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Surface Protection Systems for Reinforced Concrete in Marine Environments: A 2019–2025 Scoping Review on Chloride Ingress Mitigation and Corrosion Resistance

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***Abstract*— Chloride-induced reinforcement corrosion is a dominant degradation mechanism in reinforced concrete structures located in coastal and marine regions, leading to cracking, spalling, performance deterioration, and reduced service life. Various surface protection systems including coatings, surface modification, and material-based approaches to enhance ion-transport resistance have been developed as barriers to reduce chloride ingress and delay corrosion initiation. This study presents a scoping review of the 2019–2025 literature to map research directions, commonly used evaluation indicators, and evidence gaps in assessing the performance of surface protection for reinforced concrete in marine environments. The synthesis is organized thematically according to: (i) types of protection systems (alternative-binder-based coatings, hybrid coatings, and supporting durability approaches), (ii) evaluation indicators (pull-off adhesion, water absorption/sorptivity, chloride migration/diffusion parameters, electrochemical corrosion indicators, and microstructural characterization), and (iii) exposure protocols (immersion, wet–dry cycles, NaCl/seawater, and other aggressive environments). The literature indicates growing attention to more sustainable surface protection strategies, particularly those based on alternative binders and surface modification to improve stability and mitigate phenomena such as efflorescence. However, inconsistent testing protocols, limited long-term/field validation, and the still-weak linkage between microstructural evidence and chloride transport parameters as well as electrochemical corrosion responses remain major challenges. The proposed research agenda includes standardizing a "minimum evidence set," strengthening interface and microcrack evaluation, and integrating microstructure transport corrosion indicators to support more reliable recommendations for coastal infrastructure.**

Keywords— ***coastal reinforced concrete; surface protection; chloride; reinforcement corrosion; coating; scoping review.***

I. INTRODUCTION

Reinforced concrete structures in coastal and marine regions are exposed to high levels of chloride ions. Chlorides can penetrate through the pore network and cracks, accumulate around reinforcing steel, and destabilize the passive film, thereby initiating and accelerating corrosion. The corrosion products formed have a larger volume than the original steel, generating internal stresses within the concrete cover. These conditions promote cracking, delamination, and spalling, which ultimately reduce structural performance and shorten service life.

Improving concrete quality alone is often insufficient to withstand persistent chloride exposure, particularly in tidal and splash zones that undergo repeated wet–dry cycles. Surface protection systems therefore represent an important strategy because they act at the primary ingress pathway through the concrete surface by reducing the transport rate of water and aggressive ions and delaying corrosion initiation. Recent research shows growing attention to coating systems and surface modification, including the use of alternative binders that are considered more sustainable than conventional binders [1], [2]. Critical reviews also indicate that assessments of chloride resistance and corrosion performance remain highly sensitive to variations in test protocols and the selection of evaluation indicators, making cross-study comparisons difficult [3].

This scoping review aims to: (1) map trends in the types of surface protection systems investigated during 2019–2025, (2) identify the evaluation indicators most commonly used to assess chloride ingress mitigation and corrosion response, and (3) formulate evidence gaps and a research agenda needed to improve comparability and practical relevance for coastal infrastructure.

II. METHOD

A scoping review approach was employed to map the development of research on surface protection systems for reinforced concrete (RC) in coastal and marine environments over the period 2019–2025. The literature search was conducted in the ScienceDirect database in October 2025 using keyword combinations representing three core components: (1) the subject matter—reinforced concrete, marine, and coastal; (2) the issue of interest—chloride ingress and corrosion; and (3) the intervention—surface protection system, coating, surface treatment, overlay, and surface modification. The screening and full-text eligibility assessment were completed in November 2025.

Only peer-reviewed journal articles published between 2019 and 2025 were considered. Studies were included when they addressed surface protection performance for RC under marine/coastal exposure and reported at least one relevant durability indicator (e.g., pull-off adhesion for coatings, water absorption/sorptivity, chloride transport metrics such as migration/diffusion or chloride profiling, electrochemical corrosion indicators, and/or supporting microstructural characterization). Studies were excluded when the exposure setting was not marine/coastal or when the study design was not aligned with the review objective.

