

Research Article

Research Progress and Performance Evaluation of Repair Materials for Damaged Concrete Structures in Marine Environments

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Abstract

Research on rapid-repair concrete for marine environments is dedicated to addressing the deterioration of infrastructure under harsh marine conditions. By developing specialty materials and processes that feature rapid hardening, early strength, high durability, and good workability, it aims to achieve swift and durable repairs of key projects such as ports and sea-crossing bridges. This shortens maintenance windows, reduces economic losses, and ensures structural safety. However, this field still faces challenges at multiple levels: at the material level, it is difficult to balance "rapidity" and "durability"; the interface between old and new concrete is weak; underwater anti-washout performance is insufficient; at the engineering level, there is poor adaptability to complex working conditions, difficulties in quality control, and a lagging standard system; at the comprehensive level, costs are high, life-cycle assessment systems are incomplete, and integration with intelligent technologies is inadequate. This research holds significant strategic and practical importance for supporting the "Maritime Power" strategy, ensuring the safety of maritime routes under the "Belt and Road" initiative, and enhancing the resilience of critical infrastructure. It is also a key practice for implementing marine ecological civilization and promoting the sustainable development of the marine economy. Future research should focus on the long-term performance evolution mechanisms under the coupled effects of materials, structures, and the environment. Efforts should be made to develop low-cost, highly compatible, and environmentally friendly repair systems, and to promote the deep integration of digital design, intelligent monitoring, and automated construction. Ultimately, the goal is to establish a comprehensive technical system for marine engineering repair that integrates rapidity, durability, and intelligence.

Keywords

Rapid Repair, Durability, Marine Environment, High Early Strength

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1. Introduction

Oceans encompass approximately 71% of the Earth's surface, functioning as pivotal hubs for global trade and energy logistics, as well as strategic frontiers for natural resource exploitation. Driven by the deepening implementation of China's "Maritime Power" strategy and the "Belt and Road" Initiative, a surge in major marine engineering projects—including ports, sea-crossing bridges, submarine tunnels, offshore wind power foundations, and artificial islands—has been observed. These infrastructures provide critical support for the high-quality development of the marine economy.

However, concrete structures located in tidal and splash zones are subjected to exceptionally harsh service environments. They must simultaneously withstand multifaceted degradation mechanisms: reinforcement corrosion induced by chloride ingress, expansive damage from sulfate attack, accelerated ion transport under wet-dry cycling, and mechanical abrasion from wave action and floating debris. In cold regions, these effects are compounded by freeze-thaw cycles [1]. Such multi-factor coupled erosion frequently results in the premature failure of marine concrete structures, characterized by cover spalling, reinforcement corrosion, and crack propagation, thereby significantly shortening their service life relative to design expectations. This deterioration not only compromises structural safety but also incurs substantial economic burdens; globally, annual corrosion-related maintenance costs reach trillions of US dollars, with marine engineering constituting a significant proportion [2].

Conventional repair techniques, primarily based on traditional concrete and mortar, exhibit notable limitations in marine contexts, including slow setting kinetics, inadequate interfacial bonding between old and new substrates, and insufficient long-term durability [3]. Consequently, these materials often fail to satisfy the stringent construction window requirements inherent to tidal zones. The limited service life of repaired structures frequently leads to a vicious cycle of "recurrent damage and repetitive repair." In this context, the development of novel repair materials that integrate rapid constructability, superior marine durability, and robust interfacial adhesion has emerged as a focal point of international research in civil engineering materials and represents a critical technical challenge for marine infrastructure maintenance [4].

Currently, marine concrete repair materials have evolved into three mainstream technical systems: inorganic cementitious composites, polymer-modified mortars, and fiber-reinforced materials. Additionally, emerging green technologies, such as geopolymers and microbial-induced mineralization, have demonstrated promising application potential due to their distinct advantages [5]. While extensive

experimental and theoretical investigations have been conducted globally regarding component modification, performance optimization, and process improvement [6], no single material system currently satisfies the synergistic engineering requirements of "rapid hardening, high strength, durability, strong adhesion, anti-washout resistance, and cost-effectiveness." Furthermore, persistent industry challenges remain, including weak old-new interfaces, limited construction adaptability, a lack of specialized standards, and insufficient integration of intelligent technologies [7].

