J. Chem. Eng. Energy Mater., **(2026),** Volume 2, Issue 3, 220-233

Journal of Chemical Engineering and Energy Materials (JCEEM)

Journal homepage: https://www.jceem.com/

DOI: https://doi.org/10.5281/zenodo.21792561

Corrosion of Reinforced Concrete Structures: Causes, Monitoring, and Durability Enhancement Strategies

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Article info

Article info

Received: 02.06.2026
Accepted: 27.07.2026
Available Online: 04.08.2026
Checked for Plagiarism: Yes

Keywords:
Reinforced concrete corrosion, chloride-induced corrosion, electrochemical monitoring, corrosion inhibitors, cathodic protection

A B S T R A C T

Corrosion of steel reinforcement in concrete structures is one of the most critical durability challenges facing global infrastructure, with annual economic losses estimated at approximately US$2.5 trillion, accounting for 3.4% of global GDP. This comprehensive review systematically examines the causes, monitoring technologies, and durability enhancement strategies for reinforcement corrosion in concrete structures. The electrochemical mechanism of corrosion involves anodic dissolution of iron ($Fe \rightarrow Fe^{2+} + 2e^-$) coupled with cathodic oxygen reduction ($O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$), with rust formation and its 2-6× volumetric expansion relative to steel inducing tensile stresses exceeding concrete's tensile strength. Two primary depassivation mechanisms govern corrosion initiation: chloride-induced pitting corrosion, where chloride ions disrupt the passive γ-Fe_2O_3 layer, and carbonation-driven pH reduction compromising protective film stability. Monitoring technologies have evolved from conventional half-cell potential and linear polarization resistance methods to advanced techniques including electrochemical impedance spectroscopy (EIS), distributed fiber optic sensing, and AI-driven predictive models achieving >98% detection accuracy. Mitigation strategies encompass electrochemical methods (cathodic protection, chloride extraction, realkalization), corrosion inhibitors with demonstrated ~45% weight loss reduction, and emerging polymer-modified concretes reducing chloride penetration by 30-50% while extending service life by 2-3 times. The review concludes that effective corrosion management requires integrated approaches combining mechanistic understanding, advanced monitoring, and sustainable material solutions.

Introduction

Reinforced concrete (RC) is the most extensively utilized structural material globally, renowned for its durability properties, strength, and economic viability. The synergy between steel reinforcement and concrete is fundamental to this success: steel compensates for concrete's low tensile strength, while the highly alkaline pore solution of concrete (pH≈13) promotes the formation of a passive protective γ-Fe_2O_3 film on the steel surface, isolating it from aggressive environmental agents [1].

This passive layer constitutes the primary mechanism for steel protection, enabling RC structures to perform effectively throughout their intended service life [2]. Despite these inherent protective qualities, reinforcement corrosion remains one of the most severe durability threats to concrete infrastructure. Corrosion leads to a cascade of detrimental effects: progressive loss of steel

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cross-section and ductility, expansive corrosion products inducing tensile stresses and cover cracking, steel-concrete bond deterioration, and eventual structural failure [3-10]. The socioeconomic impact is staggering annual global corrosion costs exceed US$2.5 trillion, with reinforcement corrosion accounting for over 40% of concrete-related economic losses. In China alone, corrosion-induced damage to roads and bridges represents 4.03% of total industry investment, equating to 62.37 billion yuan. The corrosion process is fundamentally electrochemical in nature, requiring four essential components: anode, cathode, metallic conductor [11-19], and electrolyte. The concrete pore solution serves as electrolyte, while the steel reinforcement provides the metallic path. Anodic dissolution of iron ($Fe \rightarrow Fe^{2+} + 2e^-$) is balanced by cathodic oxygen reduction ($O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$). The passive oxide film fails through two primary mechanisms: chloride-induced depassivation where chloride ions penetrate the concrete cover and locally disrupt the protective film or carbonation, where atmospheric CO_2 reduces concrete alkalinity, destabilizing the passive layer.

The expanding portfolio of monitoring, protection, and repair technologies reflects the scale of this challenge [20-29]. This comprehensive review provides an integrated examination of mechanisms, monitoring, and mitigation strategies for reinforcement corrosion in concrete structures.

