

## Review

# Advancements in Surface Coatings and Inspection Technologies for Extending the Service Life of Concrete Structures in Marine Environments: A Critical Review

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**Abstract:** Concrete structures in marine environments are subjected to severe conditions that significantly compromise their durability and service life. Exposure to chloride penetration, sulfate attack, and physical erosion accelerates deterioration, leading to extensive maintenance requirements and high associated costs. To address these challenges, significant advancements in surface coatings and inspection technologies have been developed to enhance the longevity of concrete structures. This review examines recent progress in protective surface coatings that mitigate environmental damage and explores state-of-the-art inspection techniques for assessing structural integrity. By providing a comprehensive analysis of innovative materials, coating applications, and non-destructive evaluation methods, this paper aims to equip researchers and industry professionals with effective strategies for preserving concrete infrastructure in marine environments.

**Keywords:** concrete structures; marine environment; surface coating; surface inspection



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## 1. Introduction

Concrete structures in marine environments, such as ports, bridges, offshore platforms, and coastal defense systems, all play a significant role in global infrastructure and economic activities [1–4]. However, these structures directly face consistent and severe environmental challenges that threaten their durability and service life [5,6]. Concrete structures in marine environments face distinct corrosion mechanisms compared to those constructed on land, largely due to heightened exposure to chlorides, seawater spray, and frequent wetting–drying cycles [7–11]. These conditions accelerate chloride ingress and increase the likelihood of steel reinforcement corrosion. Once chlorides penetrate the concrete cover and reach the steel, electrochemical reactions occur, forming expansive corrosion products that can crack or spall the surrounding concrete and reduce the load-bearing capacity [12–15]. In contrast, land-based concrete structures typically experience lower chloride concentrations and less aggressive moisture cycles, resulting in a slower corrosion rate and reduced risk of severe steel degradation. Consequently, marine structures often require more robust protective measures, ongoing maintenance, and specialized material selection to prolong their service life and ensure safe performance under harsh coastal conditions.

The economic implications of concrete deterioration in marine settings are substantial [16]. Maintenance, repair, and rehabilitation of damaged structures require significant financial resources, and failure to address these issues in a timely manner can result in catastrophic structural failures, service disruptions, and safety hazards [17,18]. For instance,

corrosion-related damage accounts for a significant portion of the annual maintenance budget for marine infrastructure worldwide [19]. As such, there is a growing need for cost-effective and sustainable strategies to enhance the durability and service life of concrete structures in such harsh environments.

To mitigate these challenges, advancements in surface protection technologies and inspection methods have emerged as critical areas of research and application. Protective surface coatings have gained significant attention as a means to shield concrete from environmental stressors. These coatings generally act as barriers, preventing chloride ingress, sulfate attack, and moisture penetration, thereby reducing the rate of deterioration. The development of advanced coating materials, such as polymer-based systems, hybrid coatings, and nanotechnology-enhanced solutions, has greatly improved the protective performance and durability of these systems. Additionally, the optimization of coating application techniques and quality control measures has contributed to more effective and long-lasting protection. In parallel with advancements in protective coatings, inspection and monitoring technologies have evolved to address the need for reliable, efficient, and non-destructive assessment of structural integrity. Despite their established utility, conventional inspection techniques for marine concrete structures such as core sampling and diver-based surveys often fail to deliver real-time insights and typically necessitate invasive procedures [20,21].

Recent technological advancements in non-destructive evaluation (NDE) techniques have significantly improved our ability to detect and monitor structural damage in real time without compromising the integrity of the asset [22–25]. Ground-penetrating radar (GPR), which employs electromagnetic waves to identify subsurface anomalies—like voids, cracks, or delaminations—within concrete structures [22]. Infrared thermography, which detects subtle temperature variations on surfaces, revealing hidden defects or moisture ingress indicative of ongoing degradation [23]. Acoustic emission (AE) monitoring, which captures stress waves caused by micro-cracking or other structural changes, thus providing early warnings of potential failures [24]. Advanced electrochemical sensors, which measure in situ corrosion activity and rates, allow engineers to pinpoint problem areas before significant damage occurs [25]. These innovative NDE solutions offer enhanced capabilities for early-stage defect detection, ongoing corrosion monitoring, and comprehensive assessment of coating performance. Consequently, engineers and asset managers can implement more effective maintenance strategies, minimize costly repairs or downtime, and extend the overall service life of critical infrastructure.

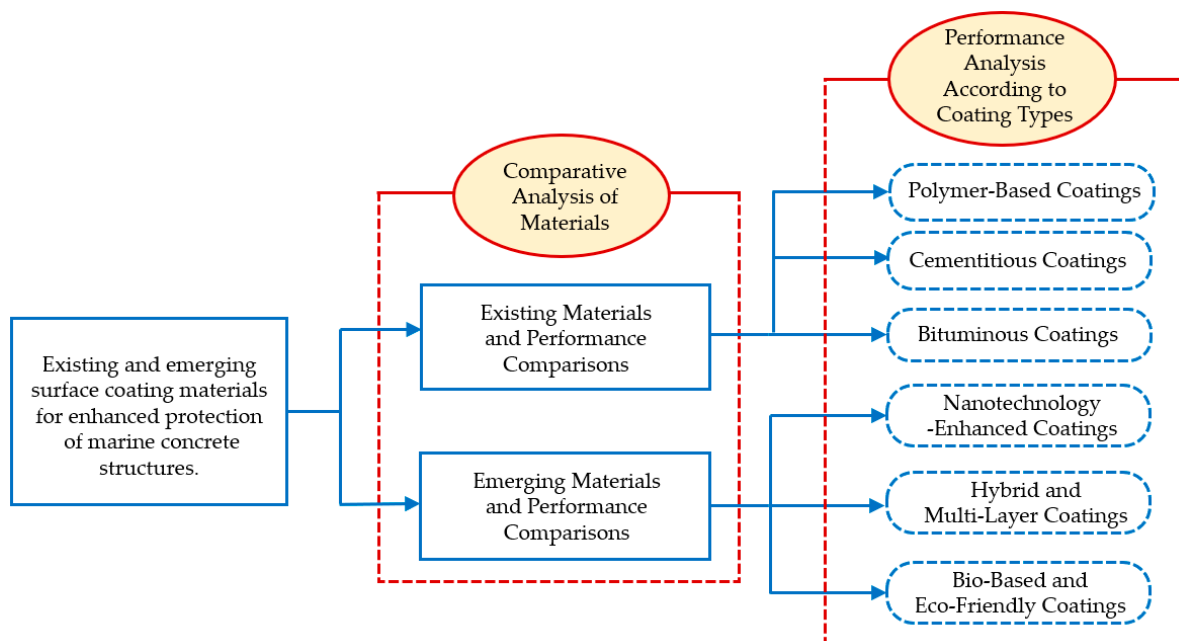
Surface repair and protective coatings are integral to maintaining the structural integrity of marine concrete infrastructure. Despite the existence of national and international guidelines (e.g., [Relevant Standard/Code]), these documents often employ prescriptive rather than performance-based approaches, overlooking the complex and variable conditions encountered in marine settings. Factors such as frequent wetting–drying cycles, high chloride concentrations, and temperature oscillations can significantly degrade both the concrete matrix and embedded steel reinforcements. A key deficiency lies in the limited recognition of the site-specific parameters that drive deterioration mechanisms in marine environments. Current regulations commonly specify universal requirements for repair and coating applications (e.g., minimum layer thickness, adhesion strength) but may fall short in addressing localized loading scenarios or variable exposure zones (submerged, tidal, splash, and atmospheric). As a result, material-mechanical properties deteriorate more rapidly than anticipated, undermining the intended service life of repaired sections. Enhancing these standards to incorporate performance-based testing, flexible selection criteria for new coating technologies, and tailored maintenance protocols could offer more robust protection. This approach would better align regulatory provisions with real-world

conditions, reducing the risk of premature failure and ensuring the long-term durability of marine concrete structures.

This review provides a comprehensive examination of recent advancements in protective surface coatings and state-of-the-art inspection technologies aimed at extending the service life of concrete structures in marine environments. The discussion encompasses innovative coating materials, application methods, and performance evaluations, as well as the latest developments in inspection tools and techniques. By synthesizing current knowledge and highlighting future research directions, this paper aims to serve as a valuable resource for researchers, engineers, and industry professionals striving to improve the resilience and sustainability of marine concrete infrastructure. In the following Sections, we discuss: (1) the environmental challenges faced by concrete structures in marine settings, (2) the development and performance of advanced protective coatings, (3) non-destructive inspection and monitoring technologies, and (4) emerging trends and future directions for improving concrete durability in harsh marine environments. By addressing these topics, the article provides actionable insights into effective strategies for preserving and maintaining critical concrete infrastructure.

## 2. Surface Coatings for Marine Concrete Structures

As mentioned previously, surface coatings play a pivotal role in enhancing the durability and service life of concrete structures in marine environments. These coatings act as protective barriers against environmental stressors—such as chloride ingress, sulfate attack, and physical erosion—which are especially severe in coastal and offshore locations. Over time, significant advancements in coating formulations have emerged, ranging from traditional epoxy- or cementitious-based solutions designed to seal concrete surfaces, to more advanced, innovative systems that utilize polymeric compounds, nanomaterials, and even self-healing additives [26–29]. These newer approaches extend service life, reduce maintenance demands, and offer enhanced durability under aggressive marine conditions. The detailed types of surface coatings investigated in this study are summarized in Figure 1. The surface coatings discussed in this review are intended for the exterior surfaces of marine concrete structures rather than for the reinforcements inside them.



**Figure 1.** Type of surface coatings for marine concrete structures investigated in this study.

### 2.1. Existing Materials, Surface Preparation, and Performance Analysis

In this Section, we comprehensively review the characteristics and application effects of various coating materials designed to improve the performance of concrete structures exposed to marine environments. To this end, we systematically analyzed key research findings on polymer coatings, cementitious coatings, and bituminous coatings from existing literature, and discussed each material's properties as well as its feasibility for marine applications. In particular, we compared and analyzed the chloride penetration resistance, waterproofing capability, chemical resistance, and mechanical properties of each coating material to evaluate their impact on the durability and functional enhancement of the structures. Based on these results, we derive the characteristics of coating materials suitable for marine environments and comprehensively assess their overall effectiveness.

Surface preparation is essential to ensure both the effectiveness and durability of protective coatings on marine concrete structures [30–33]. The process typically begins with a thorough inspection to identify cracks, spalls, or corroded reinforcing steel, all of which must be repaired prior to coating application. Contaminants such as marine growth, salt deposits, and loose debris should then be removed using high-pressure water jetting, mechanical abrasion (e.g., grit or shot blasting), or suitable chemical cleaners. Any structural damage is addressed next: cracks are repaired with epoxy injection or polyurethane grouts, and spalled or delaminated areas are patched with compatible repair mortars. Achieving the correct surface profile is critical for coating adhesion, and abrasive blasting methods can simultaneously roughen and clean the concrete. It is equally important to ensure the substrate is sufficiently dry, as residual moisture can compromise adhesion, and to apply a primer if recommended by the coating manufacturer. Throughout the process, temperature and humidity must be carefully controlled, and the work area protected from wind-blown salt or excessive moisture. Finally, each coating should be applied promptly after surface preparation to prevent the infiltration or bonding of harmful ions and contaminants [34]. By following these steps, coating performance is maximized, and marine concrete enjoys an extended service life in harsh coastal or offshore environments.

#### 2.1.1. Polymer-Based Coatings

Table 1 summarizes the properties of various polymeric coatings reported by previous studies [35–41]. As shown in Figure 2, polymer coatings have proven their excellent durability and chemical resistance in numerous prior works and are widely employed for maintaining and reinforcing concrete structures exposed to marine environments.