Against this backdrop, this paper systematically reviews the latest advancements in repair materials for marine concrete environments. It comparatively analyzes the performance merits and applicability of diverse material systems, proposes a targeted multi-dimensional performance evaluation framework, and discusses future trajectories for technological integration and innovation. This work aims to provide theoretical insights and practical references for upgrading marine infrastructure maintenance strategies and facilitating the engineering application of high-performance repair materials in China.

2. Types, Curing Mechanisms, and Research Progress of Concrete Repair Materials in Marine Environments

Based on their constituent materials and curing mechanisms, rapid repair materials for marine environments are broadly categorized into three conventional systems—inorganic cementitious composites, polymer-modified mortars, and fiber-reinforced materials—alongside emerging green technologies such as geopolymers and microbial-induced mineralization. Governed by their intrinsic compositional attributes, each material system exhibits a distinct performance profile, rendering them suitable for specific marine operational conditions and damage typologies. Currently, research in this domain is predominantly directed toward mitigating inherent material limitations and enhancing environmental adaptability through strategic compositional modification and process optimization.

2.1. Cement-Based Materials

Rapid-hardening and early-strength cementitious repair materials, governed by inorganic hydration reactions, are capable of attaining engineering-grade strength within hours, thereby establishing them as the predominant choice for emergency marine infrastructure repairs [8]. This category primarily encompasses two distinct systems: sulfoaluminate

cement (SAC)-based and magnesium phosphate cement (MPC)-based composites. Although both systems achieve rapid setting via divergent hydration pathways, their long-term stability remains suboptimal, necessitating further optimization through multi-component blending strategies [9].

2.1.1. Sulfoaluminate Cement-Based Materials

The rapid-hardening and early-strength attributes of sulfoaluminate cement (SAC)-based materials are predicated on the swift hydration kinetics of their primary constituent, calcium sulfoaluminate. During hydration, the prolific formation of ettringite (AFt) crystals not only facilitates rapid early strength development but also induces a controlled expansive effect. This expansion effectively compensates for autogenous shrinkage and enhances the structural compactness of the matrix. Empirical studies demonstrate that SAC-based repair mortars can attain compressive strengths exceeding 20 MPa within 4 hours and surpassing 40 MPa at 24 hours. Such performance ensures the rapid restoration of load-bearing capacity, thereby satisfying the stringent construction window requirements inherent to tidal zone operations.

Application of SAC materials: inadequate reinforcement protection and susceptibility to long-term degradation in sulfate-rich environments. First, the alkalinity of the SAC pore solution ($\text{pH} \approx 10.5\text{--}11.5$) is significantly lower than that of ordinary Portland cement ($\text{pH} > 13$), hindering the formation of a stable passive film on the reinforcement surface. Second, upon prolonged exposure to marine sulfate environments, the metastable AFt phase tends to transform into monosulfoaluminate, a phase with inferior mechanical properties. This crystallographic transformation precipitates strength loss and microstructural deterioration. To address these challenges, the prevailing modification strategy involves the incorporation of active mineral admixtures, such as silica fume and ground granulated blast-furnace slag (GGBS). These admixtures undergo secondary pozzolanic reactions to generate additional calcium silicate hydrate (C-S-H) gel, which refines the pore structure and bolsters long-term stability and erosion resistance. For instance, incorporating 30% GGBS into SAC-based mortar has been shown to increase the strength retention rate after 180 days of seawater immersion from 75% to over 90%, markedly enhancing resistance to sulfate attack.

2.1.2. Polymer-Modified Repair Mortar

Magnesium phosphate cement (MPC)-based materials derive their setting and hardening characteristics from an acid-base reaction between an acidic phosphate source (typically potassium dihydrogen phosphate) and a basic magnesia component (magnesium oxide, MgO). This reaction rapidly yields a ceramic-like bonded matrix, with struvite as the

primary crystalline product. Consequently, MPC systems currently represent the pinnacle of early-age strength performance among cementitious repair materials [10]. Their technical superiority is distinguished by three key attributes: (1) tunable setting kinetics, allowing the setting time to be precisely regulated from several minutes to tens of minutes to suit specific engineering demands; (2) exceptional early strength development, achieving compressive strengths exceeding 20 MPa within 1 hour and reaching 40–50 MPa by 4 hours; and (3) superior interfacial adhesion to existing concrete substrates, where bond strength typically surpasses the cohesive tensile strength of the mortar itself. Furthermore, MPC exhibits remarkable low-temperature adaptability, maintaining effective hydration kinetics even in the range of 0°C to -20°C . This unique characteristic renders it particularly suitable for emergency marine infrastructure repairs under winter conditions.