Literature Review

Corrosion Mechanisms in Reinforced Concrete:

- ✓ **Fundamental Electrochemistry**: Corrosion is fundamentally an electrochemical process where steel oxidizes at anodic regions while oxygen reduced at cathodic sites. The primary anodic reaction is iron dissolution: $Fe \rightarrow Fe^{2+} + 2e^-$. This balanced by cathodic reactions—typically oxygen reduction in neutral/alkaline environments: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$. In highly oxidizing conditions, ferrous ions further oxidized $Fe^{2+} \rightarrow Fe^{3+} + e^-$. The overall corrosion reaction yields iron hydroxides that subsequently oxidize to the rust products ($Fe_2O_3 \cdot H_2O$) responsible for expansive damage.
- ✓ **Passive Film Formation and Stability**: Under normal conditions, concrete's high alkalinity (pH 12.6-13.5) promotes formation of a continuous passive γ-Fe_2O_3 film on the steel surface [30-38]. This reaction proceeds through intermediate $Fe(OH)^+$ adsorption: $Fe + OH^- \rightarrow [Fe(OH)]_{ads} + e^- + H^+$, followed by oxidation to ferric oxide: $Fe(OH)^+ + H_2O \rightarrow Fe_2O_3 + 2e^- + 4H^+$.
- ✓ **Chloride-Induced Corrosion**: Chloride ions are the primary cause of reinforcement corrosion, particularly in marine environments and regions employing de-icing salts. The critical chloride threshold approximately 0.15% by cement mass under ACI 318 triggers local passive film breakdown. While chloride ions serve as catalysts rather than reactants in the corrosion process, they facilitate formation of soluble iron-chloride complexes that migrate from the anodic site, preventing passivation and sustaining localized pitting corrosion.
- ✓ **Carbonation-Driven Corrosion**: Atmospheric CO_2 penetrates concrete and reacts with calcium hydroxide, forming calcium carbonate ($CaCO_3$), reducing pH to below 11 [39-46]. This pH reduction destabilizes the passive film, rendering steel susceptible to uniform corrosion when moisture and oxygen are present.
- ✓ **Tuutti's Two-Stage Service Life Model**: Reinforcement corrosion proceeds through two distinct phases: an initiation stage where aggressive agents reach the steel surface and progressively deteriorate the passive layer, followed by a propagation stage where active corrosion spreads and produces structural damage [47].

Detection and Monitoring Technologies

- ✓ **Half-Cell Potential (HCP) Method**: This non-destructive technique measures potential differences between embedded reinforcement and an external reference electrode [48-55]. While enabling rapid identification of high-corrosion zones at low cost, HCP provides probabilistic corrosion assessment rather than quantitative rates, with readings affected by temperature, moisture, and chloride content. The ASTM C876 standard indicates potentials more negative than -350 mV $Cu/CuSO_4$ correspond to >90% corrosion probability.
- ✓ **Linear Polarization Resistance (LPR)**: The LPR method evaluates corrosion rates by measuring polarization resistance ($R_p = \Delta E / \Delta I$) during small potential perturbations. Corrosion current density derived via the Stern-Geary relationship: $i_{corr} = B/R_p$, where B ranges from 25-52 mV. As the only technique providing instantaneous corrosion

rates, LPR is valuable for real-time monitoring, though limited by concrete resistance effects and unknown polarization areas.

- ✓ **Electrochemical Impedance Spectroscopy (EIS)**: EIS applies small AC perturbations over a broad frequency range, measuring impedance magnitude and phase angle. The low-frequency region primarily reflects steel corrosion state, while high frequencies probe dielectric concrete properties [56-66]. Beyond Rp determination, EIS reveals electrochemical reaction dynamics, enabling identification of corrosion initiation and propagation stages.
- ✓ **Emerging Monitoring Technologies**: Advanced physical monitoring techniques include distributed fiber optic sensing for continuous strain/temperature measurement, piezoelectric-based sensing with probabilistic imaging, and wireless eddy-current sensors using LC resonators for non-destructive corrosion assessment. Three-dimensional visualization using micro-X-ray computed tomography (X-CT) provides detailed rust distribution characterization within cementitious matrices.
- ✓ **AI-Driven Predictive Modeling**: Machine learning applications have demonstrated exceptional capability for corrosion prediction, achieving >98% detection accuracy and enabling quantitative characterization of the entire corrosion process through damage factor correlation.