**Table 1.** Material properties of various polymeric coatings [35–41].

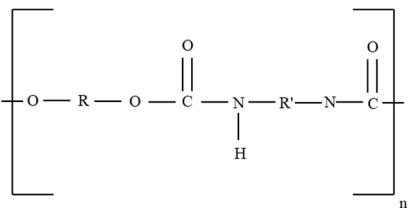
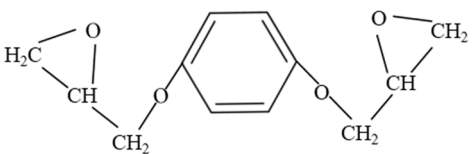
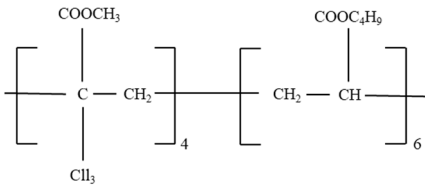
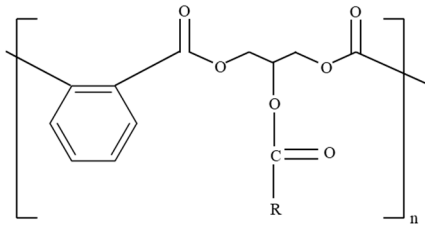
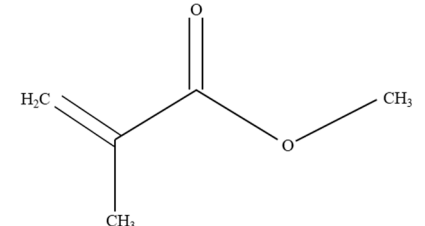
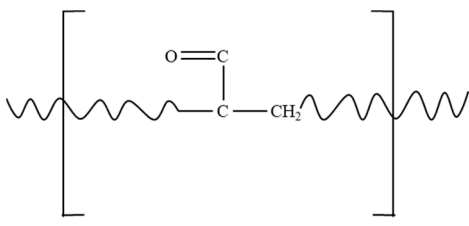
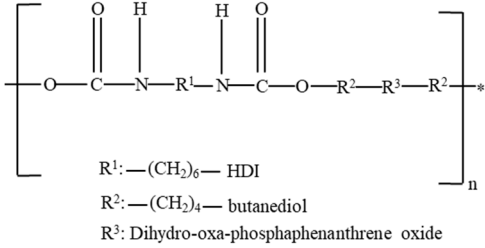
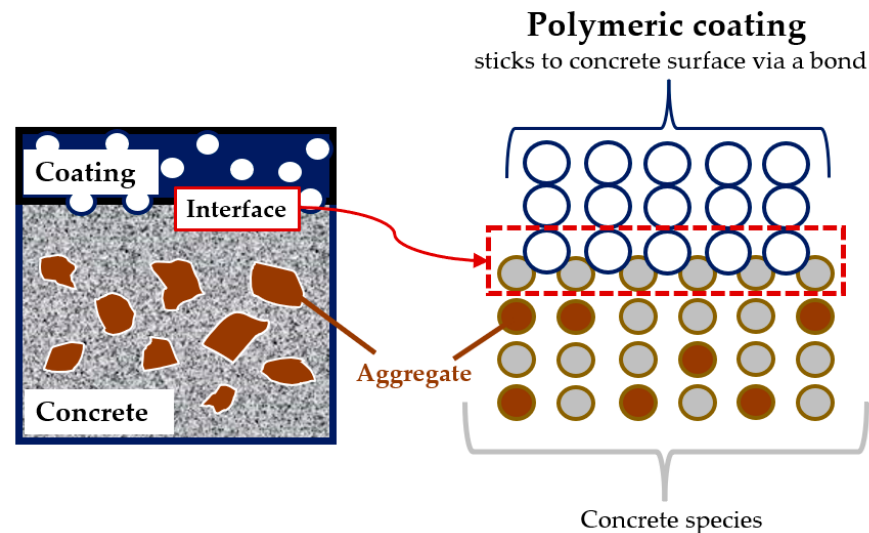
| Polymeric Coatings         | Chemical Formula                                                                    | Material Evaluation Outcomes                                                                                                                   | Refs. |
|----------------------------|-------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|-------|
| Polyurethane-based polymer |  | The coating showed high cohesion after 27 weeks of alternating exposure: 4 h at 60 °C with UVA radiation (QUV) and 1 h at 25 °C (Prohesion).   | [35]  |
| Epoxy resin-based polymer  |  | The coating penetrated 2376 µm, dehydrated at 168.1 °C, with charge and oxygen permeability reduced to 63 °C and 4.438 cc/m <sup>2</sup> ·day. | [36]  |

Table 1. Cont.

| Polymeric Coatings                 | Chemical Formula                                                                    | Material Evaluation Outcomes                                                                                                                                             | Refs. |
|------------------------------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|
| Polyacrylates                      |    | Disc adhesion time (hours): $4.8 \pm 0.2$<br>total work of adhesion ( $\mu\text{J}$ ): $92.8 \pm 6.9$<br>detachment force (mN): $47.0 \pm 11.9$                          | [37]  |
| Conductive polymer (alkyd)         |    | Thermogravimetric analysis (0–850 °C) showed the primer is highly stable, with decomposition starting at 300 °C.                                                         | [38]  |
| Methacrylate-based materials       |    | Provides excellent durability and an appealing finish when coated with appropriate film thickness                                                                        | [39]  |
| Acrylic polymer                    |   | PU coating showed minimal penetration: <20 mm (3 years), <30 mm (5 years), vs. >45 mm for others.                                                                        | [40]  |
| Aliphatic acrylic and polyurethane |  | Aliphatic acrylic and polyurethane coatings reduced the chloride diffusion coefficient ( $D_c$ ) by 29% and 36%, respectively, after 88 months, compared to the control. | [41]  |

In particular, tests that simulate aggressive marine conditions—such as the chlorine spray test and the accelerated corrosion test—have demonstrated the superior corrosion resistance of conductive polymer coatings, including polyurethane [35,38].

Based on the onsite tests, preventing chloride-induced corrosion is a key concern; therefore, the chloride penetration depth, diffusion coefficient, and surface chloride ion concentration of polymer coatings were evaluated [36,40–42]. Results show that epoxy resin and acrylic coatings form highly impermeable layers in corrosive marine environments, effectively blocking chloride ion penetration. Notably, polyurethane coatings are reported to reduce the chloride diffusion coefficient by up to 86%, indicating that polymer coatings effectively prevent corrosive agents in marine environments from easily entering through pores and cracks on the concrete surface. This protective barrier function helps slow structural deterioration and minimize damage to concrete.



**Figure 2.** Schematic representation of polymeric coatings applied to a concrete surface.

Additionally, when applied with an appropriate film thickness, polyacrylate-, urethane-, and methyl methacrylate-based coatings exhibit excellent adhesion, significantly improving the durability of concrete [37,39]. These findings suggest that polymer coatings play a critical role in minimizing concrete damage caused by moisture, temperature fluctuations, and chloride and sulfate ions present in seawater under marine conditions.

#### 2.1.2. Cementitious and Bituminous Coatings

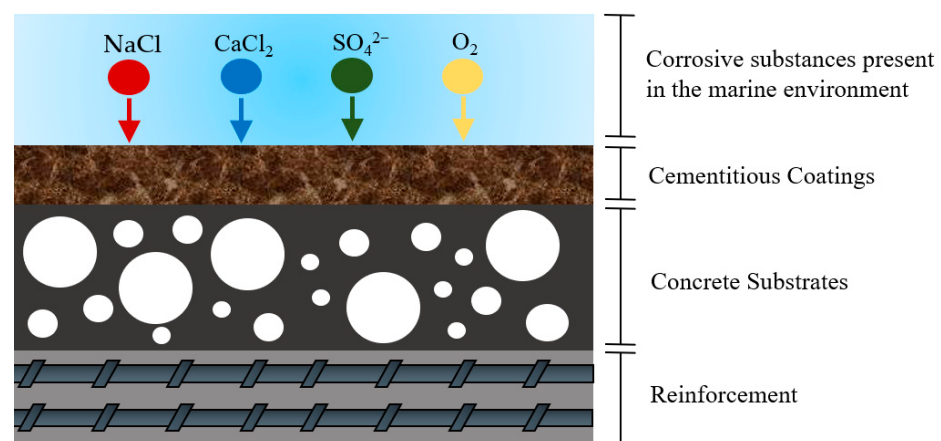
Table 2 presents the types, test methods, and major findings of previous studies that employed cementitious and bituminous coatings [43–58]. Cementitious coatings are reported to offer excellent tensile properties, adhesive strength, waterproofing capability, and flexibility even at low temperatures [47]. Accordingly, researchers have investigated cementitious coatings (see Figure 3) that demonstrate strong adhesion to concrete exposed to marine environments and also exhibit outstanding waterproof performance by effectively blocking moisture and water penetration.

**Table 2.** Performance comparisons of cementitious and bituminous coatings [28–43].

| Type                  | Materials                              | Exposure Environment or Test Method             | Test Results                                                 | Refs. |
|-----------------------|----------------------------------------|-------------------------------------------------|--------------------------------------------------------------|-------|
| Cementitious Coatings | Cement mixed with polydimethylsiloxane | Corrosion resistance test (3.5 wt% NaCl).       | Water absorption rate: 14.57% (3.77% lower than the control) | [43]  |
|                       | Calcium sulfoaluminate cement          | Water absorption test                           | Water absorption rate: 6.10% (after 72 h of immersion)       | [44]  |
|                       | Phosphate aluminate cement             | Chloride penetration (10% NaCl)                 | Penetration depth: 33.24 mm (erosion period of 120 days)     | [45]  |
|                       | Cement mixed with styrene acrylate     | Artificial accelerated weather resistance tests | UV reflectance decrease: 11.7% (after 400 h of weathering)   | [46]  |
|                       | Styrene acrylic cement-based coating   | Water impermeability measurements               | Tensile strength: (2.23 ± 0.10) MPa (after water immersion)  | [47]  |

Table 2. Cont.

| Type                | Materials                                                       | Exposure Environment or Test Method                                     | Test Results                                                                                                          | Refs. |
|---------------------|-----------------------------------------------------------------|-------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------|-------|
| Bituminous Coatings | Polyacrylic acid (PA) cement                                    | Water absorption test                                                   | Absorption rate: 29.6% decrease (720 min of water immersion)                                                          | [48]  |
|                     | Cement mortar reinforced with epoxy resin                       | Coating adhesion test.                                                  | Bonding strength: 4.90 MPa (16.67% higher than the control)                                                           | [49]  |
|                     | TiO <sub>2</sub> -mixed sulfoaluminate cement composite coating | Water repellency test                                                   | Water repellency test results: 0.04 (33.33% higher than the control)                                                  | [50]  |
|                     | Bitumen Rubber Emulsion (BRE)                                   | Marine environment (Northern Persian Gulf)                              | Carbonation depth: 5.5 mm (88 months of marine exposure)                                                              | [51]  |
|                     | Asphalt Polyurethane                                            | Chloride permeability (5% MgCl <sub>2</sub> )                           | Chloride diffusion: 88~100 ppm (30 days exposure)                                                                     | [52]  |
|                     | Mixture of Water-Based Asphalt and Polyurethane Dispersion      | Adhesion in Peel Test                                                   | Average peel strength: 5~10 Psi                                                                                       | [53]  |
|                     | Multi-Coating with Asphalt Emulsion                             | Drying time test                                                        | Demonstrates quick drying characteristics and excellent durability                                                    | [54]  |
|                     | Bitumen Dispersion Mixed with Hydroxylated Polybutadiene        | Evaluation of the stability                                             | Stable (30 days at room Temperature)                                                                                  | [55]  |
|                     | Bitumen Modified with HDPE (High-Density Polyethylene)          | High-temperature exposure test                                          | Melting temperature: 122.27 °C (binder modified with 2% HDPE)                                                         | [56]  |
|                     | Blown Asphalt Modified with Polypropylene Ester                 | Chemical resistance test (2.5% H <sub>2</sub> SO <sub>4</sub> solution) | Compressive strength: Decreased by 51.11% at a rate of 12.77 kg/cm <sup>2</sup> /week (1.83 kg/cm <sup>2</sup> /day). | [57]  |
|                     | Emulsified Modified Bitumen (EMB)                               | Accelerated weathering test                                             | Weight loss rate: up to 2.72%. (7 days exposure)                                                                      | [58]  |



**Figure 3.** Schematic representation of cementitious coatings that are applied to reinforced concrete to mitigate aggressive ion penetration in marine environments.

Previous studies have primarily focused on coatings based on calcium sulfoaluminate cement, phosphate aluminate cement, and polymer-modified Portland cement, evaluating their physical properties, resistance to chloride ion penetration, and microstructural characteristics [44,45,49]. As a result, cementitious coatings have shown excellent resistance to chloride ion penetration, with a decrease in chloride ion concentration observed on the

coating surface. Moreover, various studies have been conducted to improve the ultraviolet (UV) aging resistance, artificial accelerated weather resistance, and corrosion resistance of cementitious coatings for application to concrete structures in marine environments. Cement-based coatings containing styrene acrylate have exhibited excellent artificial accelerated weather resistance [46], while those blended with polydimethylsiloxane have shown a 99.3% efficiency in preventing deterioration [43]. In addition, polyacrylic acid (PA)-based cement coatings have been reported to significantly enhance durability under acidic, alkaline, and various environmental conditions [48]. This is because the high density and fewer microdefects in cementitious coatings allow them to remain compact and undamaged even after UV aging and saltwater immersion tests. Furthermore, incorporating  $\text{TiO}_2$  at ratios of 0.4–0.6% into cementitious coatings improved workability and mechanical properties, increasing bond strength by 59% [50]. This result is attributed to the formation of an optimized network structure during the cement hydration process in the presence of these additives. In conclusion, owing to their excellent interfacial tensile strength, cementitious coatings play a crucial role in preventing corrosion of concrete structures exposed to marine environments and effectively enhancing their durability.