Despite their exceptional performance attributes, the widespread engineering deployment of magnesium phosphate cement (MPC) systems is currently impeded by three critical bottlenecks. First, economic viability is compromised by the prohibitive cost of specialty raw materials; essential components such as reactive magnesia and borax-based retarders are substantially more expensive than conventional binders, thereby escalating overall project expenditures. Second, the intense exothermic nature of the acid-base hydration reaction generates significant thermal gradients, inducing thermal stresses that precipitate micro-cracking. This characteristic renders MPC unsuitable for mass concrete applications or large-volume marine structural repairs. Third, concerns regarding long-term volumetric stability and inadequate water resistance often lead to strength regression in later ages. To address these challenges, contemporary research focuses on the partial substitution of binders with industrial solid wastes, such as fly ash and metakaolin. This strategy not only mitigates the hydration heat release and reduces material costs but also leverages the micro-aggregate filling effect and pozzolanic activity of these wastes to refine the pore structure. Consequently, this approach significantly enhances water resistance, offering a viable technical pathway for the broader application of MPC in demanding marine engineering environments.

2.1.3. Polymer-Modified Cementitious Materials

Polymer-modified cementitious materials (PCM) are fabricated using ordinary Portland cement as the binder matrix, incorporated with polymer emulsions such as styrene-butadiene rubber, polyacrylate, or ethylene-vinyl acetate. The fundamental strengthening mechanism relies on the coalescence and film formation of polymer particles during cement hydration. These polymer films interlock with cement hydration products to establish a continuous organic-inorganic

interpenetrating network (IPN). This microstructural architecture effectively occludes capillary pores and bridges micro-cracks, thereby reducing the chloride ion diffusion coefficient by an order of magnitude. Concurrently, the IPN structure significantly enhances flexural strength, toughness, and interfacial adhesion. Notably, the bond strength, as characterized by splitting tensile tests, can attain values ranging from 3 to 5 MPa. Comparative studies indicate that polymer films in seawater sea-sand mortars refine the interfacial transition zone and act as physicochemical barriers, yielding corrosion resistance comparable to or exceeding freshwater counterparts [11].

From an engineering practice perspective, polymer-modified materials have demonstrated exceptional repair efficacy. Empirical evidence from a wharf breastwork rehabilitation project at a coastal port revealed that the interfacial bond strength between styrene-butadiene rubber-modified mortar and the existing concrete substrate exceeded double that of conventional mortar. Follow-up inspections conducted after five years of service confirmed the absence of distress, such as debonding or cracking, in the repaired zones. However, the primary limitation of these materials lies in the vulnerability of the polymeric phase to environmental degradation. In marine environments characterized by prolonged ultraviolet (UV) exposure, elevated temperatures, high humidity, and cyclic wet-dry conditions, the polymer films are prone to oxidative aging and micro-cracking. This degradation mechanism inevitably compromises the long-term durability of the composite. To mitigate these concerns, current industry practices focus on enhancing anti-aging performance through the incorporation of UV stabilizers and antioxidants, alongside the optimization of polymer dosage and mixture proportions [12].

2.1.4. Anti-Washout Concrete/Mortar

Underwater Non-Dispersible Concrete/Mortar (NDC/NDM) represents a specialized class of materials engineered specifically for the rehabilitation of submerged marine structures. Its fundamental technical attribute relies on the incorporation of anti-washout admixtures (AWA), such as water-soluble cellulose ethers and polyacrylamide-based flocculants. These agents drastically enhance the mixture's cohesion and viscosity, thereby imparting robust resistance against washout and segregation induced by water currents during underwater placement. Consequently, this rheological modification enables self-leveling and self-compacting capabilities in submerged environments. The performance quality of NDC/NDM is governed by stringent control criteria, specifically requiring water turbidity levels below 150 mg/L and pH variations less than 1.2 units. This technology has been successfully deployed in critical repair projects for submerged infrastructure, including harbor breakwaters and cross-sea

bridge piers [13].