The search identified 438 records; 36 duplicates were removed, leaving 402 records for title/abstract screening. After screening, 104 full-text articles were assessed for eligibility; 47 were excluded with reasons, resulting in 57 studies included for thematic synthesis. The study selection process is summarized in the text due to space constraints. Evidence was synthesized along three axes: type of protection system, evaluation indicators, and exposure protocols.

III. RESULTS AND DISCUSSION

3.1. Research directions on surface protection systems (2019 2025)

The reviewed literature indicates a shift from viewing surface protection as a simple “covering layer” toward treating it as an integrated durability system governed by interfacial integrity, transport resistance, and corrosion-related response. Considerable attention has been directed to alternative-binder-based coatings and surface modifications intended to improve barrier performance while addressing practical issues such as dimensional stability and surface defects. For instance, coating studies increasingly discuss shrinkage control and microstructural refinement as key determinants of long-term integrity [4]. Surface modification strategies have also been developed to mitigate efflorescence, a recurring durability and aesthetic concern associated with alkali migration and moisture transport to the surface [5].

Parallel to coating development, durability studies on alternative binder systems provide essential baseline knowledge for chloride transport and corrosion susceptibility under marine exposure. Investigations using chloride transport indicators and corrosion-related measurements demonstrate that mixture design and matrix densification strongly influence resistance to chloride ingress [6], [7]. Marine exposure conditions have also been explored in relation to reinforcement performance and composite systems, highlighting the importance of system-level compatibility between protective layers, substrate concrete, and reinforcement materials in seawater environments [8]. Research on hybridization, including polymer-modified alternative binder composites, suggests performance gains in marine durability, while simultaneously raising questions regarding permeability evolution, interfacial compatibility, and long-term stability under cyclic exposure [9].

Review articles further consolidate these developments by discussing potential coating applications of geopolymer/alkali-activated systems and contrasting their durability behavior against conventional Portland cement systems in aggressive environments [1], [2]. Critical reviews emphasize that conclusions across studies remain strongly dependent on test selection and exposure design [3], underscoring the need for harmonized evaluation frameworks.

3.2. Evaluation indicators: from barrier performance to corrosion response

The indicators adopted across studies can be grouped into several core categories that collectively define the performance of surface protection systems in marine RC applications.

(a) Coating–substrate adhesion and interfacial integrity.

Pull-off adhesion is frequently treated as a prerequisite for coating effectiveness, since interfacial debonding or delamination can negate barrier performance even when the coating matrix itself exhibits low porosity. Coating studies commonly combine adhesion testing with material characterization to support anticorrosion claims [10], [11].

(b) Water transport and chloride transport metrics.

Water absorption and sorptivity serve as practical proxies for near-surface transport, particularly relevant under wet–dry marine cycles. Chloride transport indicators—such as migration/diffusion parameters or chloride profiling—provide the most direct evidence for ingress mitigation and are central to service-life reasoning under chloride exposure. Studies integrating chloride migration testing with corrosion-related indicators offer a stronger basis for durability interpretation in marine conditions [6], [8].

(c) Electrochemical corrosion indicators.

Corrosion potential and polarization resistance are widely recognized as essential for linking transport reduction to corrosion initiation delay and corrosion rate development.

Critical reviews stress that electrochemical data require careful interpretation alongside moisture state, concrete resistivity, and chloride content at the steel level to avoid overgeneralization [3]. Experimental work also illustrates the use of electrochemical indicators to compare curing conditions and corrosion behavior in alternative binder concretes [12].

(d) Microstructural and physicochemical characterization.

SEM/EDS, XRD, and FTIR are commonly employed to explain densification, phase assemblage, and pore refinement mechanisms that may underpin improved transport resistance. Mechanistic interpretation becomes more robust when microstructural evidence is explicitly linked to quantified chloride transport and corrosion indicators, rather than being presented as a standalone explanation [1], [7].