Bituminous coatings are known as coatings based on asphalt or bitumen, and when applied to concrete, they are reported to exhibit excellent resistance against sulfuric acid and sodium chloride, low water absorption and chloride permeability, and outstanding thermal insulation performance [52,58]. Researchers have employed various modification methods to enhance the performance of bituminous coatings. For instance, mixing polyurethane dispersion, polybutadiene hydroxide, asphalt emulsion, or high-density polyethylene (HDPE) into bitumen coatings has been shown to improve elongation, waterproofing, and mechanical properties [53–56]. In particular, after coating mortar with blown asphalt modified by polypropylene ester and immersing it in 3% NaCl and 2.5%  $\text{H}_2\text{SO}_4$  solutions, the weight percentage change of the coated samples was reduced by up to 81.25% compared to the uncoated samples [57]. This indicates that, in corrosion tests simulating marine environments, bituminous coatings effectively protected the mortar by reducing weight loss. Moreover, in a study aimed at improving the long-term performance of concrete exposed to marine environments, bitumen rubber emulsion (BRE) was used as a surface coating, and the results showed that BRE inhibited chloride ion diffusion and reduced the carbonation area of the concrete [51]. Hence, bituminous coatings also can be considered as an effective protective coating in marine and corrosive environments, offering low water absorption and excellent resistance to acids and salts.

## 2.2. Emerging Materials and Performance Comparisons

While existing coating materials provide effective protection in many applications, ongoing research has led to the development of advanced, innovative coating materials that address current limitations and deliver superior performance in marine environments. In this Section, we specifically investigate nanotechnology-enhanced coatings, hybrid and multi-layer coatings, as well as bio-based and eco-friendly coatings [59–82]. The results demonstrating the performance of the coating material are summarized in Table 3 [59,64–67,69–72,74,75,77–82].

**Table 3.** Emerging coating materials and their performance [59,64–67,69–72,74,75,77–82].

| Type                                | Materials                                                                                                             | Substrate | Performance Verification                                                                         | Refs.   |
|-------------------------------------|-----------------------------------------------------------------------------------------------------------------------|-----------|--------------------------------------------------------------------------------------------------|---------|
| Nanotechnology Enhanced Coatings    | Nano ZrP-based Composite Polymer Functional Coating                                                                   | Mortar    | The tribological test value decreased from 0.82 to 0.35                                          | [59]    |
|                                     | Nano-SiO <sub>2</sub> Modified Polymer Coatings                                                                       | Concrete  | Nano-SiO <sub>2</sub> increased the lifespan of coatings by up to 78%                            | [64]    |
|                                     | Hydrophobic Photo-Polymerizable Organic–Inorganic Nano-Structured                                                     | Concrete  | The viscosity is 11–20 mPa·s (suitable for use)                                                  | [65]    |
|                                     | Silane/Clay Nanocomposites                                                                                            | Concrete  | Nanocomposite coating reduced chloride content by 92% and 69%                                    | [66]    |
| Hybrid and Multi-Layer Coatings     | Synthetic Resin Emulsion-based Multilayer                                                                             | Concrete  | Improves alkalinity, UV degradation, and heat in concrete                                        | [67]    |
|                                     | Multi-layered Superhydrophobic                                                                                        | Concrete  | Remains superhydrophobic (after 300 °C, 115 days)                                                | [69]    |
|                                     | Multi-component Coatings (TiCN/ZrO <sub>2</sub> /TiO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub> /MOS <sub>2</sub> ) | Concrete  | Wear-resistant, robust, and corrosion- and thermal cycling-resistant                             | [70–72] |
|                                     | Chlorinated Rubber (CR)                                                                                               | Concrete  | Coating degradation occurs between 300 °C and 600 °C                                             | [74]    |
| Bio-Based and Eco-Friendly Coatings | Bionic Superhydrophobic Coating for Concrete                                                                          | Mortar    | Water contact angle: 156 ± 3°, water absorption: 86% reduction                                   | [75]    |
|                                     | Biological ( <i>C. gigas</i> ) Coating                                                                                | Concrete  | Interfacial adhesion: 0.62–1.45 MPa (450 days marine exposure)                                   | [77]    |
|                                     | Biological Cool Barnacles Coating                                                                                     | Concrete  | Salt ion concentration in concrete decreased after 5 years                                       | [78]    |
|                                     | Crustaceans and Biofilm                                                                                               | Concrete  | Reduce the chloride diffusion coefficient (D <sub>e</sub> ) by up to 20%                         | [79]    |
|                                     | Calcareous Settling Organisms                                                                                         | Mortar    | Surface with GGBS microcrack length is 5 times smaller than general mortar                       | [80]    |
|                                     | Oyster-based bio-coating                                                                                              | Concrete  | Capillary absorption of concrete with 10.4% coating is 1.95 times higher than with 75.2% coating | [81]    |
|                                     | Bacterial Biofilm coating ( <i>Pseudoalteromonas</i> and <i>Paracoccus marcusii</i> )                                 | Mortar    | Bacterial biofilms significantly reduce concrete permeability and improve durability             | [82]    |

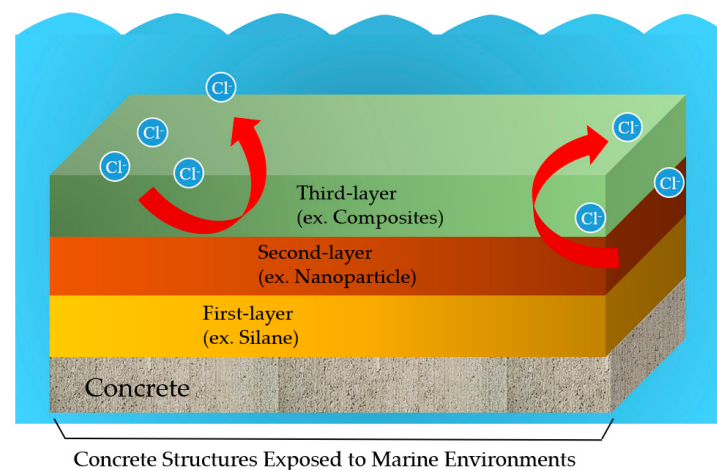
### 2.2.1. Nanotechnology-Enhanced Coatings

Nanotechnology-based coatings have been reported to exhibit stable reactivity in both low-temperature and moderate-temperature environments, maintaining their performance even after severe aging [65]. Consequently, there is growing interest in using these coatings as surface treatments to enhance the carbonation resistance and durability of

marine-exposed concrete. To that end, researchers have studied various nanotechnology-enhanced coatings under aggressive environmental conditions, including hydrophobic photo-polymerizable organic–inorganic nano-structured coatings (HEP), graphene oxide/polyaniline (GO/PANI) nanocomposites, tannic acid, and d-limonene—each demonstrating excellent corrosion resistance and minimal loss of adhesion [60,62,63]. Notably, polymers modified with nano-SiO<sub>2</sub> have been shown to extend the average service life of coatings by up to 78% [64]. In addition, functional nano-coatings significantly improve the durability of marine concrete due to the superior dispersion stability of nanocomposites [59,61]. Overall, these findings indicate that the presence of nanoparticles reduces micro-defects and increases coating density, thereby preventing spalling in marine-exposed concrete and enhancing the protective performance of the substrate.

### 2.2.2. Hybrid and Multi-Layer Coatings

Researchers have investigated the feasibility of using multiple coating layers to improve the durability of concrete in harsh environments, including those found in marine settings. Studies on two-layer and three-layer systems [67,69] show that multi-layer coatings effectively prevent corrosion in bridges, ships, and other structures exposed to marine conditions (see Figure 4).



**Figure 4.** Schematic representation of the penetration barrier formed by multi-layer coatings applied to marine concrete structures exposed to marine environments.

Notably, three-layer coatings can form an engineering barrier resistant to corrosion, radiation, and damage from thermal cycles [70–72]. As a result, multi-layer coatings exhibit high wear resistance and mechanical robustness. In one study, the application of modified polyethylene powder in a multi-layer system effectively blocked chloride penetration in chlorine-rich environments, while also providing strong resistance against humidity and temperature fluctuations [68]. Other researchers have evaluated four-layer and five-layer coatings under marine conditions. For instance, refs. [73,74] investigated multi-layer coatings designed to protect steel and concrete in offshore wind farms, marine buildings, and ocean bridges, which are regularly exposed to water and chemicals. Their findings indicate that four-layer coatings take longer than three-layer coatings to reach a 50% corrosion rate—one to two years in actual marine exposure. Furthermore, five-layer coatings demonstrated excellent thermal stability and durability even under extreme marine conditions. Overall, these results confirm that multi-layer coatings enhance the barrier performance of concrete surfaces by more effectively blocking moisture and chemicals, thereby improving resistance to chemical attacks in marine environments.

### 2.2.3. Bio-Based and Eco-Friendly Coatings

Applying waterproof coating technologies to enhance the durability of concrete in marine environments is essential. High-performance waterproof coatings made from renewable, eco-friendly bio-materials are gaining prominence as a key research area for sustainable development, ensuring the stability of concrete in these harsh conditions. Various studies have examined bio-bitumen coatings and eco-friendly biofilm coatings derived from crustaceans under marine conditions [77–81]. Bio-based superhydrophobic coatings can reduce the water absorption rate of concrete by up to 86%, and the coated mortar maintains its hydrophobic stability even after 120 h of exposure to seawater [75]. This superior performance is attributed to the fine microstructure of the bio-coating. Moreover, incorporating esterified lignin (OEL) into bio-materials significantly improves coating flexibility, with an increase in peel strength observed even after aging [76]. It has also been confirmed that bacterial biofilms exposed to sterilized seawater effectively reduce the ion permeability of mortar, likely due to the fibrous and colloidal substances contained in the film [82]. These findings demonstrate that bio-based, eco-friendly coatings can substantially enhance concrete protection in marine environments by reducing moisture absorption and limiting the penetration of chlorides and salt ions.

### 2.3. Performance Comparisons Between Surface Coatings

The general performance was evaluated previously, and a performance comparison will be conducted in this Section. Polymeric coatings (e.g., epoxy, polyurethane, polyurea) typically offer excellent adhesion, low permeability, and high chemical resistance, making them well suited to harsh marine conditions; however, they often require rigorous surface preparation, may carry higher initial costs, and can emit volatile organic compounds (VOCs). Cementitious coatings, by contrast, match concrete's thermal expansion characteristics more closely, which reduces cracking risks, and they are relatively easy to apply using conventional methods. Still, their lower elasticity makes them susceptible to cracks when subjected to repeated loading or temperature fluctuations, and they often require thicker layers for optimal performance. Nano-based coatings incorporate nanoparticles to enhance properties like impermeability, abrasion resistance, and, in some cases, self-healing functionality, but these advanced features can come with higher production costs, limited field data, and demanding application conditions. Finally, bio-based coatings rely on renewable materials, offering a sustainable and environmentally friendly alternative that may incorporate self-healing mechanisms via microorganisms; however, their long-term durability in highly saline, fluctuating marine environments remains under investigation. Balancing factors such as mechanical performance, cost, application complexity, environmental impact, and service life is crucial when deciding among these coating options.

In addition, each type of coating—polymer-based, cementitious/bituminous, nanotechnology-enhanced, hybrid multi-layer, and bio-based—has distinct advantages and limitations when exposed to environmental stressors such as UV radiation, temperature fluctuations, moisture ingress, and chloride attack. While polymer-based and hybrid systems generally provide robust barrier properties and strong adhesion, they may require specialized formulations (e.g., UV stabilizers) or multiple layers to maintain performance in harsh conditions. Cementitious and bituminous coatings are cost-effective and straightforward to apply; however, they can be more prone to cracking or embrittlement under severe freeze–thaw cycles or prolonged UV exposure. Nanotechnology-enhanced coatings show considerable promise in improving durability and reducing permeability, though comprehensive long-term field data remain limited. Finally, bio-based eco-friendly coatings address growing sustainability needs, but achieving performance comparable to conventional systems in extreme environments often requires further formulation refinements.

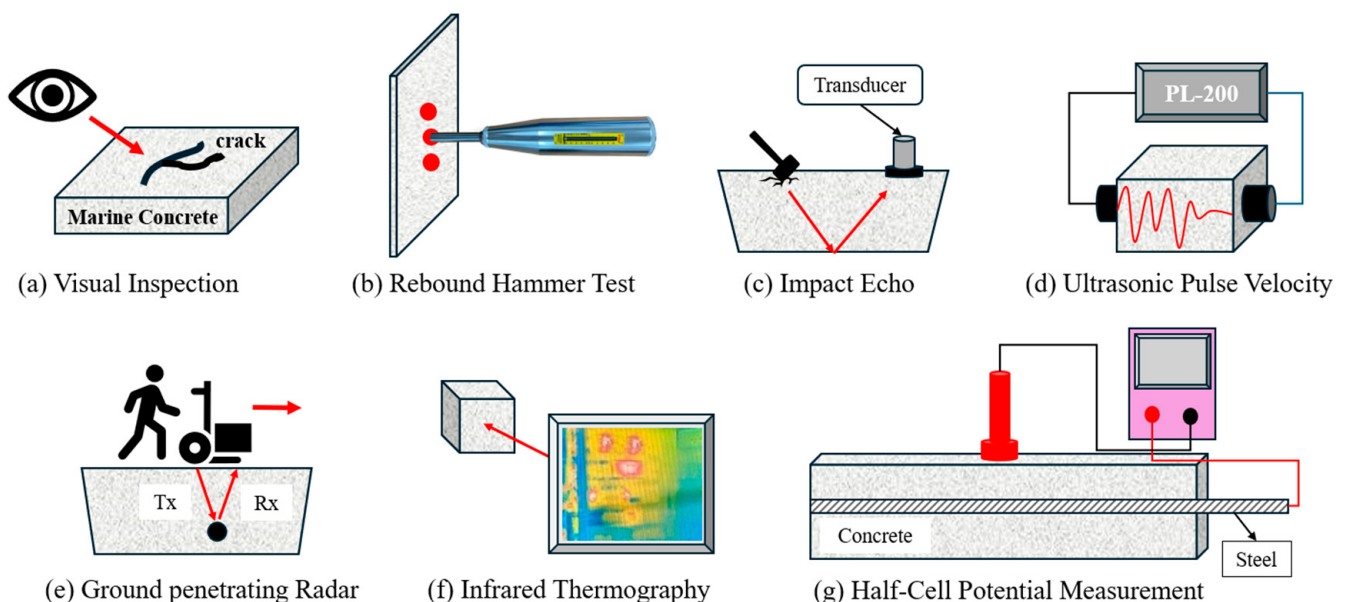
Balancing protection, environmental impact, cost, and maintenance considerations is therefore essential when selecting and specifying coatings for concrete structures—particularly in marine or highly aggressive settings.