The intrinsic performance limitations of Underwater Non-Dispersible Concrete/Mortar (NDC/NDM) are primarily manifested as retarded setting behavior, excessive drying shrinkage, and compromised long-term strength. The incorporation of anti-washout admixtures (AWA) inherently retards the cement hydration kinetics, resulting in prolonged setting times. Furthermore, these polymeric components tend to exacerbate drying shrinkage. Consequently, underwater-cast specimens often exhibit a 10% to 30% reduction in long-term compressive strength compared to their land-cast counterparts with identical mix proportions. Current research frontiers in this domain focus on the development of novel composite AWAs designed to strike an optimal balance between washout resistance and hydration kinetics through synergistic formulation. Concurrently, strategies involving optimized mix designs—specifically the integration of expansive agents and internal curing materials—are being employed to mitigate shrinkage, thereby enhancing the consistency of strength evolution [14].

2.2. Fiber-Reinforced Repair Materials

Fiber-reinforced repair materials achieve a synergistic enhancement in cracking resistance, toughness, and impact durability through the incorporation of discrete short fibers into the cementitious matrix. These materials are frequently employed in hybrid systems, combining rapid-hardening early-strength binders with polymer-modified matrices. This multi-scale reinforcement strategy serves as a critical technical solution for mitigating repair layer distress induced by cyclic wave loading and wet-dry alternation in aggressive marine environments.

Fibers incorporated into repair materials primarily fulfill three critical functions: crack bridging, crack arrest, and toughness enhancement. Mechanistically, fibers effectively suppress the initiation and propagation of cracks induced by plastic and drying shrinkage. By dispersing localized macro-cracks into a network of benign micro-cracks, they significantly augment the material's fracture energy, flexural toughness, and fatigue resistance. Furthermore, fibers spanning the interface between the repair overlay and the existing substrate reinforce the interfacial bond, thereby enhancing the structural integrity of the composite system. In marine engineering practice, these materials are particularly suited for rehabilitating structural components within tidal and splash zones subjected to dynamic loading. For instance, in the rehabilitation of dock slabs damaged by vessel impact, steel fiber-reinforced rapid-hardening concrete has demonstrated an impact resistance five- to eight-fold greater than that of conventional repair concrete.

Fiber selection needs to focus on both alkali resistance and compatibility with the marine environment: ordinary steel

fibers are prone to corrosion in marine chloride environments, therefore, corrosion-resistant fibers such as stainless steel fibers, polypropylene, polyvinyl alcohol synthetic fibers, or basalt fibers are preferred in marine engineering [15]. At the same time, it is essential to ensure uniform dispersion of fibers within the cementitious matrix to avoid localized performance deterioration caused by fiber clumping. This can be achieved through methods such as adding fiber dispersants or optimizing the mixing process.

2.3. Emerging Green Repair Material Systems

Driven by the growing imperative for green and low-carbon development in civil engineering, emerging repair materials focused on the valorization of industrial solid wastes and biomineralization technologies have become frontiers of research. Notably, geopolymers and microbial-induced calcite precipitation (MICP) materials, distinguished by their superior erosion resistance and environmental sustainability, have demonstrated significant potential for marine engineering applications. Currently, these innovative systems are undergoing a pivotal transition from laboratory-scale investigations to field-scale demonstration projects.

2.3.1. Geopolymer

Geopolymers are primarily synthesized using aluminosilicate industrial solid wastes such as fly ash, slag, and metakaolin as main raw materials, which are activated by alkaline activators to form a three-dimensional network gel structure. They possess multiple advantages including rapid hardening and early strength, high-temperature resistance, acid and alkali corrosion resistance, low permeability, and low carbon emissions. Relevant studies have shown that geopolymer materials exhibit significantly superior resistance to corrosive agents such as chloride ions and sulfates compared to ordinary cement-based materials, and demonstrate good interfacial bonding properties with old concrete, making them ideal green repair materials suitable for marine environments. Long-term service studies on 3D-printed geopolymers in marine atmospheric zones, submerged zones, and tidal zones indicate that their performance remains stable in the atmospheric zone. However, in the tidal zone, they are prone to gel decalcification deterioration due to dry-wet cycles. Meanwhile, fly ash-slag based geopolymer concrete can achieve a compressive strength increase up to 50 MPa under marine curing conditions without any salt efflorescence phenomenon.

At the current stage, the engineering application of geopolymer materials still needs to address two key technical issues: first, poor construction performance, characterized by high material viscosity and short workable time, making it difficult to meet the requirements of complex marine construction conditions; second, long-term volumetric

stability needs improvement, as some geopolymer materials exhibit excessive later-age shrinkage, which can easily lead to interface cracking. Currently, the industry is gradually improving the construction performance and volumetric stability of geopolymer materials through methods such as optimizing the type and dosage of alkaline activators, compounding retarders, and incorporating fibers or lightweight aggregates.