Across these categories, the strongest evidence base emerges when adhesion (for coatings), transport metrics (water and chloride), electrochemical corrosion indicators, and microstructural characterization are used in a complementary manner. Single-indicator evaluations tend to be insufficient for distinguishing true barrier effects from short-term conditioning artifacts.

3.3. Exposure protocols and comparability challenges

Marine durability studies employ a wide range of exposure conditions, including NaCl or synthetic seawater immersion, wet–dry cycling, and combined aggressive environments (e.g., sulfate, acidic media, freeze thaw, and elevated temperature). This diversity reflects the complexity of field exposure, yet it also complicates cross-study comparisons. Differences in chloride concentration, cycling regime, temperature, curing history, and conditioning procedures can lead to markedly different transport behavior and corrosion response, even for similar materials.

Studies focusing on aggressive environments indicate that combined actions can significantly alter microstructure and transport pathways, reinforcing the importance of defining exposure histories clearly and selecting protocols aligned with targeted service conditions [13], [14], [15], [16]. Consistency in reporting is also critical, particularly for exposure duration, wet–dry ratio, solution renewal, specimen preconditioning (saturation or drying), and the location/depth at which chloride is assessed relative to the steel depth.

For improved comparability and practical relevance, evaluation of surface protection systems for marine RC can be anchored on a “minimum evidence set” comprising: (1) pull-off adhesion (for coatings), (2) water absorption/sorptivity, (3) chloride transport assessment (migration/diffusion or chloride profiling), (4) electrochemical corrosion indicators (at minimum corrosion potential and, where feasible, polarization resistance), and (5) microstructural characterization to support mechanistic interpretation. Critical synthesis suggests that such a framework would strengthen the reliability of performance ranking across different protection systems and exposure designs [3].

3.4. Evidence gaps

Several recurring gaps emerge from the reviewed literature and define priorities for future work in marine RC surface protection:

1. Lack of harmonized testing and reporting. Protocol variability remains a major barrier to comparability. Alignment on core indicators, conditioning procedures, and exposure parameters is needed for reproducible benchmarking.
2. Limited long-term and field validation. Many studies remain laboratory-based and short-term. Field exposure programs in tidal and splash zones, coupled with periodic electrochemical monitoring and chloride profiling, would improve transferability to practice.
3. Insufficient focus on interfacial behavior and microcracking.
   Coating performance depends strongly on interface quality and crack tolerance. Testing on cracked substrates and assessments of delamination resistance and crack-bridging behavior are necessary for realistic service conditions.
4. Weak integration of microstructure–transport–corrosion relationships.

   Microstructural evidence is frequently reported, yet quantitative linkage to chloride transport parameters and corrosion indicators is not consistently established. Integrated experimental designs that measure all three domains concurrently would strengthen mechanistic conclusions [1], [3].
5. Need for broader benchmarking against conventional systems.

   Alternative-binder-based protection strategies show promise, yet broader comparisons with conventional sealers/coatings under harmonized protocols are required to support decision-making and specification development [2].

Overall, the literature supports continued development of sustainable surface protection solutions, while indicating that methodological harmonization and system-level evaluation (interface–transport–corrosion) represent the most critical steps toward reliable implementation in coastal infrastructure.

3.5. Implications for practice: selection and application considerations

Surface protection performance in marine reinforced concrete depends not only on intrinsic material properties but also on application-related factors that control the continuity and durability of the protective barrier. The reviewed studies collectively imply that coating systems should be selected and designed as part of a system solution, considering the substrate condition, expected exposure regime, and maintenance strategy. In particular, the tidal and splash zones are characterized by repeated wetting-drying cycles, salt accumulation, and fluctuating moisture states that can amplify transport and corrosion processes if the protective layer exhibits defects or debonding [1], [3], [8].

Substrate preparation and interfacial integrity are frequently identified as decisive for long-term performance. Surface contaminants, laitance, and insufficient roughness can reduce coating adhesion and accelerate delamination, even when laboratory-scale material characterization indicates low porosity. For practical implementation, reporting should therefore include the surface preparation method, surface moisture condition at application, coating thickness control, curing regime, and any primer or interlayer used, because these parameters directly affect pull-off adhesion and permeability evolution [2], [10], [11].