### 3. Inspection Methods for Marine Concrete Structures

In this Section, we discuss both existing and emerging non-destructive testing (NDT) technologies for inspecting and monitoring concrete structures exposed to marine environments. In Section 3.1, we review conventional NDT methods for marine-exposed concrete—such as ultrasonic pulse velocity (UPV), rebound hammer testing, and GPR—and evaluate their performance and limitations. Section 3.2 explores the latest NDT technologies, including AE, fiber-optic sensors, drone and UAV-based remote sensing, and AI-based analysis. In Section 3.3, we focus on the monitoring and repair of underwater marine concrete structures, highlighting real-world examples of ongoing maintenance and illustrating how these techniques enhance deterioration assessment and maintenance efficiency. Overall, this discussion offers a comprehensive approach to managing the long-term performance of marine concrete structures and predicting their deterioration.

#### 3.1. Conventional Non-Destructive Testing Methods to Examine Marine Concrete Structures

NDT methods allow for the detection of defects and the evaluation of structural integrity without causing physical damage to the structure, providing relatively reliable data even under harsh marine conditions. Table 4 shows a systematic overview of the main objectives, advantages, and limitations of these established technologies, comparing their characteristics and potential applications [83–103]. It covers visual inspections, rebound hammer tests, UPV, impact echo, GPR, infrared thermography, and half-cell potential measurements, enabling a quick understanding of each method's scope and constraints. In addition, Figure 5 provides a visual depiction of the principles and application methods for these inspection technologies.



**Figure 5.** Conventional non-destructive inspection techniques for concrete structures: (a) Visual inspection; (b) Rebound hammer test; (c) Impact echo; (d) Ultrasonic Pulse Velocity; (e) Ground penetrating radar; (f) Infrared thermography; (g) Half-cell potential measurement.

**Table 4.** Comparisons of non-destructive inspection techniques for concrete structures [83–103].

| Inspection Technique            | Primary Objective                                        | Advantages                              | Limitations                                                    | Refs.     |
|---------------------------------|----------------------------------------------------------|-----------------------------------------|----------------------------------------------------------------|-----------|
| Visual Inspection               | Identify early signs of deterioration                    | Cost-effective, simple                  | Unable to detect internal defects                              | [83–85]   |
| Rebound Hammer Test             | Indirect evaluation of compressive strength              | Portable, quick assessment              | Sensitive to environmental factors (e.g., moisture, chlorides) | [86,87]   |
| Impact Echo                     | Diagnose location and size of internal defects           | Enables quantitative defect evaluation  | Sensitive to ambient noise, requires skilled operation         | [88]      |
| Ultrasonic Pulse Velocity (UPV) | Detect voids, cracks, and inhomogeneities                | Non-invasive internal assessment        | Affected by environmental factors, requires calibration        | [89–93]   |
| Ground Penetrating Radar (GPR)  | Detect rebar corrosion, delamination                     | Rapid inspection of large areas         | Complex signal interpretation, requires expertise              | [94–98]   |
| Infrared Thermography           | Detect defects based on surface temperature distribution | Non-contact, rapid evaluation           | Sensitive to external conditions (e.g., sunlight, wind)        | [99–101]  |
| Half-Cell Potential Measurement | Assess rebar corrosion state                             | Effective for early corrosion diagnosis | Sensitive to chloride concentration, moisture levels           | [102,103] |

Loreto et al. [83] demonstrated early deterioration regions through visual inspection and gathered data for further evaluation. Pushpakumara and Thusitha [84] proposed a standardization for surface deterioration phenomena in underwater concrete structures, emphasizing that stains and bleeding marks are major indicators of structural problems. In aging wharf structures in Nigeria’s Niger Delta region, researchers used BPVC codes to locate deteriorated areas and employed both visual inspection and various non-destructive testing methods to analyze the degree of rebar corrosion and its primary causes [85]. Celerinos et al. [86] compared rebound hammer readings with compressive strength tests on concrete specimens exposed to different environmental conditions (splash zones) and reported low accuracy for the rebound hammer. Law et al. [87] used Schmidt hammer and UPV tests on alkali-activated concrete (AAC) exposed to marine environments for two years and correlated material properties with field performance by integrating these tests with microstructural analysis techniques, such as FT-IR, NMR, and TGA.

At the Nantes–Saint-Nazaire port in France, a 15-year-old reinforced concrete structure in a tidal zone was evaluated by measuring porosity, chloride ion concentration, and moisture saturation, which informed durability assessments and maintenance plans. In particular, the dynamic modulus of elasticity was correlated with physical defects to assess the structure’s condition [88]. A study aimed at diagnosing rebar corrosion in chloride and oxidative environments used UPV to distinguish cross-sectional reduction caused by chlorides from surface corrosion caused by oxidation. By leveraging ultrasonic guided waves in surface-sensing and center-sensing modes, researchers identified fitting due to signal attenuation under chloride exposure and delamination via increased signal amplitude in oxidative conditions [89].

In the roughly 22-year-old breakwater superstructure at the Port of Malaga in Spain, reduced ultrasonic velocity measurements confirmed delamination and rebar corrosion [90]. Researchers inspecting a 25-year-old jetty in Indonesia employed both UPV and core drilling

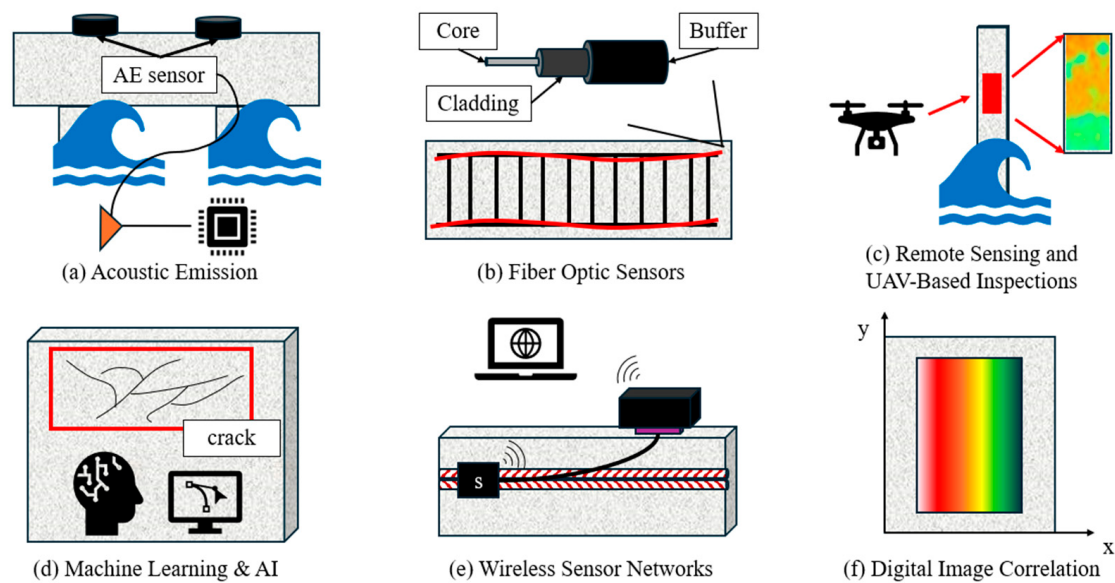
to evaluate damage and compressive strength in key members (slab, beam, pile cap). The average ultrasonic velocity was 1772 m/s, offering valuable durability insights [91]. Another study in a 20-year-old cooling water canal at an Indonesian power plant used UPV to assess marine exposure damage; the measured velocity ranged from about 2400 to 2900 m/s, enabling quantitative evaluations of crack depth and chloride penetration [92].

Recently, UPV was combined with deep learning (DNN) to detect coating delamination in coated marine concrete. By analyzing the phase and frequency of reflected waves using a trained DNN model, researchers achieved a 100% detection accuracy for delaminated coatings [93]. In the case of the Jimei River Dam in Guangdong, China, GPR effectively identified cracks and settlement in the concrete waterproofing panels, as well as scouring in the underlying soil [97]. At Italy's Hydrogeosite Laboratory, GPR was used to provide high-resolution evaluations of submerged archaeological structures, detecting discontinuities and density variations in multi-layer components [98]. However, high salinity and moisture content can affect GPR signal interpretation, highlighting the need for advanced correction techniques.

When assessing rebar corrosion, the corrosion of uncoated rebar increased thermal insulation, thereby inhibiting surface temperature rise, whereas the corrosion of epoxy-coated rebar caused cracking and delamination of the coating layer, raising thermal conductivity [100]. Infrared thermography based on these observations successfully detected heat distribution differences caused by coating debonding and facilitated early diagnosis of structural damage due to internal corrosion [101]. A study on M25 concrete using accelerated corrosion testing and potential measurements found that potential differences gradually increased as corrosion progressed [102]. Another investigation on concrete beams with water–binder ratios ( $w/b$ ) of 0.3–0.6 compared corrosion potentials under static and fatigue loads. Samples subjected to fatigue loads exhibited more negative potentials—indicating higher corrosion tendencies—than those under static loads, with more pronounced corrosion and strength loss at higher  $w/b$  [103]. In conclusion, each non-destructive testing method for evaluating concrete in marine environments has its own strengths and limitations. Therefore, future research should focus on combining multiple techniques, applying precise corrections for environmental factors, and incorporating the latest signal-processing technologies.

### *3.2. New and Emerging Inspection Technologies for Marine Concrete Structures*

Advancements in real-time monitoring technologies have dramatically transformed the way structures are inspected. AE technology enables early detection of microcracks and corrosion, while fiber-optic sensors (FOS) provide a durable solution for real-time measurement of strain, temperature, and vibration. Drone- and LiDAR-based remote sensing allows for rapid assessment of hard-to-reach structures, and AI and machine learning process large datasets to predict damage patterns. Wireless sensor networks (WSN) remotely monitor chloride concentrations and humidity, while digital image correlation (DIC) precisely measures surface deformation and cracks without direct contact. These technologies enhance the efficiency of inspecting and maintaining marine structures, contributing to their long-term performance management (see Figure 6). Table 5 summarizes key information on NDT methods used to monitor marine concrete structures [104–126].



**Figure 6.** Advanced non-destructive monitoring and inspection techniques for marine concrete structures: (a) Acoustic emission for crack detection; (b) Fiber optic sensors for structural health monitoring; (c) UAV-based remote sensing inspections; (d) Machine learning and AI for structural damage assessment; (e) Wireless sensor networks for real-time monitoring; (f) Digital image correlation for surface deformation analysis.

**Table 5.** Advanced monitoring technologies for marine concrete structures [104–126].

| Inspection Technique                     | Key Features                                                                          | Case Studies                                                                                               | Ref.      |
|------------------------------------------|---------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|-----------|
| Acoustic Emission (AE)                   | Detects high-frequency waves from microcracks and corrosion; real-time monitoring     | Successfully monitored damage progression in RC piles, providing detailed analysis of a 40-year-old bridge | [104–106] |
| Fiber Optic Sensors (FOS)                | Monitors deformation, temperature, and vibration with high sensitivity and durability | Applications include salinity detection and real-time chloride ion monitoring                              | [107–112] |
| Remote Sensing and UAV-Based Inspections | Monitors hard-to-reach areas with LiDAR, thermal imaging, and AI-based analysis       | Case studies demonstrated successful damage detection in harbors and underwater structures                 | [113–118] |
| Data Analysis                            | Predicts deterioration trends and analyzes damage patterns using advanced algorithms  | Techniques like AI-based ultrasound analysis and hybrid regression models showed high precision            | [119–121] |
| Wireless Sensor Networks (WSN)           | Real-time monitoring of chloride concentration, humidity, and strain; remote access   | Systems like CoCoMo and RFID-based tags provide accurate and energy-efficient monitoring                   | [122,123] |
| Digital Image Correlation (DIC)          | Non-contact method for precise analysis of surface deformation and crack propagation  | Combined DIC with other methods to evaluate marine concrete performance and corrosion mechanisms           | [124–126] |

Recent advancements in underwater concrete structure maintenance and monitoring technologies have led to significant improvements in both efficiency and accuracy. AE technology has shown high practicality by enabling early detection of damage, effectively tracking crack formation and corrosion in large-scale RC piles and aging bridges. Studies that combine AE data with physical and chemical evaluations have successfully analyzed the causes of damage—such as cracking, rebar corrosion, and CFRP debonding—but also highlighted challenges related to data interpretation expertise and ambient noise [104–106].

