled water). To achieve a mirror-like surface, the surface was then polished using diamond powder lubricant on cloths; this same polishing technique was frequently employed in the studies that were published. In order to reduce the impact of oxygen and moisture on the surface properties of the working electrode, the electrode was polished, washed in an ultrasonic bath using ethanol (C2H5OH), and then kept in a N2 environment.

Table 1. Chemical composition of the reinforcement used in the study (wt. %).

Element	C	Si	Mn	S	P	Fe
Content	0.16	0.28	0.57	0.04	0.03	98.92

In order to prepare simulated pore solutions, ordinary Portland cement and fly ash were melted into tablets, and the contents were then measured by XRF analysis using a wavelength spectrometer (AXIOS PW4400, Netherlands). Table 3 displays the chemical compositions of fly ash and cement as oxides. To create the alkali-activating solution (modulus: 1.5; Na2O: 7 wt.%), NaOH (analytical grade) and distilled water were combined with Na2SiO3 solution (modulus: 2.37; SiO2: 28.61 wt.%; Na2O: 12.34 wt.%).

Table 2. The chemical compositions of the cement and fly ash in this study (wt. %)

Empty Cell	SiO_2	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	SO_3	Na_2O	rest	LOI[a]
CEM	20.52	5.21	59.46	3.15	0.61	2.80	2.24	0.23	5.78	−1.20
FA	49.82	26.74	10.39	6.66	1.43	1.24	1.07	0.95	1.7	−0.70

- LOI means the loss on ignition.

- **Sample preparation in a simulated pore solution-**

It was observed that AAFA was typically cured under 40 °C. The cement ash and distilled water/Na2SiO3 solution were combined with a weight ratio of 1:1 for 24 hours at 20 °C (simulated cement pore (SCP) solution) and 40 °C (SAFP solution). Centrifugation at 10,000 rpm was then used to get the simulated pore solution. To study the corrosion performance of the reinforcement in the presence of chlorides, sodium chlorides (3.5 weight percent or 7 weight percent) were added to the aforementioned solutions (3.5 weight percent NaCl was utilized in the SCP solution and both 3.5 weight percent and 7 weight percent NaCl were used in the SAFP solution).

ICP-OES (8300 series, PE Optima, USA) was used to measure the primary element species in the produced simulated pore solutions. The pH of the simulated pore solution was measured using a pH meter (Mettler Toledo FE20K). Furthermore, the standard rotational viscometer (Rotational viscometer NDJ-1, Shanghai Hengping Instrument) was used to assess the viscosity of the simulated pore solution. The chemical makeup and viscosity of the several simulated pore solutions are compiled in Table 3. When Table 3 and Table 1 were compared, it was found that the values of the ions concentrations found in this investigation were comparable to those found in the published studies.

Table 3. Chemical composition of different simulated pore solutions

Solution	Na (mM)	K (mM)	Ca (mM)	Si (mM)	S (mM)	Al (mM)	pH	Viscosity (mPa·s)
SCP (CEM)	19.91	138.46	1.77	0.52	0.23	0.023	13.32	25.10
SAFP (FA)	1847.82	5.00	0.059	667.85	36.46	7.09	13.51	40.50

Table 4 displays the sample designations used in this investigation. Sample CEM3.5 was the reinforcement in the SCP solution with 3.5 weight percent NaCl; samples FA3.5 and FA7 were the reinforcement in the SAFP solution with 3.5 weight percent and 7 weight percent NaCl, respectively, for the purpose of examining the corrosion performance of the reinforcement in chloride-contaminated simulated pore solutions (Group 1 in Table 4). Sample CEM served as the reinforcement in the SCP solution, and sample FA served as the reinforcement in the SAFP solution, in order to calculate the chloride threshold concentration (Group 2 in Table 4).

Table 4. Sample designations in this present study

Group	Sample	Immersion solution	NaCl content
1	CEM3.5	SCP solution	3.5 wt.%
	FA3.5	SAFP solution	3.5 wt.%
	FA7	SAFP solution	7 wt.%
2	CEM	SCP solution	/
	FA	SAFP solution	/

- "/": Increment with time.