Crack-related behavior represents another critical practical consideration. Marine structures commonly experience microcracks from restrained shrinkage, thermal gradients, and service loading, which can localize chloride ingress. Coatings and surface treatments should therefore be evaluated under crack-representative conditions, including crack-bridging capacity and resistance to debonding under cyclic opening. Where rigid coatings are used, compatibility between coating stiffness and substrate deformation should be addressed to minimize crack-assisted transport pathways [3], [6], [7].

Sustainability-oriented formulations, such as alternative-binder-based coatings and hybrid systems, offer potential advantages in reducing embodied carbon while providing adequate barrier performance. However, practical adoption requires a balanced appraisal of durability under marine cycling, constructability, and life-cycle maintenance. Accordingly, durability claims should be supported by transport metrics and corrosion indicators under exposure protocols that reflect targeted service conditions, consistent with the sensitivity issues highlighted in critical reviews [1], [2], [3].

3.6. Proposed evaluation workflow and reporting checklist

To improve comparability and support specification development, an evaluation workflow is proposed that integrates interface integrity, transport resistance, and corrosion response. The workflow emphasizes transparent reporting of application parameters and exposure history, followed by performance indicators that can be mapped to service-life reasoning under chloride exposure [3], [6], [10], [11].

Step 1: Substrate characterization, including concrete cover quality, surface condition, and representative crack state (if present) [3].

Step 2: Application protocol documentation, including surface preparation, moisture condition, coating composition, thickness, curing, and any primers/interlayers [2], [10], [11].

Step 3: Interface integrity assessment using pull-off adhesion and qualitative inspection for defects (voids, pinholes, debonding) [10], [11].

Step 4: Transport assessment using water absorption/sorptivity and chloride transport metrics (migration/diffusion or chloride profiling), reported with conditioning details [6], [7], [8].

Step 5: Corrosion response assessment using electrochemical indicators (at minimum corrosion potential; polarization resistance where feasible) interpreted alongside moisture state and resistivity [3], [6], [12].

Step 6: Durability under representative exposure regimes (immersion and wet-dry cycling, NaCl/seawater, and combined actions where relevant) with time-dependent monitoring [8], [13], [14], [15], [16].

Recommended minimum reporting checklist (minimum evidence set).

- Application and interface quality: surface preparation; substrate moisture at application; coating thickness and curing; pull-off adhesion value and failure mode; defect inspection (pinholes/voids).
- Near-surface transport resistance: water absorption and/or sorptivity with specimen conditioning, testing age, and temperature reported.
- Chloride ingress resistance: chloride transport metric (migration/diffusion) and/or chloride profiling to steel depth; exposure medium, concentration, and duration documented.
- Corrosion response: corrosion potential monitoring; polarization resistance where feasible; measurement configuration and interval reported; interpretation alongside moisture state and resistivity.
- Microstructural support: representative SEM/EDS and, where relevant, XRD/FTIR; microstructural evidence explicitly linked to transport and corrosion outcomes.
- Exposure protocol transparency: immersion or wet-dry cycling details (cycle ratio, temperature, solution renewal); preconditioning history and monitoring time points reported.

3.7. Service-life implications and performance-based specification

In marine reinforced concrete, the practical objective of surface protection is commonly expressed as an extension of the time to corrosion initiation and a reduction in corrosion propagation severity. From a service-life perspective, surface treatments and coatings primarily act by lowering effective chloride transport (e.g., apparent diffusion or migration parameters) and by reducing moisture availability at the near-surface region, thereby delaying depassivation at the reinforcing steel depth [3], [6]. Studies that combine chloride transport testing with corrosion potential measurements provide a useful basis for translating laboratory indicators into service-life reasoning under chloride exposure [3], [6].

Performance-based specification benefits from defining target indicators rather than prescribing a single material type. For example, a project requirement may specify a maximum chloride transport parameter at a defined testing age, together with minimum coating adhesion and a corrosion potential trend limit over a defined exposure period. Such criteria allow multiple protective systems to be compared on a consistent basis while accommodating local constructability constraints

[3]. However, the sensitivity of results to conditioning and exposure history requires that acceptance criteria be tied to clearly defined protocols, consistent with observations in critical reviews [3].