FOS demonstrate robust durability, providing long-term monitoring of key parameters like chloride concentration and operating reliably in marine conditions. Sensors with high selectivity for salt detection and alkaline environments have been particularly useful in accurately analyzing corrosion. However, high initial installation costs still limit their applicability to large-scale structures [107–112]. Drones and unmanned robots (UAVs and ROVs) enable structural assessments without direct human access, delivering cost savings and improved safety. Combined with AI-based data analysis, these systems rapidly detect cracks, delamination, and exposed rebar. Although UAVs excel at collecting large datasets in expansive structures such as ports, they are sensitive to weather conditions. On the other hand, ROVs can perform thorough underwater evaluations using ultrasound and rebound hammer tests, offering advantages in safety and efficiency [113–118]. Data analysis, machine learning (ML), and artificial intelligence (AI) technologies play a pivotal role in damage pattern prediction and maintenance strategy optimization. AI models leveraging ultrasonic data have classified corrosion caused by chloride ingress with greater accuracy than conventional methods, and YOLO-based models significantly improved damage detection by enhancing the resolution of image data. While these technologies facilitate detailed damage localization and deterioration rate predictions, challenges remain regarding complex model configurations and high computational costs [119–121]. Wireless sensor networks (WSN) contribute to enhanced maintenance efficiency by providing real-time detection of chloride penetration and strain levels. In particular, RFID-based sensor tags offer self-powered systems and extended communication ranges, making them suitable for marine structures; however, signal interference and network stability require further development before widespread adoption [122,123]. Digital image correlation (DIC) has become a critical tool for durability assessments, delivering precise analyses of crack propagation and stress distribution. Research combining DIC with X-ray CT has quantified stress expansion from corrosion, aiding in a clearer understanding of crack and corrosion mechanisms. Although these technologies enable durability assessments across diverse environments, their high equipment costs and lengthy data processing times hinder broader commercialization [124–126]. Overall, these technologies play an important role in damage detection and maintenance strategy optimization for marine concrete structures. Nevertheless, overcoming the limitations of each method, standardizing data interpretation, and improving cost-effectiveness are essential next steps. In the future, autonomous AI- and ML-driven solutions, eco-friendly and economical monitoring systems, and long-term performance validation are expected to become central to marine structure management.

### 3.3. Additional Repair Technologies for Marine Concrete Structures

This Section reviews various advanced technologies that have been applied to the monitoring and repair of real-world marine concrete structures. Developed to maintain performance and restore damage in underwater environments, these technologies are comprehensively summarized in Table 6, which outlines key examples, performance indicators, and experimental verification methods [116,127–132].

Epoxy coating technology, utilizing a Bisphenol-A-based coating, enhances bonding strength (1.26–3.21 MPa) and surface protection (coating thickness of 27–635  $\mu\text{m}$ ). Its performance has been validated through ASTM C1583 [133] pull-off tests, SEM analyses, and both laboratory and real-world marine conditions [127]. Wall-climbing robots can detect cracks and perform 3D restoration on structures such as bridge piers. Tested on 3682 underwater and above-water images, they achieved a detection accuracy of 0.867 and a processing speed of 21.76 FPS [128]. A small underwater robot equipped with a tool-exchange system demonstrated efficient repair via remote operation, with a positional error of up to  $5^\circ$  and a speed of 0.4 m/s validated through simulations and lab experiments [129].

**Table 6.** Repair and monitoring technologies for underwater concrete structures [116,127–132].

| Repair Technology                              | Case Studies                                                                                                                                                 | Performance Metrics                                                        | Validation Method                                                                                                | Refs  |
|------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------|-------|
| Epoxy Coating with BPA Resins                  | Underwater concrete repair using three methods: Roller (D1), Gun-type device (D2), Two-handed device (D3) under tap water, seawater, and real sea conditions | Bond strength: 1.26–3.21 MPa, Thickness: 27–635 $\mu\text{m}$              | ASTM C1583 pull-off test, SEM analysis, Real Sea and lab experiments                                             | [127] |
| Wall-climbing Robot                            | Underwater crack detection and 3D reconstruction in bridge piers                                                                                             | Detection accuracy: 0.867, 21.76 FPS                                       | Tested on 3682 images from underwater and air environments                                                       | [128] |
| Compact Underwater Robotic Tool Changer System | Utilized in underwater concrete repair for tool switching using ROV; tested in a controlled engineering pool with four light sources                         | Orientation error: within $5^\circ$ , Speed: $\leq 0.4$ m/s                | Simulation using ANSYS, Laboratory experiments with underwater docking system                                    | [129] |
| Aquanaut Transformable Subsea Vehicle          | Subsea inspection, maintenance, and repair operations; demonstrated at 3000 m depth without tether or surface vessel                                         | Manipulation precision: $\pm 5^\circ$ , Long-range AUV cruising            | Tested in tank environments, simulation trials, and real-world conditions                                        | [130] |
| YOLOX-DG Robotic Detection System              | Monitoring and damage detection of underwater concrete structures in Gouqi Island harbor, East China Sea                                                     | Detection accuracy: mAP 0.5: 78%, mAP 0.5:0.95: 58.5%                      | Real-site testing with robotic systems, 5-fold cross-validation, and comparison with YOLOv5 and Faster-RCNN      | [116] |
| CNN-Based Crack Detection Method               | Detection of cracks in PCCP pipelines under underwater conditions using high-precision robots                                                                | Accuracy: 97%, Precision: 96.1%, Recall: 98%, F-measure: 97.04%            | Tested on 4900 labeled images, 2000 iterations, confusion matrix analysis                                        | [131] |
| Underwater Robotic Manipulator Systems         | Concrete maintenance tasks such as subsea crack sealing, debris clearing, and valve operation on marine concrete structures                                  | Depth rating: up to 11,000 m, Payload: up to 500 kg, Precision: $\pm 5$ cm | Tested on marine concrete structures using commercial ROVs and simulations; validation with ISO subsea standards | [132] |

The transformable underwater vehicle “Aquanaut” can perform inspections and maintenance at depths of up to 3000 m with  $\pm 5^\circ$  operating precision, having undergone both laboratory and field testing [130]. Likewise, a robotic detection system called YOLOX-DG recorded 78% detection accuracy (mAP@0.5) and 58.5% (mAP@0.5:0.95) on underwater structures at Gouqi Island Port. Its performance was assessed in field tests and compared with YOLOv5 and Faster-RCNN [116]. A CNN-based crack detection technology accurately identified cracks in underwater PCCP pipes with 97% accuracy and 98% recall, verified using 4900 labeled images, 2000 iterative experiments, and confusion matrix analysis [131]. Finally, an underwater robot manipulator supporting depths of up to 11,000 m and a payload of 500 kg achieved  $\pm 5$  cm operating precision for tasks like crack sealing and debris removal, validated according to ISO standards [132].

While the technologies discussed in this Section demonstrate high reliability, some have yet to establish long-term performance verification in extreme marine environments and face commercialization barriers due to high costs. To further strengthen their reliability and practical viability, standardized evaluation systems and long-term performance assessments are needed.

### *3.4. Comparison of Conventional and Emerging Inspection Methods and Repair Strategies for Marine Concrete Structures*

Conventional NDT methods, such as visual inspection, ultrasonic pulse velocity, rebound hammer testing, and half-cell potential measurements, remain popular for examining marine concrete structures due to their accessibility, lower costs, and straightforward data interpretation. However, they often focus on surface-level assessments and can be subjective, relying heavily on inspector expertise and environmental conditions. In contrast, newer inspection technologies—including ground-penetrating radar, infrared thermography, digital image correlation, and sensor-based monitoring—offer enhanced detection of subsurface anomalies, real-time data collection, and high-resolution results, albeit at higher capital costs and with greater training requirements. Once issues are identified, a variety of repair technologies can be employed to address both immediate damage and long-term durability. Techniques such as electrochemical treatments (e.g., cathodic protection), surface coatings, crack injection, patch repairs, and structural reinforcements using fiber-reinforced polymers can arrest ongoing corrosion, minimize chloride ingress, and extend the service life of marine concrete. However, these approaches can be expensive, call for specialized skills, and must be carefully adapted to the harsh and variable conditions typical of marine environments. Ultimately, selecting the optimal combination of inspection and repair strategies should consider project-specific factors—such as budget, environmental constraints, and long-term performance goals—to ensure both immediate efficacy and long-lasting structural integrity.

## **4. Limitations and Future Studies**

Although considerable progress has been made in developing protective surface coatings and non-destructive inspection methods for concrete structures in marine environments, several key limitations and research gaps continue to warrant attention. Addressing these challenges will be crucial for ensuring the longevity and reliability of critical infrastructure such as ports, bridges, offshore platforms, and coastal defense systems.

Despite laboratory and short-term field experiments demonstrating the effectiveness of novel coatings (e.g., nanotechnology-enhanced, multi-layer, and bio-based systems) and inspection technologies, long-term performance data remain limited. Marine environments are inherently multifaceted, featuring cyclic loading, wet–dry cycles, salt spray, wave action, freeze–thaw cycles, and varying temperature gradients. Prolonged exposure to such conditions may degrade materials at rates or via mechanisms not fully captured by accelerated laboratory tests. Future research should thus prioritize extended field monitoring—potentially lasting five to ten years or more—in diverse marine locations. Additionally, comprehensive, standardized test protocols that simulate multiple marine stressors simultaneously (e.g., chloride–sulfate interaction, mechanical abrasion, and microbial activity) will help validate or refine current findings on coating durability and structural integrity.

State-of-the-art sensor technologies—such as FOS, AE systems, and WSNs—have significantly advanced real-time monitoring of concrete structures. However, their integration with protective coatings remains underexplored. Coatings can alter sensor readings by changing surface reflectivity, affecting temperature distribution, or influencing local humidity. Conversely, sensing technologies can optimize coating selection by detecting early signs of localized deterioration or coating delamination. Research that focuses on the synergy between next-generation coatings and embedded or surface-mounted sensors could substantially improve both protective and diagnostic capabilities, leading to a more holistic approach to structural health management.

Innovative coatings—especially those incorporating specialized nanomaterials, multiple layers, or biological components—often have higher production costs and require more complex application procedures. In parallel, emerging inspection methods (e.g., AI-guided drones, high-resolution LiDAR systems) necessitate expensive equipment and specialized training. These cost and operational challenges can impede large-scale adoption in publicly funded infrastructure projects with tight budgets. Future research should therefore explore cost-effective manufacturing methods, streamlined application protocols, and targeted repair or monitoring strategies designed to minimize resource usage. Collaboration between industry and research institutions can further facilitate the transition of these technologies from laboratory settings to real-world construction and maintenance scenarios.

The absence of unified standards and guidelines specific to marine-exposed concrete coatings and cutting-edge inspection methods poses a significant challenge. Although many globally recognized standards (e.g., ASTM, ISO) are available for generic coatings and testing procedures, they may not adequately address the unique chemical and mechanical demands of marine environments. Furthermore, new inspection methods—particularly those involving AI or machine learning—require standardized training datasets and validation protocols to ensure reliable interpretation. Collaborative efforts between researchers, standards organizations, and industry stakeholders are needed to develop specialized protocols for marine coating application, inspection-data interpretation, and maintenance decision-making.

In summary, the design and implementation of surface protection strategies and advanced monitoring techniques have significantly improved our ability to safeguard concrete structures against the harsh conditions of marine environments. Nevertheless, persistent challenges—including long-term performance validation, cost-effectiveness, integration of multiple technologies, and the need for standardized evaluation—must be addressed. By tackling these limitations through interdisciplinary research and broader collaboration among academia, industry, and regulatory bodies, the field can move toward more robust, eco-friendly, and cost-efficient solutions that ensure the safety and sustainability of marine concrete infrastructure well into the future.