Mitigation Strategies

- ✓ **Electrochemical Methods**: Four principal electrochemical techniques provide active corrosion prevention: cathodic protection (impressed current or sacrificial anodes), cathodic prevention for chloride-exposed structures, electrochemical chloride extraction (removing chlorides by ion migration), and electrochemical realkalization for carbonated concrete. Impressed current cathodic protection where external anodes deliver DC current to steel reinforcement has proven particularly effective, achieving re-passivation through OH^- generation and chloride migration. The hybrid system combining impressed current and galvanic operation offers sustained passive protection with reduced energy requirements.
- ✓ **Corrosion Inhibitors**: Organic inhibitors such as hexamethylenetetramine demonstrate substantial effectiveness, reducing steel weight loss by approximately 45% at 0.5% addition [67-80]. Dual-action inhibition combines direct electrochemical protection through adsorption and protective film formation with indirect benefits through pore refinement reducing transport properties and chloride penetration.
- ✓ **Advanced Coating Technologies**: Polymer-modified concretes incorporating hydrophobic agents (silanes, siloxanes, fluoropolymers) achieve 30-50% reductions in chloride penetration, extending service life by 2-3 times through self-healing coating mechanisms [81-92]. Natural polymer inhibitors, including gum Arabic, tannins, and alginates, offer environmentally sustainable alternatives with comparable performance.

Methodology

This comprehensive review was developed through systematic analysis of peer-reviewed literature indexed in major scientific databases including Scopus, Web of Science, ScienceDirect, and Google Scholar. Search strategies employed combinations of keywords including "reinforced concrete corrosion," "chloride-induced corrosion," "carbonation," "corrosion monitoring," "electrochemical impedance spectroscopy," "cathodic protection," "corrosion inhibitors," and related terms. Priority placed on studies from 2019-2026, with seminal earlier works included were mechanistically significant [93-110]. The screening process selected peer-reviewed research articles, review papers, and industry reports based on methodological rigor, mechanistic significance, and industrial applicability. Quantitative data synthesis focused on corrosion rates, inhibitor efficiencies, monitoring accuracy, and service life prediction metrics. Electrochemical principles drawn from established frameworks including Butler-Volmer kinetics, Stern-Geary relationships, and Tuutti's service life model. Environmental and industrial contexts examined through application case studies across marine, highway, and industrial sectors, with particular emphasis on chloride and carbonation exposures [111].

Results

Table 1. Reinforcement Corrosion Mechanisms and Key Characteristics

Mechanism	Primary Cause	Chemical Process	Corrosion Type	Threshold/Indicator	Key Damage Mode
Chloride-Induced Corrosion	Cl^- penetration; de-icing salts; marine environment	Pitting: Cl^- disrupts passive γ-Fe_2O_3 film; $FeCl_2$ complex formation	Localized pitting; limited anodic area	Critical threshold: 0.06-0.15% Cl^- by cement mass	Localized cross-section loss; pitting reduces ductility; brittle failure mode transition
Carbonation-Induced Corrosion	Atmospheric CO_2 penetration; pH reduction	$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$; pH < 11 destabilizes passive layer	General/uniform corrosion	CO_2 penetration depth; carbonation front; alkalinity reduction	Uniform cross-section loss; bond degradation; cover cracking
Oxygen Concentration Cell	Differential aeration (e.g., waterline corrosion)	O_2 gradient creates anodic (oxygen-poor) and cathodic (oxygen-rich) regions	Localized corrosion	O_2 concentration gradient; moisture content variation	Localized attack; macro-cell corrosion; potential differences