Exposure zoning is also relevant for specifying protection strategies. The splash zone generally demands the highest barrier robustness because cyclic wetting and salt accumulation can accelerate ingress, whereas permanently submerged zones may exhibit different oxygen availability and corrosion kinetics. Consequently, a single protection system may not be optimal for all zones, and zoned specification can improve reliability and cost effectiveness when combined with planned inspection and maintenance intervals [3], [8].

Exposure-zone linkage for evaluation focus.

- Atmospheric/coastal spray: emphasize sorptivity/absorption, near-surface chloride profiling, and adhesion/defect inspection for coatings [6], [10], [11].
- Splash zone: emphasize wet–dry cycling, crack tolerance, delamination resistance, chloride transport metrics, and time-dependent electrochemical monitoring [3], [8], [13].
- Tidal zone: emphasize cyclic immersion with controlled cycle ratio, transport testing under relevant conditioning, and corrosion indicators interpreted with saturation state [3], [8].
- Submerged zone: emphasize long-term immersion stability, permeability evolution, and corrosion indicators interpreted with oxygen availability and resistivity context [3], [8].

3.8. Limitations of the review

This study is structured as a scoping review and is intended to map themes, evaluation indicators, and methodological patterns across the literature rather than to provide a quantitative meta-analysis. As a result, no pooled effect estimates are reported, and performance comparisons are discussed primarily in terms of indicator selection, exposure protocols, and interpretability.

In addition, the reviewed studies exhibit substantial heterogeneity in specimen conditioning, exposure histories, and measurement practices. These differences may introduce variability that is not solely attributable to material performance. Evidence from long-term field exposure remains limited in the open literature, which constrains the direct translation of laboratory findings to specific marine service conditions [1], [3].

3.9. Roadmap for standardization and future studies

The synthesis suggests that future progress will benefit from a stronger level of methodological standardization that enables inter-study and inter-laboratory comparability. Beyond the selection of indicators, standardization should address specimen conditioning, exposure definition, measurement frequency, and transparent reporting of application parameters for coatings and surface treatments. A structured reporting template can reduce ambiguity and improve the interpretability of transport and electrochemical results across different protection systems [1], [2], [3].

A practical roadmap for future studies is proposed as follows:

- Define the exposure zone and target service condition explicitly (atmospheric spray, splash, tidal, or submerged) [3], [8].
- Report substrate concrete parameters relevant to transport (binder system, w/b or liquid-to-binder ratio where applicable, curing history, and cover depth) [1], [7].
- Document coating/surface treatment application parameters (surface preparation, moisture state, thickness, curing, primers/interlayers, and defect control) [2], [10], [11].
- Use a minimum evidence set comprising adhesion (for coatings), water transport, chloride transport, electrochemical indicators, and microstructural support linked to performance outcomes [1], [3], [6].
- Provide conditioning details for each test (saturated/surface-dry, drying temperature, preconditioning duration) to avoid misinterpretation of apparent transport metrics [3].
- Adopt time-dependent monitoring for corrosion indicators under representative exposure regimes, rather than single-time-point measurements [3], [12].
- Include crack-representative evaluation where relevant, including crack-bridging behavior and delamination resistance under cyclic opening [3].
- Complement laboratory exposure with long-term field validation where feasible, supported by periodic chloride profiling and electrochemical monitoring [3], [8].

Implementation of these reporting and testing practices is expected to strengthen the evidence base for performance-based specification and to support more reliable translation from laboratory indicators to service-life decision-making for marine reinforced concrete infrastructure [3], [6].

3.10. Failure modes and durability of protected systems

Beyond intrinsic transport resistance, the durability of surface-protected reinforced concrete is governed by the long-term stability of the protection layer and the persistence of interfacial integrity under marine exposure. Common deterioration pathways include microcracking and shrinkage-induced defects within rigid coatings, interfacial debonding due to moisture gradients and salt crystallization pressures, and progressive permeability increase caused by cyclic wetting and drying [3], [4]. Mechanical actions such as abrasion from sand-laden spray, wave impact, and maintenance activities can further accelerate defect formation, enabling localized chloride ingress despite acceptable average transport indicators measured on intact regions [3].