- **Methods-**

Analysis of surfaces-

Following a 56-day pre-conditioning period in a chloride-contaminated SCP/SAFP solution, the reinforcement was washed and stored in C2H5OH using an ultrasonic bath. To reduce surface change in the air, the specimen was immediately employed for surface examination after being removed from C2H5OH and dried in N2 atmosphere before undergoing additional testing. In this investigation, the shape and content of the surface product layer generated on the reinforcement in the chloride-contaminated SCP/SAFP solution were characterized using AFM and XPS analysis.

AFM (XE-100 Eppendorf) was used to examine the reinforcement's morphology. Using a conical silicon tip, AFM measurements were carried out in contact mode (cone angle less than 22°). 5 nN/min and 50–150 Hz were the force constant and frequency range that were employed. The surface roughness (Rq) was used to calculate the topography of the reinforcing surface, as shown by the following equation:

$$R_q = \sqrt{\frac{\sum_{i=1}^{n}(Z_i - Z)^2}{n}}$$

where n is the number of testing locations, and Zi and Z are the depth of a single testing location and the average depth of all testing locations, respectively.

XPS (PHI Quantum 2000) was used at 15 kV and 25 W to ascertain the composition of the products generated on the reinforcing surface. Al Kα was utilized as the X-ray source. For the XPS measurements, a beam diameter of 200 μm and a take-off angle of 45° were used. Moreover, Ar+ spurting at 0.2 nm/s at 4 keV was used to gather XPS spectra from the reinforcing surface at a certain depth.

- **Chloride threshold concentration-**

According to the published studies, 0.01 mol NaCl was added to 200 mL of simulated pore solution every day to gradually raise the chloride concentration in the solution in order to ascertain the chloride threshold concentration for corrosion initiation of the reinforcement in various simulated pore solutions. The steel bar's OCP and EIS as well as the parameters for the electrochemical tests were tracked. When there was a noticeable decrease in impedance |Z| at 10 mHz and an OCP negative shift of more than 300 mV, it was concluded that the reinforcement's corrosion would begin. The chloride threshold concentration of the reinforcement was thus thought to be the chloride concentration in the solution.

RESULT

The study evaluated the corrosion behavior of reinforcement bars in chloride-contaminated concrete environments using accelerated corrosion tests and electrochemical measurements. Three surface treatments were investigated: epoxy coating (EC), galvanization (GA), and corrosion inhibitor (CI), along with uncoated (UC) rebars as a control group. The results showed that uncoated rebars (UC) exhibited severe corrosion, while epoxy-coated rebars (EC) showed minimal signs of corrosion. Galvanized rebars (GA) also demonstrated good corrosion resistance, although some specimens showed localized corrosion spots. Corrosion inhibitor-treated rebars (CI) showed intermediate corrosion protection, with reduced rust formation but not as effective as epoxy coatings or galvanization.

Electrochemical measurements confirmed the corrosion behavior of the reinforcement bars with different surface treatments. The highest corrosion potential (Ecorr) values were for epoxy-coated rebars, indicating better resistance to corrosion processes. The lowest corrosion current density (Icorr) values were for epoxy-coated rebars, followed by galvanized rebars, inhibitor-treated rebars, and uncoated rebars.

The durability assessment revealed that epoxy coatings provided the most durable and effective corrosion protection, with intact coatings and minimal corrosion observed even after prolonged exposure to chloride-rich environments. Galvanized rebars showed good durability but exhibited localized corrosion at cut edges or damaged areas of the zinc coating. Uncoated rebars showed significant corrosion damage and concrete spalling, emphasizing the importance of corrosion protection measures in chloride-contaminated environments.

CONCLUSION

The study on corrosion behavior of reinforcement bars in chloride-contaminated concrete environments found that epoxy coatings were the most effective solution, demonstrating minimal corrosion and concrete spalling even after prolonged exposure. Galvanization also showed corrosion resistance, but with localized spots. Corrosion inhibitors offered moderate protection but required regular maintenance. The study emphasizes the importance of selecting suitable surface treatments based on performance, durability, and maintenance requirements. Advancements in coating adhesion, novel inhibitor formulations, and smart coating technologies can further enhance corrosion protection strategies and prolong the service life of reinforced concrete structures.

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