Table 2. Electrochemical Monitoring Technologies and Performance Characteristics

Monitoring Technology	Measurement Principle	Key Parameters	Advantages	Limitations	Development Status
Half-Cell Potential (HCP)	Potential difference between steel and reference electrode	Corrosion potential (Ecorr); 90% corrosion probability at E < -350 mV $Cu/CuSO_4$	Low cost; simple equipment; rapid corrosion zone identification	Probabilistic only; environmental sensitivity; no quantitative rate	Mature/Commercial
Linear Polarization Resistance (LPR)	$Rp = \Delta E/\Delta I$; $icorr = B/Rp$ (B=25-52 mV)	Polarization resistance (Rp); corrosion current density (icorr)	Only instantaneous corrosion rate method; rapid response	Concrete resistance effects; unknown polarization area; non-uniform corrosion	Mature/Commercial
Electrochemical Impedance Spectroscopy (EIS)	Frequency-domain AC response; equivalent circuit fitting	Charge transfer resistance (Rct); double-layer capacitance (Cdl); concrete resistance	Reveals reaction dynamics; identifies initiation/propagation; polarization resistance + mechanism	Complex interpretation; equipment cost; data fitting ambiguity	Commercial/Advanced
Distributed Fiber Optic Sensing	Strain/temperature measurement along fiber length	Continuous strain; crack detection; early warning	>100 km continuous coverage; >98% detection accuracy for damage	Installation complexity; data management; specialization required	Emerging Commercial
AI-Driven Prediction (ML, CNN)	Pattern recognition;	Corrosion rate; crack detection; quantitative	>98% detection accuracy; integrated multi-	Data quality dependency; standardizatio	Emerging

	multi-feature analysis	damage characterization	source data; predictive maintenance	n needed; validation requirements	

Table 3. Corrosion Mitigation Strategies and Performance

Mitigation Strategy	Mechanism of Action	Efficiency/Performance	Application Context	Key Advantages	Primary Limitations	Development Status
Impressed Current Cathodic Protection	DC current applied from external anode; OH^- generation; chloride migration	Re-passivation of steel; extended service life	Chloride-contaminated RC structures; marine; highway	Effective for large structures; sustained protection; proven technology	Requires continuous power; anode maintenance; incipient anode risk	Mature/Commercial
Sacrificial Anode System	Galvanic protection; active anode material (Zn, Al, Mg) dissolves preferentially	Continuous protection without external power	Buried pipelines; tidal/splash zones; localized repair	Simple installation; maintenance-free; no power required	Limited anode capacity; finite life; effectiveness depends on resistivity	Mature/Commercial
Electrochemical Chloride Extraction	Electric field drives Cl^- migration away from rebar	50-80% chloride removal efficiency; simultaneous realkalization	Chloride-contaminated structures without extensive cracking	Non-destructive; eliminates aggressive ions; reestablishes passive film	Requires temporary setup; treatment time; possible alkali-aggregate effects	Commercial
Electrochemical Realkalization	Alkali ions migrate into concrete; pH restoration	pH restored to > 12; re-passivation achieved	Carbonated concrete structures; historic buildings	Restores passive film; non-destructive; rapid treatment (days)	Limited to carbonation; chloride contamination not addressed	Commercial
Corrosion Inhibitors (Organic: HMTA)	Adsorption; protective film formation; pore structure refinement	~45% steel weight loss reduction at 0.5% addition; 6.7% porosity reduction; 20% chloride diffusion reduction	Admixture addition; surface application for rehabilitation	Practical; cost-effective; dual-action (direct + indirect); compatibility	Inconsistency in performance data; long-term durability questions	Research/Commercial
Polymer-Modified Concrete	Hydrophobic barrier; pore refinement; passive film stabilization	30-50% reduction in Cl^- penetration; 2-3× service life extension	New construction; surface coating for rehabilitation	Multifunctional; self-healing potential; diverse material options	Standardization gaps; long-term validation needed; cost considerations	Emerging Commercial/Research