## 5. Conclusions

This review highlights that advancements in protective surface coatings and non-destructive inspection (NDI) technologies are critical for extending the service life and durability of marine concrete structures. The following key conclusions can be drawn:

1. Recent progress in polymer-based systems, hybrid coatings, and nanotechnology-enhanced materials has significantly improved resistance to chloride ingress, sulfate exposure, and moisture penetration. Enhanced application techniques and rigorous quality control further bolster their effectiveness and longevity, making coatings a vital strategy for mitigating environmental stressors.
2. Conventional NDI methods—such as ground-penetrating radar, infrared thermography, acoustic emission monitoring, and electrochemical sensors—reliably provide non-invasive assessments of structural integrity. These technologies facilitate early damage detection, monitor corrosion processes, and offer valuable insights into coating performance.
3. The fusion of advanced protective coatings with real-time monitoring systems holds considerable potential for improving structural durability. Emerging research on embedding sensors within coatings may lead to optimized protection and diagnostic capabilities, enabling a holistic approach to infrastructure health management.
4. Concrete deterioration in marine environments entails substantial economic costs associated with repair, maintenance, and service disruptions. Eco-friendly options, in-

- cluding bio-based and nanotechnology-enhanced coatings, present viable, sustainable solutions aligned with modern environmental standards while reducing long-term expenses.
5. Although laboratory studies and short-term field tests show promising results, long-term performance data across diverse real-world conditions remain limited. The lack of unified standards specific to marine applications, coupled with high initial costs and complex implementation procedures, hampers widespread adoption.
  6. To address these gaps, future work should emphasize both advanced experimental investigations and refined numerical simulations. Large-scale field trials, coupled with accelerated aging experiments and sophisticated computational models, can provide deeper insights into the long-term behavior of protective coatings. Additionally, implementing machine learning or artificial intelligence frameworks could help predict coating performance and degradation processes, guiding more effective maintenance strategies.

In summary, this review underscores the transformative potential of next-generation protective coatings and inspection technologies to resolve the durability challenges of marine concrete structures. By expanding research efforts to include both cutting-edge experimental methods and robust numerical models, the field can ultimately ensure the sustainability, safety, and resilience of vital coastal and offshore infrastructure.

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## References

1. Yang, Z.; Barroca, B.; Laffréchine, K.; Weppe, A.; Bony-Dandrieux, A.; Daclin, N. A Multi-Criteria Framework for Critical Infrastructure Systems Resilience. *Int. J. Crit. Infrastruct. Prot.* **2023**, *42*, 100616. [\[CrossRef\]](#)
2. Cadenazzi, T.; Lee, H.; Suraneni, P.; Nolan, S.; Nanni, A. Evaluation of Probabilistic and Deterministic Life-Cycle Cost Analyses for Concrete Bridges Exposed to Chlorides. *Clean. Eng. Technol.* **2021**, *4*, 100247. [\[CrossRef\]](#)
3. Melchers, R.E.; Chaves, I.A. Durability of reinforced concrete bridges in marine environments. *Struct. Infrastruct. Eng.* **2019**, *16*, 169–180. [\[CrossRef\]](#)
4. Krivy, V.; Kuzmova, M.; Kreislova, K.; Urban, V. Characterization of corrosion products on weathering steel bridges influenced by chloride deposition. *Metals* **2017**, *7*, 336. [\[CrossRef\]](#)
5. Cavaco, E.S.; Neves, L.A.C.; Casas, J.R. On the robustness to corrosion in the life cycle assessment of an existing reinforced concrete bridge. *Struct. Infrastruct. Eng.* **2018**, *14*, 137–150. [\[CrossRef\]](#)
6. Andisheh, K.; Scott, A.; Palermo, A.; Clucas, D. Influence of chloride corrosion on the effective mechanical properties of steel reinforcement. *Struct. Infrastruct. Eng.* **2019**, *15*, 1036–1048. [\[CrossRef\]](#)
7. Yi, Y.; Zhu, D.; Guo, S.; Zhang, Z.; Shi, C. A review on the deterioration and approaches to enhance the durability of concrete in the marine environment. *Cem. Concr. Compos.* **2020**, *113*, 103695. [\[CrossRef\]](#)
8. Atahan, H.N.; Dikme, D. Use of mineral admixtures for enhanced resistance against sulfate attack. *Constr. Build. Mater.* **2011**, *25*, 3450–3457. [\[CrossRef\]](#)
9. Irassar, E.F. Sulfate attack on cementitious materials containing limestone filler—A review. *Cem. Concr. Res.* **2009**, *39*, 241–254. [\[CrossRef\]](#)

10. Fan, Y.; Zhang, S.; Wang, Q.; Shah, S.P. Effects of nano-kaolinite clay on the freeze–thaw resistance of concrete. *Cem. Concr. Compos.* **2015**, *62*, 1–12. [\[CrossRef\]](#)
11. Kazmi, S.M.S.; Munir, M.J.; Wu, Y.-F.; Patnaikuni, I.; Zhou, Y.; Xing, F. Effect of different aggregate treatment techniques on the freeze-thaw and sulfate resistance of recycled aggregate concrete. *Cold Reg. Sci. Technol.* **2020**, *178*, 103126. [\[CrossRef\]](#)
12. Zhang, M.H.; Xu, R.H.; Liu, K.; Sun, S.H. Research progress on durability of marine concrete under the combined action of Cl<sup>−</sup> erosion, carbonation, and dry–wet cycles. *Rev. Adv. Mater. Sci.* **2022**, *61*, 622–637. [\[CrossRef\]](#)
13. Ma, D.; Zhang, M.; Cui, J. A review on the deterioration of mechanical and durability performance of marine-concrete under the scouring action. *J. Build. Eng.* **2023**, *66*, 105924. [\[CrossRef\]](#)
14. Mehta, P.K. Durability of Concrete Exposed to Marine Environment—A Fresh Look. *ACI Struct. J.* **1988**, *109*, 1–30.
15. Francois, R.; Arliguie, G. Effect of microcracking and cracking on the development of corrosion in reinforced concrete members. *Mag. Concr. Res.* **1999**, *51*, 143–150. [\[CrossRef\]](#)
16. Costa, A.; Appleton, J. Case studies of concrete deterioration in a marine environment in Portugal. *Cem. Concr. Compos.* **2002**, *24*, 169–179. [\[CrossRef\]](#)
17. Capacci, L.; Biondini, F.; Frangopol, D.M. Resilience of Aging Structures and Infrastructure Systems with Emphasis on Seismic Resilience of Bridges and Road Networks: Review. *Resilient Cities Struct.* **2022**, *1*, 23–41. [\[CrossRef\]](#)
18. Yang, Z.; Clemente, M.F.; Laffréchine, K.; Heinzlef, C.; Serre, D.; Barroca, B. Resilience of Social-Infrastructural Systems: Functional Interdependencies Analysis. *Sustainability* **2022**, *14*, 606. [\[CrossRef\]](#)
19. Rincon, L.F.; Moscoso, Y.M.; Hamami, A.E.A.; Matos, J.C.; Bastidas-Arteaga, E. Degradation Models and Maintenance Strategies for Reinforced Concrete Structures in Coastal Environments under Climate Change: A Review. *Buildings* **2024**, *14*, 562. [\[CrossRef\]](#)
20. Rizzo, P. Sensing solutions for assessing and monitoring underwater systems. *Sens. Technol. Civ. Infrastruct.* **2014**, *2*, 525–549.
21. Gharehbaghi, V.R.; Noroozinejad Farsangi, E.; Noori, M.; Yang, T.; Li, S.; Nguyen, A.; Málaga-Chuquitaype, C.; Gardoni, P.; Mirjalili, S. A critical review on structural health monitoring: Definitions, methods, and perspectives. *Arch. Comput. Methods Eng.* **2021**, *29*, 2209–2235. [\[CrossRef\]](#)
22. Boldrin, P.; Fornasari, G.; Rizzo, E. Review of Ground Penetrating Radar Applications for Bridge Infrastructures. *NDT* **2024**, *2*, 53–75. [\[CrossRef\]](#)
23. Palma, V.; Iovane, G.; Hwang, S.; Mazzolani, F.M.; Landolfo, R.; Sohn, H.; Faggiano, B. Innovative Technologies for Structural Health Monitoring of SFTs: Proposal of Combination of Infrared Thermography with Mixed Reality. *J. Civ. Struct. Health Monit.* **2023**, *13*, 1653–1681. [\[CrossRef\]](#)
24. Anastasopoulos, A.; Kourousis, D.; Botten, S.; Wang, G. Acoustic emission monitoring for detecting structural defects in vessels and offshore structures. *Ships Offshore Struct.* **2009**, *4*, 363–372. [\[CrossRef\]](#)
25. Jeong, J.-A.; Jin, C.-K.; Kim, Y.-H.; Chung, W.-S. Electrochemical Performance Evaluation of Corrosion Monitoring Sensor for Reinforced Concrete Structures. *J. Adv. Concr. Technol.* **2013**, *11*, 1–6. [\[CrossRef\]](#)
26. Verma, S.; Mohanty, S.; Nayak, S. A review on protective polymeric coatings for marine applications. *J. Coat. Technol. Res.* **2019**, *16*, 307–338. [\[CrossRef\]](#)
27. Thomas, C.; Lombillo, I.; Polanco, J.A.; Villegas, L.; Setien, J.; Biezma, M.V. Polymeric and cementitious mortars for the reconstruction of natural stone structures exposed to marine environments. *Compos. Part B* **2010**, *41*, 663–672. [\[CrossRef\]](#)
28. Esteban-Arranz, A.; de la Osa, A.R.; García-Lorefice, W.E.; Sacristan, J.; Sánchez-Silva, L. Long-Term Performance of Nanomodified Coated Concrete Structures under Hostile Marine Climate Conditions. *Nanomaterials* **2021**, *11*, 869. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Lorwanishpaisarn, N.; Srikhao, N.; Jetsrisuparb, K.; Knijnenburg, J.T.N.; Theerakulpisut, S.; Okhawilai, M.; Kasemsiri, P. Self-healing Ability of Epoxy Vitrimers Nanocomposites Containing Bio-Based Curing Agents and Carbon Nanotubes for Corrosion Protection. *J. Polym. Environ.* **2022**, *30*, 472–482. [\[CrossRef\]](#)
30. Santos, D.S.; Santos, P.M.D.; Dias-da-Costa, D. Effect of surface preparation and bonding agent on the concrete-to-concrete interface strength. *Constr. Build. Mater.* **2012**, *37*, 102–110. [\[CrossRef\]](#)
31. Yazdi, M.A.; Dejager, E.; Debraekeleer, M.; Gruyaert, E. Bond strength between concrete and repair mortar and its relation with concrete removal techniques and substrate composition. *Constr. Build. Mater.* **2020**, *230*, 116900. [\[CrossRef\]](#)
32. Momayez, A.; Ehsani, M.R.; Ramezani-pour, A.A.; Rajaie, H. Comparison of methods for evaluating bond strength between concrete substrate and repair materials. *Constr. Build. Mater.* **2005**, *35*, 748–757. [\[CrossRef\]](#)
33. Zhang, Y.; Zhu, P.; Liao, Z.Q.; Wang, L. Interfacial bond properties between normal strength concrete substrate and ultra-high performance concrete as a repair material. *Constr. Build. Mater.* **2020**, *235*, 117431. [\[CrossRef\]](#)
34. Kim, S.; Hong, H.; Han, T.H.; Kim, M.O. Early-age tensile bond characteristics of epoxy coatings for underwater applications. *Coatings* **2019**, *9*, 757. [\[CrossRef\]](#)
35. Yang, X.F.; Tallman, D.; Bierwagen, G.; Croll, S.; Rohlik, S. Blistering and degradation of polyurethane coatings under different accelerated weathering tests. *Polym. Degrad. Stab.* **2002**, *77*, 103–109. [\[CrossRef\]](#)
36. Luo, S.; Wei, J.; Xu, W.; Chen, Y.; Huang, H.; Hu, J.; Yu, Q. Design, preparation, and performance of a novel organic–inorganic composite coating with high adhesion and protection for concrete. *Compos. Part B Eng.* **2022**, *234*, 109695. [\[CrossRef\]](#)