For polymer-modified and hybrid systems, aging mechanisms may involve changes in pore structure and permeability over time, as well as potential incompatibility between coating stiffness and substrate deformation. In practice, the protection layer should therefore be evaluated not only for initial barrier performance but also for resistance to cyclic exposure, crack-assisted transport, and defect tolerance [3], [9], [11]. Evidence that combines transport metrics with time-dependent electrochemical monitoring is particularly valuable for distinguishing true long-term barrier effects from short-term conditioning artifacts [3], [12].

The reviewed studies also imply that a single transport parameter is insufficient to characterize performance in the presence of cracks or discrete defects. Chloride ingress in marine structures is frequently dominated by preferential pathways, and the effective performance can be controlled by the weakest locations rather than by the bulk average. Accordingly, reporting should include observations of coating continuity, pinhole density (where relevant), and representative testing on cracked or defect-introduced specimens when the intended application involves crack-prone substrates [3], [6], [10], [11].

3.11. Integration with repair and maintenance strategies

Surface protection systems are commonly implemented as part of a broader durability management plan that may include crack sealing, patch repair, re-alkalization, corrosion inhibitors, or cathodic protection depending on the deterioration stage. For new structures, surface protection can be designed as a preventive measure to delay chloride threshold attainment at steel depth. For existing structures, protective systems are often applied after repair to reduce re-contamination and to stabilize the near-surface moisture and chloride transport conditions [3], [8]. In practice, the selection of protection measures and on-site application quality control should be aligned with established requirements for surface protection systems and workmanship control [17].

From an asset management standpoint, protection selection should therefore consider inspectability and renewability. Thin-film coatings may offer ease of renewal but may be more sensitive to substrate preparation and mechanical damage, whereas overlays can provide substantial transport resistance but introduce additional thickness, potential restraint, and interface requirements. A maintenance-oriented specification that defines inspection intervals, acceptance criteria for adhesion and defect development, and re-application triggers can improve reliability and life-cycle cost effectiveness in coastal infrastructure [3], [18].

IV. CONCLUSIONS

The 2019–2025 literature indicates that surface protection for marine reinforced concrete (RC) is increasingly treated as an integrated durability system rather than a simple surface layer. Recent studies show growing interest in sustainability-oriented solutions, including alternative-binder-based coatings, hybrid systems, and surface modification approaches aimed at enhancing barrier performance while addressing practical issues such as efflorescence, dimensional instability, and interfacial durability. Although microstructural characterization is widely used to support mechanistic interpretations, many studies still lack the concurrent use of quantified chloride transport metrics and corrosion-related electrochemical indicators, which limits the strength of cross-study performance comparisons.

A central finding of this scoping review is that conclusions regarding chloride ingress mitigation and corrosion resistance are highly sensitive to exposure design (e.g., immersion versus wet–dry cycling), specimen conditioning, and the selected performance indicators. Improving comparability and engineering relevance requires evaluation frameworks to be anchored on a minimum evidence set that integrates (i) coating–substrate adhesion and failure mode (for coatings), (ii) near-surface water transport (absorption/sorptivity), (iii) chloride ingress assessment (migration/diffusion and/or chloride profiling to reinforcement depth), (iv) electrochemical corrosion indicators (at minimum corrosion potential and, where feasible, polarization resistance) interpreted with moisture state and resistivity context, and (v) microstructural evidence explicitly linked to transport and corrosion outcomes.

Future research should prioritize harmonized protocols and reporting (including transparent application parameters), expanded long-term and field validation under tidal and splash-zone exposures, crack-representative performance assessment (crack tolerance and delamination resistance), and quantitative microstructure–transport–corrosion linkages. Aligning laboratory evaluation with exposure-zoned specification and established practice frameworks for surface protection and on-site quality control (e.g., EN 1504 series) is essential to produce reliable, evidence-based recommendations for extending the service life of coastal and marine RC infrastructure.

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