Table 4. Service Life Prediction Models and Approaches

Model Type	Methodology	Key Inputs	Outputs/Predictions	Strengths	Limitations	References
Fick's Law Diffusion Models	Analytical solution to 1D diffusion equation; Fick's 2nd law	Dapp (chloride diffusion coefficient); C_s (surface Cl^-); cover depth; critical threshold	Time to corrosion initiation (ti)	Established; simple; well-validated; widely adopted	Assumes homogeneous material; ignores binding; temperature	

					variations not fully captured	
Tuutti Two-Stage Life Model	Initiation period (transport) + Propagation period (corrosion damage)	Depassivation time; corrosion rate; acceptable damage limit	Total service life; remaining life estimation	Conceptually clear; practical; widely accepted	Simplifies complex processes; corrosion rate not constant; environmental variability	
AI-Based Service Life Prediction	Machine learning (Extra Trees, Hybrid models); multi-feature analysis	Environmental data (T, P); material properties; inspection data	Remaining service life; failure timing; probabilistic reliability assessment	Captures nonlinear relationships; integrates multi-source data; R^2 = 90.35%	Data quality dependency; physical interpretability; standardization needs	
Probabilistic/Reliability Models	Monte Carlo Simulation; probability of exceedance	Uncertainty distributions of inputs; statistical variability	Time-dependent reliability; failure probability	Accounts for uncertainty; risk-based decisions; design optimization	Data intensive; complex; computational cost	

Discussion

Mechanistic Understanding of Reinforced Concrete Corrosion

The electrochemical framework governing reinforcement corrosion provides robust foundations for prediction and prevention, yet significant complexity emerges from environmental and material interactions [112-122]. Thermodynamic stability through passive film formation under high alkalinity is the central protective mechanism, but kinetic factors particularly chloride ingress rates and carbonation fronts determine structural durability. The critical ratio Cl^-/OH^- for depassivation highlights the nonlinear nature of the corrosion process, where small changes in ionic activity can trigger substantial degradation.

Tuutti's two-stage model remains the guiding framework for service life prediction, yet its simplicity masks important nuances. Recent studies demonstrate that corrosion rates are not constant during propagation, varying with moisture content, oxygen availability, and temperature. Moreover, the coupling of fatigue loading with corrosion creates synergistic damage mechanisms that accelerate degradation. The behavior of corroded RC beams reveals that pitting corrosion can reduce ductility significantly, causing transition from ductile to brittle failure modes. This transformation has profound implications for structural safety.

Monitoring Technologies: Capabilities and Limitations

The evolution from conventional to advanced monitoring technologies reflects increasing recognition that accurate assessment requires complementary approaches. HCP and LPR remain valuable for routine inspection, providing rapid identification of corrosion-prone zones. However, their limitations HCP's probabilistic nature and LPR's sensitivity to concrete resistance and unknown polarization area necessitate integration with more sophisticated techniques.

EIS provides the mechanistic insights that simpler methods lack, revealing reaction dynamics, charge transfer resistance, and polarization behavior across frequency domains. The ability to distinguish passive, initiation, and propagation states through characteristic impedance spectra makes EIS particularly valuable for research and critical infrastructure monitoring. The development of three-dimensional visualization using X-ray μCT has enabled unprecedented understanding of rust distribution within cementitious matrices, linking microstructural damage to electrochemical indicators. Emerging technologies particularly distributed fiber optic sensing and AI-driven prediction offer transformative potential. Continuous monitoring over distances exceeding 100 km with >98% detection accuracy enables transition from periodic inspection to continuous condition assessment. However, challenges persist in data standardization, model validation, and field deployment of these technologies.

Mitigation Strategies: Performance and Sustainability:

Electrochemical protection methods represent the most robust active protection strategies. Impressed current cathodic protection has proven effective for large structures, with the DC current generating OH^- and migrating chlorides away from the steel surface. Hybrid systems combining impressed current and galvanic operation optimize energy efficiency while maintaining sustained protection. Electrochemical chloride extraction and realkalization provide non-destructive treatment options for contaminated and carbonated structures, respectively, but require temporary installation and are not suitable for heavily cracked structures. Corrosion inhibitors offer practical, cost-effective solutions, particularly for rehabilitation applications. Organic inhibitors like hexamethylenetetramine demonstrate dual-action protection: direct electrochemical inhibition through adsorption and protective film formation, coupled with indirect durability enhancement through pore structure refinement. The observed 6.7% reduction in water-accessible porosity and 20% decrease in chloride diffusion coefficient contribute to extended service life beyond electrochemical protection. Polymer-modified concretes represent the frontier of sustainable protection, with hydrophobic modifications reducing chloride penetration by 30-50% while extending service life by 2-3 times. The emergence of self-healing coatings and molecular dynamics simulations for nanoscale understanding signals continued innovation, yet standardization gaps and long-term performance validation remain critical challenges.