37. Lam, H.T.; Zupančič, O.; Laffleur, F.; Bernkop-Schnürch, A. Mucoadhesive properties of polyacrylates: Structure–function relationship. *Int. J. Adhes. Adhes.* **2021**, *107*, 102857. [\[CrossRef\]](#)
38. Armelin, E.; Oliver, R.; Liesa, F.; Iribarren, J.I.; Estrany, F.; Alemán, C. Marine paint formulations: Conducting polymers as anticorrosive additives. *Prog. Org. Coat.* **2007**, *59*, 46–52. [\[CrossRef\]](#)
39. Safiuddin, M. Concrete damage in field conditions and protective sealer and coating systems. *Coatings* **2017**, *7*, 90. [\[CrossRef\]](#)
40. Moradillo, M.K.; Shekarchi, M.; Hoseini, M. Time-dependent performance of concrete surface coatings in tidal zone of marine environment. *Constr. Build. Mater.* **2012**, *30*, 198–205. [\[CrossRef\]](#)
41. Sadati, S.; Arezoumandi, M.; Shekarchi, M. Long-term performance of concrete surface coatings in soil exposure of marine environments. *Constr. Build. Mater.* **2015**, *94*, 656–663. [\[CrossRef\]](#)
42. Medeiros, M.H.; Helene, P. Surface treatment of reinforced concrete in marine environment: Influence on chloride diffusion coefficient and capillary water absorption. *Constr. Build. Mater.* **2009**, *23*, 1476–1484. [\[CrossRef\]](#)
43. Lu, S.; Zhao, P.; Liang, C.; Liu, L.; Qin, Z.; Wang, S.; Hou, P.; Lu, L. Utilization of polydimethylsiloxane (PDMS) in polymer cement-based coating to improve marine environment service performance. *Constr. Build. Mater.* **2023**, *367*, 130359. [\[CrossRef\]](#)
44. Liang, C.; Zhao, P.; Gong, X.; Liu, H.; Yang, L.; Li, Q.; Lu, L. Investigation on the mechanical properties of CSA cement-based coating and its application. *Constr. Build. Mater.* **2021**, *305*, 124724. [\[CrossRef\]](#)
45. Bi, H.; Zhang, W.; Xu, X.; Ming, A.; Shen, Y.; Wang, S.; Cheng, X. Chloride binding and transport characteristic of phosphoaluminate cement-based marine sand coating subjected to marine environment. *Constr. Build. Mater.* **2021**, *281*, 122505. [\[CrossRef\]](#)
46. Xue, X.; Yang, J.; Zhang, W.; Jiang, L.; Qu, J.; Xu, L.; Zhang, H.; Song, J.; Zhang, R.; Li, Y. The study of an energy efficient cool white roof coating based on styrene acrylate copolymer and cement for waterproofing purpose—Part I: Optical properties, estimated cooling effect and relevant properties after dirt and accelerated exposures. *Constr. Build. Mater.* **2015**, *98*, 176–184. [\[CrossRef\]](#)
47. Xue, X.; Yang, J.; Zhang, W.; Jiang, L.; Qu, J.; Xu, L.; Zhang, H.; Song, J.; Zhang, R.; Li, Y. The study of an energy efficient cool white roof coating based on styrene acrylate copolymer and cement for waterproofing purpose—Part II: Mechanical and water impermeability properties. *Constr. Build. Mater.* **2015**, *96*, 666–672. [\[CrossRef\]](#)
48. Zhao, Z.; Qu, X.; Li, J. Application of polymer modified cementitious coatings (PCCs) for impermeability enhancement of concrete. *Constr. Build. Mater.* **2020**, *249*, 118769. [\[CrossRef\]](#)
49. Guo, S.-Y.; Zhang, X.; Chen, J.-Z.; Mou, B.; Shang, H.-S.; Wang, P.; Zhang, L.; Ren, J. Mechanical and interface bonding properties of epoxy resin reinforced Portland cement repairing mortar. *Constr. Build. Mater.* **2020**, *264*, 120715. [\[CrossRef\]](#)
50. Zhao, P.; Wang, H.; Wang, S.; Du, P.; Lu, L.; Cheng, X. Assessment of nano-TiO<sub>2</sub> enhanced performance for photocatalytic polymer-sulphoaluminate cement composite coating. *J. Inorg. Organomet. Polym. Mater.* **2018**, *28*, 2439–2446. [\[CrossRef\]](#)
51. Sadati, S.; Khanzadeh Moradillo, M.; Shekarchi, M. Long-term performance of silica fume concrete in soil exposure of marine environments. *J. Mater. Civ. Eng.* **2017**, *29*, 04017126. [\[CrossRef\]](#)
52. Elnaggar, E.M.; Elsokkary, T.M.; Shohide, M.A.; El-Sabbagh, B.A.; Abdel-Gawwad, H.A. Surface protection of concrete by new protective coating. *Constr. Build. Mater.* **2019**, *220*, 245–252. [\[CrossRef\]](#)
53. Mellott, I.J.W.; Smith, J.D. Polyurethane Dispersions in an Aqueous Asphalt Emulsion. U.S. Patent US20090069460A1, 27 April 2010.
54. Hernandez, P.; Peters, S.R. Water-Based Asphalt Coating Composition. U.S. Patent US20090251969A1, 17 February 2009.
55. Bonnet, E.; Martin, L. Compositions Based on Aqueous Dispersions of Bitumen and Polyurethane: Method for the Preparation Thereof and Uses Thereof. U.S. Patent Application No. 10/504,827, 9 June 2005.
56. Pérez-Lepe, A.; Martínez-Boza, F.; Attané, P.; Gallegos, C. Destabilization mechanism of polyethylene-modified bitumen. *J. Appl. Polym. Sci.* **2006**, *100*, 260–267. [\[CrossRef\]](#)
57. ElSawy, M.; Taher, M.; Ebrahime, A.A.; Farag, R.K.; Saleh, A. Improvement performance of soft asphalt for coating applications. *Constr. Build. Mater.* **2016**, *128*, 47–56. [\[CrossRef\]](#)
58. Razali, M.N.; Ramli, N.M.; Zuhair, K.N.M.; Musa, M.; Nour, A.H. Coating and insulation effect using emulsified modification bitumen. *Constr. Build. Mater.* **2020**, *260*, 119764. [\[CrossRef\]](#)
59. Yin, B.; Zhao, E.; Hua, X.; Xu, H.; Fan, F.; Qi, D.; Hua, X.; Zhen, J.; Hou, D. Polymer functional coatings modified by ZrP-based composites: Preparation and applications on marine concrete. *J. Appl. Polym. Sci.* **2022**, *139*, e52384. [\[CrossRef\]](#)
60. Yang, S.; Zhu, S.; Hong, R. Graphene oxide/polyaniline nanocomposites used in anticorrosive coatings for environmental protection. *Coatings* **2020**, *10*, 1215. [\[CrossRef\]](#)
61. Atta, A.M.; El-Saeed, A.M.; Al-Lohedan, H.A.; Wahby, M. Effect of montmorillonite nanogel composite fillers on the protection performance of epoxy coatings on steel pipelines. *Molecules* **2017**, *22*, 905. [\[CrossRef\]](#)
62. Chang, J.; Wang, Z.; Han, E.-H.; Liang, X.; Wang, G.; Yi, Z.; Li, N. Corrosion resistance of tannic acid, d-limonene, and nano-ZrO<sub>2</sub> modified epoxy coatings in acid corrosion environments. *J. Mater. Sci. Technol.* **2021**, *65*, 137–150. [\[CrossRef\]](#)
63. Yin, B.; Zhang, L.; Li, J.; Liu, T. Change in interfacial properties of polymer antifouling coating by controlling ring architecture of functional nanocomposites. *Mater. Res. Express* **2014**, *1*, 045505. [\[CrossRef\]](#)

64. Li, G.; Hu, W.; Cui, H.; Zhou, J. Long-term effectiveness of carbonation resistance of concrete treated with nano-SiO<sub>2</sub> modified polymer coatings. *Constr. Build. Mater.* **2019**, *201*, 623–630. [\[CrossRef\]](#)
65. Corcione, C.E.; Striani, R.; Capone, C.; Molfetta, M.; Vendetta, S.; Frigione, M. Preliminary study of the application of a novel hydrophobic photo-polymerizable nano-structured coating on concrete substrates. *Prog. Org. Coat.* **2018**, *121*, 182–189. [\[CrossRef\]](#)
66. Woo, R.S.; Zhu, H.; Chow, M.M.; Leung, C.K.; Kim, J.-K. Barrier performance of silane–clay nanocomposite coatings on concrete structure. *Compos. Sci. Technol.* **2008**, *68*, 2828–2836. [\[CrossRef\]](#)
67. Kim, J.; Choi, I. A Study on the Improvement of Multi-Layer Coating Methods for Molded Concrete. *J. Korean Inst. Build. Constr.* **2003**, *3*, 93–105.
68. Lee, M.K.; Kim, D.; Kim, M.O. Experimental Study on the Chlorine-Induced Corrosion and Blister Formation of Steel Pipes Coated with Modified Polyethylene Powder. *Polymers* **2024**, *16*, 2415. [\[CrossRef\]](#) [\[PubMed\]](#)
69. Gu, W.; Liu, R.; Zhang, Y.; Yu, X.; Feng, P.; Ran, Q.; Zhang, Y.; Zhang, Y. Robust water-borne multi-layered superhydrophobic coating on concrete with ultra-low permeability. *Constr. Build. Mater.* **2024**, *411*, 134573. [\[CrossRef\]](#)
70. Radwan, S.; Winfrey, L.; Bourham, M. Simulation of particle impact on protective coating of high-level waste storage packages. *Prog. Nucl. Energy* **2015**, *81*, 196–202. [\[CrossRef\]](#)
71. Fusco, M.A.; Winfrey, L.; Bourham, M.A. Shielding properties of protective thin film coatings and blended concrete compositions for high level waste storage packages. *Ann. Nucl. Energy* **2016**, *89*, 63–69. [\[CrossRef\]](#)
72. Winfrey, L. *Enhanced Shielding Performance of HLW Storage Packages via Multi-Component Coatings*; Virginia Polytechnic Institute and State University (Virginia Tech): Blacksburg, VA, USA, 2017.
73. Eom, S.-H.; Kim, S.-S.; Lee, J.-B. Assessment of anti-corrosion performances of coating systems for corrosion prevention of offshore wind power steel structures. *Coatings* **2020**, *10*, 970. [\[CrossRef\]](#)
74. Schmidt, M.J.; Li, L.; Spencer, J.T. Characteristics of high power diode laser removal of multilayer chlorinated rubber coatings from concrete surfaces. *Opt. Laser Technol.* **1999**, *31*, 171–180. [\[CrossRef\]](#)
75. Yin, B.; Xu, T.; Hou, D.; Zhao, E.; Hua, X.; Han, K.; Zhang, Y.; Zhang, J. Superhydrophobic anticorrosive coating for concrete through in-situ bionic induction and gradient mineralization. *Constr. Build. Mater.* **2020**, *257*, 119510. [\[CrossRef\]](#)
76. Ren, Y.; Cao, H.; Xu, H.; Xiong, X.; Krastev, R.; Liu, L. Improved aging properties of bio-bitumen coating sheets by using modified lignin. *J. Environ. Manag.* **2020**, *274*, 111178. [\[CrossRef\]](#) [\[PubMed\]](#)
77. Lv, J.; Cao, Z.; Hu, X. Effect of biological coating (*Crassostrea gigas*) on marine concrete: Enhanced durability and mechanisms. *Constr. Build. Mater.* **2021**, *285*, 122914. [\[CrossRef\]](#)
78. Coombes, M.A.; Viles, H.A.; Naylor, L.A.; La Marca, E.C. Cool barnacles: Do common biogenic structures enhance or retard rates of deterioration of intertidal rocks and concrete? *Sci. Total Environ.* **2017**, *580*, 1034–1045. [\[CrossRef\]](#) [\[PubMed\]](#)
79. Chlayon, T.; Iwanami, M.; Chijiwa, N. Combined protective action of barnacles and biofilm on concrete surface in intertidal areas. *Constr. Build. Mater.* **2018**, *179*, 477–487. [\[CrossRef\]](#)
80. Chlayon, T.; Iwanami, M.; Chijiwa, N. Impacts from concrete microstructure and surface on the settlement of sessile organisms affecting chloride attack. *Constr. Build. Mater.* **2020**, *239*, 117863. [\[CrossRef\]](#)
81. Lv, J.; Mao, J.; Ba, H. Influence of *Crassostrea gigas* on the permeability and microstructure of the surface layer of concrete exposed to the tidal zone of the Yellow Sea. *Biofouling* **2015**, *31*, 61–70. [\[CrossRef\]](#) [\[PubMed\]](#)
82. Lv, J.; Mao, J.; Ba, H. Influence of marine microorganisms on the permeability and microstructure of mortar. *Constr. Build. Mater.* **2015**, *77*, 33–40. [\[CrossRef\]](#)
83. Loreto, G.; Di Benedetti, M.; De Luca, A.; Nanni, A. Assessment of Reinforced Concrete Structures in Marine Environment: A Case Study. *Corros. Rev.* **2019**, *37*, 57–69. [\[CrossRef\]](#)
84. Pushpakumara, B.H.J.; Thusitha, G.A. Development of a Structural Health Monitoring Tool for Underwater Concrete Structures. *J. Constr. Eng. Manag.* **2021**, *147*, 04021135. [\[CrossRef\]](#)
85. Osuji, S.O.; Ogirigbo, O.R.; Atakere, F.U.O. Assessment of the Condition of an Existing Marine Concrete Structure in the Niger Delta Region of Nigeria. *J. Civ. Eng. Res.* **2020**, *10*, 63–71.
86. Celerinos, P.J.S.; Frigillana, S.J.; Jonielle, J.; Grande, D.; Ali, N.G.; Navarro, J.A.C.; Navarro, J.A.C. Influence of Seawater Exposure at the Splash Zone on the Reliability of the Rebound Hammer Test in Estimating Concrete Compressive Strength. *Res. Eng. Struct. Mater.* **2023**, *9*, 947–967. [\[CrossRef\]](#)
87. Law, D.; Patrisia, Y.; Gunasekara, C.; Castel, A.; Nguyen, Q.D.; Wardhono, A. Durability Assessment of Alkali-Activated Concrete Exposed to a Marine Environment. *J. Mater. Civ. Eng.* **2023**, *35*, 04023275. [\[CrossRef\]](#)
88. Villain, G.; Sbartaï, Z.M.; Dérobert, X.; Garnier, V.; Balayssac, J.P. Durability Diagnosis of a Concrete Structure in a Tidal Zone by Combining NDT Methods: Laboratory Tests and Case Study. *Constr. Build. Mater.* **2012**, *37*, 893–903. [\[CrossRef\]](#)
89. Sharma, S.; Mukherjee, A. Monitoring Corrosion in Oxide and Chloride Environments Using Ultrasonic Guided Waves. *J. Mater. Civ. Eng.* **2011**, *23*, 207–211. [\[CrossRef\]](#)
90. Martín, J.E.T.; Ramos, N.R.; Chinchón-Payá, S.; Arcila, I.H.; Toledo, A.S.; Montero, J.S.; de Haan, L. Durability of a Reinforced Concrete Structure Exposed to Marine Environment at the Málaga Dock. *Case Stud. Constr. Mater.* **2022**, *17*, e01582.