Environmental and Sustainability Considerations:

The environmental footprint of reinforced concrete corrosion extends beyond economic costs. Steel replacement for corroded structures constitutes a significant contributor to global CO_2 emissions, paralleling trends in general infrastructure corrosion. Additionally, expansive corrosion products approximately 2-6 times the volume of parent steel create cracking that accelerates moisture ingress, further degrading structural performance and necessitating resource-intensive repairs. The shift toward sustainable mitigation strategies including natural polymer inhibitors, bio-based materials, and polymer-modified concretes reflects broader environmental priorities. Lifecycle assessment approaches are essential for evaluating both immediate durability benefits and long-term environmental impacts across the full-service life.

Service Life Prediction and Decision Support:

Predictive modeling bridges mechanistic understanding with engineering decision-making. Fick's law diffusion models provide computationally efficient assessment of chloride penetration and corrosion initiation times, though they assume homogeneous properties and neglect chloride binding. Probabilistic approaches incorporating variability in material properties, environmental exposure, and modeling parameters enable risk-based decision-making.

AI-based service life prediction represents a transformative advance, with hybrid models achieving R^2 values approaching 0.99 for corrosion rate forecasting. Integration of environmental data temperature, precipitation has significantly enhanced predictive accuracy for pipeline service life, revealing that weather conditions critically influence failure timing. However, model interpretability and data quality remain key challenges, addressed through SHAP analysis and physics-informed architectures.

Conclusion

This comprehensive review has systematically examined corrosion of reinforced concrete structures, spanning mechanistic understanding, monitoring technologies, and durability enhancement strategies. Reinforcement corrosion represents one of the most critical durability challenges facing global infrastructure, with annual economic losses exceeding US$2.5 trillion and reinforcement corrosion accounting for over 40% of concrete-related costs. The electrochemical mechanism of corrosion anodic dissolution of iron coupled with cathodic oxygen reduction is fundamentally understood. The passive γ-Fe_2O_3 layer provides protection under high alkalinity, while chloride-induced pitting and carbonation-driven pH reduction constitute the primary depassivation mechanisms. The 2-6× volumetric expansion of corrosion products relative to steel induces tensile stresses exceeding concrete's tensile strength, causing cover cracking, bond degradation, and eventual structural failure. Monitoring technologies have evolved substantially from conventional HCP and LPR methods to advanced techniques including EIS, distributed fiber optic sensing, and AI-driven predictive models achieving >98% detection accuracy. The integration of multiple complementary techniques enables comprehensive assessment, from instantaneous corrosion rates to cumulative damage characterization. Mitigation strategies encompass electrochemical methods (cathodic protection, chloride extraction, realkalization), corrosion inhibitors demonstrating ~45% weight loss reduction, and polymer-modified concretes reducing chloride penetration by 30-50% while extending service life by 2-3 times. The hybrid approach combining impressed current and galvanic operation optimizes energy efficiency and protection durability. Future progress depends on standardized testing protocols, mechanistic understanding under realistic multi-factor conditions (chloride-sulfate combined exposure, fatigue-corrosion coupling), integration of AI and physics-based models for service life prediction, and development of sustainable, environmentally compatible materials. With continued innovation across materials science, electrochemistry, structural engineering, and data science, substantial reductions in reinforced concrete corrosion costs and environmental impacts are achievable.

Disclosure Statement

No potential conflict of interest reported by the authors.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Authors' Contributions

All authors contributed to data analysis, drafting, and revising of the paper and agreed to be responsible for all the aspects of this work.

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