91. Darmawan, M.S.; Bayuaji, R.; Anugraha, R.B.; Saputra, D.A.; Victoriawan, M.A. Case Study of Performance of a Jetty Structure after 25 Years of Exposure in a Marine Environment Considering Earthquake Load. *Eng. Fail. Anal.* **2024**, *156*, 107831. [[CrossRef](#)]
92. Bayuaji, R.; Darmawan, M.S.; Husin, N.A.; Anugraha, R.B.; Budipriyanto, A.; Stewart, M.G. Corrosion Damage Assessment of a Reinforced Concrete Canal Structure of Power Plant after 20 Years of Exposure in a Marine Environment: A Case Study. *Eng. Fail. Anal.* **2018**, *84*, 287–299. [[CrossRef](#)]
93. Malikov, A.K.U.; Kim, Y.H.; Yi, J.H.; Kim, J.; Zhang, J.; Cho, Y. Neural-Network-Based Ultrasonic Inspection of Offshore Coated Concrete Specimens. *Coatings* **2022**, *12*, 773. [[CrossRef](#)]
94. Fenning, P.J.; McCann, D.M. Sea Defences: Geophysical and NDT Investigation Techniques. *NDT E Int.* **1995**, *28*, 359–366. [[CrossRef](#)]
95. Quinn, J.A.; Patsia, O.; Giannopoulos, A.; Brádaigh, C.M.Ó.; McCarthy, E.D. Novel Application of Ground Penetrating Radar for Damage Detection in Thick FRP Composites. *Compos. Part B Eng.* **2024**, *284*, 111716. [[CrossRef](#)]
96. Annan, A.P. Electromagnetic Principles of Ground Penetrating Radar. In *Ground Penetrating Radar: Theory and Applications*; Jol, H.M., Ed.; Elsevier: Amsterdam, The Netherlands, 2009; Volume 1, pp. 3–41.
97. Xu, X.; Wu, J.; Shen, J.; He, Z. Case Study: Application of GPR to Detection of Hidden Dangers to Underwater Hydraulic Structures. *J. Hydraul. Eng.* **2006**, *132*, 12–20. [[CrossRef](#)]
98. Ludeno, G.; Capozzoli, L.; Rizzo, E.; Soldovieri, F.; Catapano, I. A Microwave Tomography Strategy for Underwater Imaging via Ground Penetrating Radar. *Remote Sens.* **2018**, *10*, 1410. [[CrossRef](#)]
99. Bagavathiappan, S.; Lahiri, B.B.; Saravanan, T.; Philip, J.; Jayakumar, T. Infrared Thermography for Condition Monitoring—A Review. *Infrared Phys. Technol.* **2013**, *60*, 35–55. [[CrossRef](#)]
100. Goffin, B.; Banthia, N.; Yonemitsu, N. Use of Infrared Thermal Imaging to Detect Corrosion of Epoxy Coated and Uncoated Rebar in Concrete. *Constr. Build. Mater.* **2020**, *263*, 120162. [[CrossRef](#)]
101. Nguyen, T.; Martin, J.W. Modes and Mechanisms for the Degradation of Fusion-Bonded Epoxy-Coated Steel in a Marine Concrete Environment. *JCT Res.* **2004**, *1*, 81–92. [[CrossRef](#)]
102. Sindhu, R.; Joseph, R. Half-Cell Potentiostatic Study of Reinforced Concrete in Marine Environment. *Pak. J. Biotechnol.* **2018**, *15*, 917–919.
103. Ahn, W.; Reddy, D.V. Galvanostatic Testing for the Durability of Marine Concrete under Fatigue Loading. *Cem. Concr. Res.* **2001**, *31*, 343–349. [[CrossRef](#)]
104. Zheng, Y.; Zhou, Y.; Zhou, Y.; Pan, T.; Sun, L.; Liu, D. Localized Corrosion-Induced Damage Monitoring of Large-Scale RC Piles Using Acoustic Emission Technique in the Marine Environment. *Constr. Build. Mater.* **2020**, *243*, 118270. [[CrossRef](#)]
105. Suma, A.B.; Ferraro, R.M.; Metrovich, B.; Matta, F.; Nanni, A. Nondestructive Evaluation Techniques and Acoustic Emission for Damage Assessment of Concrete Bridge in Marine Environment. *Spec. Publ.* **2011**, *277*, 109–128.
106. Guo, R.; Zhang, X.; Lin, X.; Huang, S. Active and Passive Monitoring of Corrosion State of Reinforced Concrete Based on Embedded Cement-Based Acoustic Emission Sensor. *J. Build. Eng.* **2024**, *89*, 109276. [[CrossRef](#)]
107. Chen, S.; Wang, J.; Zhang, C.; Li, M.; Li, N.; Wu, H.; Song, Y. Marine Structural Health Monitoring with Optical Fiber Sensors: A Review. *Sensors* **2023**, *23*, 1877. [[CrossRef](#)] [[PubMed](#)]
108. Alwis, L.S.; Bremer, K.; Roth, B. Fiber Optic Sensors Embedded in Textile-Reinforced Concrete for Smart Structural Health Monitoring: A Review. *Sensors* **2021**, *21*, 4948. [[CrossRef](#)] [[PubMed](#)]
109. Kumari, C.U.; Samiappan, D.; Kumar, R.; Sudhakar, T. Fiber Optic Sensors in Ocean Observation: A Comprehensive Review. *Optik* **2019**, *179*, 351–360. [[CrossRef](#)]
110. Tang, F.; Zhou, G.; Li, H.N.; Verstrynge, E. A Review on Fiber Optic Sensors for Rebar Corrosion Monitoring in RC Structures. *Constr. Build. Mater.* **2021**, *313*, 125578. [[CrossRef](#)]
111. Luo, D.; Li, P.; Yue, Y.; Ma, J.; Yang, H. In-Fiber Optic Salinity Sensing: A Potential Application for Offshore Concrete Structure Protection. *Sensors* **2017**, *17*, 962. [[CrossRef](#)]
112. Lin, Z.; Ouyang, Q.; Guo, C.; Ni, Y. Fluorescent Probe-Based Fiber Optic Sensor for Real-Time Monitoring of Chloride Ions in Coastal Concrete Structures. *Sensors* **2024**, *24*, 3700. [[CrossRef](#)] [[PubMed](#)]
113. Halder, S.; Afsari, K. Robots in Inspection and Monitoring of Buildings and Infrastructure: A Systematic Review. *Appl. Sci.* **2023**, *13*, 2304. [[CrossRef](#)]
114. Waldner, J.F.; Sadhu, A. A Systematic Literature Review of Unmanned Underwater Vehicle-Based Structural Health Monitoring Technologies. *J. Infrastruct. Intell. Resil.* **2024**, *3*, 100112. [[CrossRef](#)]
115. Tsaimou, C.N.; Sartampakos, P.; Tsoukala, V.K. UAV-Driven Approach for Assisting Structural Health Monitoring of Port Infrastructure. *Struct. Infrastruct. Eng.* **2023**, 1–20. [[CrossRef](#)]
116. Zhang, C.; Ma, H.; Chen, Z.; Li, S.; Ma, Z.; Huang, H.; Zhu, R.; Jiao, P. YOLOX-DG Robotic Detection Systems for Large-Scale Underwater Concrete Structures. *iScience* **2024**, *27*, 109337. [[CrossRef](#)] [[PubMed](#)]
117. Chen, D.; Huang, B.; Kang, F. A Review of Detection Technologies for Underwater Cracks on Concrete Dam Surfaces. *Appl. Sci.* **2023**, *13*, 3564. [[CrossRef](#)]

118. Venkatesh, V.; Kodoth, K.; Jacob, A.A.; Upadhyay, V.; Ravichandran, S.; Rajagopal, P.; Balasubramaniam, K. Assessment of Structural Integrity of Submerged Concrete Structures Using Quantitative Non-Destructive Techniques Deployed from Remotely Operated Underwater Vehicles (ROV). In Proceedings of the OCEANS 2022-Chennai, Chennai, India, 21–24 February 2022; IEEE: New York, NY, USA, 2022; pp. 1–6.
119. Mukhti, J.A.; Gucunski, N.; Kee, S.H. AI-Assisted Ultrasonic Wave Analysis for Automated Classification of Steel Corrosion-Induced Concrete Damage. *Autom. Constr.* **2024**, *167*, 105704. [[CrossRef](#)]
120. Ye, X.; Luo, K.; Wang, H.; Zhao, Y.; Zhang, J.; Liu, A. An Advanced AI-Based Lightweight Two-Stage Underwater Structural Damage Detection Model. *Adv. Eng. Inform.* **2024**, *62*, 102553. [[CrossRef](#)]
121. Chou, J.S.; Ngo, N.T.; Chong, W.K. The Use of Artificial Intelligence Combiners for Modeling Steel Pitting Risk and Corrosion Rate. *Eng. Appl. Artif. Intell.* **2017**, *65*, 471–483. [[CrossRef](#)]
122. Sun, G.; Yang, G.; Guo, B. CoCoMo: Toward Controllable and Reliable Corrosion Monitoring with a Wireless Sensor Network. *Int. J. Distrib. Sens. Netw.* **2017**, *13*, 1550147717734525. [[CrossRef](#)]
123. Zhou, S.; Sheng, W.; Deng, F.; Wu, X.; Fu, Z. A Novel Passive Wireless Sensing Method for Concrete Chloride Ion Concentration Monitoring. *Sensors* **2017**, *17*, 2871. [[CrossRef](#)] [[PubMed](#)]
124. Yuan, Y.; Wang, L.; Wu, Z.; Mou, W.; Feng, X.; Liu, J.; Yang, X. Full-Field Deformation-Aided Compressive Failure Evaluation of Seawater Concrete Using Digital Image Correlation Technique. *J. Mar. Sci. Eng.* **2022**, *10*, 518. [[CrossRef](#)]
125. Zhang, S.; Gao, D.; Zhu, H.; Chen, L.; He, Z.; Yang, L. Flexural Behavior of Seawater-Mixed Steel Fiber Reinforced Concrete Exposed to Simulated Marine Environments. *Constr. Build. Mater.* **2023**, *373*, 130858. [[CrossRef](#)]
126. Wang, X.; Jin, Z.; Liu, J.; Chen, F.; Feng, P.; Tang, J. Research on Internal Monitoring of Reinforced Concrete under Accelerated Corrosion Using XCT and DIC Technology. *Constr. Build. Mater.* **2021**, *266*, 121018. [[CrossRef](#)]
127. Kim, S.; Yi, J.-H.; Hong, H.; Choi, S.I.; Kim, D.; Kim, M.O. Interfacial Bond Properties of Underwater Concrete Coated with Bisphenol A Epoxy Resins. *Polymers* **2023**, *15*, 4290. [[CrossRef](#)] [[PubMed](#)]
128. Yu, Z.; Shen, Y.; Zhang, Y.; Xiang, Y. Automatic Crack Detection and 3D Reconstruction of Structural Appearance Using Underwater Wall-Climbing Robot. *Autom. Constr.* **2024**, *160*, 105322. [[CrossRef](#)]
129. Wang, X.; Guan, H.; Wang, W.; Lei, Y. Compact Underwater Robotic Tool Changer System. In Proceedings of the 7th International Conference on Robotics and Automation Sciences (ICRAS), Wuhan, China, 16–18 June 2023; IEEE: New York, NY, USA.
130. Manley, J.E.; Halpin, S.; Radford, N.; Ondler, M. Aquanaut: A New Tool for Subsea Inspection and Intervention. In Proceedings of the OCEANS 2018 MTS/IEEE Charleston, Charleston, SC, USA, 22–25 October 2018.
131. Qi, Z.; Zhang, J.; Liu, D. A CNN-Based Method for Concrete Crack Detection in Underwater Environments. In *Construction Research Congress 2020 Proceedings*; American Society of Civil Engineers: Reston, VA, USA, 2020.
132. Sivčev, S.; Coleman, J.; Omerdić, E.; Dooley, G.; Toal, D. Underwater Manipulators: A Review. *Ocean Eng.* **2018**, *163*, 431–450. [[CrossRef](#)]
133. ASTM C1583-13; Standard Test. Method for Tensile Strength of Concrete Surfaces and the Bond. Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method). ASTM International: West Conshohocken, PA, USA, 2013.

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