2.3.2. MICP-Based Repair Materials

Microbially Induced Calcite Precipitation (MICP) technologies leverage the metabolic activities of specific ureolytic bacteria, such as *Sporosarcina pasteurii*, to catalyze the precipitation of calcium carbonate at the substrate-overlay interface or within crack voids. This process facilitates crack sealing, matrix densification, and the enhancement of interfacial bond strength. As an eco-friendly bioremediation strategy, MICP exhibits excellent compatibility with the cementitious matrix and generates no hazardous byproducts, making it particularly suitable for rehabilitating micro-cracks (width < 0.5 mm) in marine concrete structures [16]. Investigations into MICP performance in marine environments reveal that seawater constituents can accelerate crack healing, achieving complete closure within 7 days; the resulting precipitated phases are predominantly brucite and aragonite rather than calcite. In this context, Mg^{2+} ions exert a pivotal regulatory influence on the morphology and polymorphism of the mineralized products. Furthermore, acclimated alkali-tolerant *Bacillus* strains demonstrate significantly enhanced survival rates in high-pH environments (pH 11), achieving a crack-filling mineralization efficiency of up to 92% in recycled aggregate concrete. Beyond conventional ureolytic bacteria, *Staphylococcus epidermidis* has been demonstrated to effectively precipitate carbonate minerals in micro-cracks under marine-mimicking conditions, restoring material impermeability [17].

The limitations of this type of material are mainly reflected in the strict construction conditions required: microbial activity is significantly influenced by factors such as ambient temperature, humidity, and the pH level within cracks. It can only repair narrow cracks and has a relatively slow mineralization rate, making it difficult to meet the time requirements for emergency repairs in marine engineering. Currently, it remains primarily at the laboratory research stage and has not yet achieved large-scale engineering application.

3. Performance Evaluation System and Methods for Concrete Repair Materials in Marine Environments

The multi-factor coupled erosion characteristics of the

marine environment and the rapid construction requirements of repair projects determine that the performance evaluation of repair materials must transcend the limitations of single indicators. It is necessary to establish a multi-dimensional comprehensive evaluation system covering construction performance, mechanical and bonding properties, long-term durability, and interfacial microstructure. Furthermore, targeted testing methods and indicator requirements should be formulated based on the characteristics of marine operating conditions, providing a scientific basis for material selection, mix proportion optimization, and engineering application.

3.1. Workability Evaluation

Construction performance constitutes the fundamental prerequisite for assessing the adaptability of marine repair materials to tidal work windows and complex operational conditions. The primary objective is to ensure optimal workability and scenario-specific adaptability across diverse marine zones, including submerged, tidal, and atmospheric environments. The evaluation framework encompasses three critical rheological indicators: fluidity (pumpability), setting time, and thixotropy (anti-sagging resistance), each requiring differentiated control strategies tailored to specific construction scenarios.

Firstly, fluidity is paramount for ensuring the complete filling of structural defects and achieving full consolidation. Initial slump flow serves as the primary metric, with marine repair mortars typically required to exhibit a minimum initial spread of 350 mm. Concurrently, the temporal evolution of fluidity loss must be rigorously monitored to guarantee sustained workability throughout the designated construction window.

Secondly, setting time acts as the critical control parameter for rapid rehabilitation projects, particularly in tidal zones. To prevent premature hydration disruption caused by tidal immersion—which could compromise repair quality and durability—the initial setting time must be strictly constrained within 1–3 hours, while the final setting time should not exceed 6 hours.

Thirdly, for vertical or overhead applications, such as bridge piers and revetment facades, materials must exhibit superior thixotropic behavior and anti-sagging properties. This necessitates a rheological profile that maintains adequate fluidity under shear stress during placement but rapidly recovers structural build-up (yield stress) upon cessation of shear, thereby preventing gravitational flow or sagging. The standard sag test is employed to quantify this performance, mandating a maximum sag value of ≤ 5 mm to satisfy the formwork-free requirements for vertical surface repairs [18].

In summary, the systematic evaluation and precise regulation of these construction performance parameters—fluidity, setting time, and thixotropy—are essential for

ensuring the adaptability of marine repair materials to complex environmental constraints and guaranteeing the reliability of engineering outcomes.

3.2. Mechanical and Bond Performance Evaluation

In marine environment concrete repair, the mechanical properties and interfacial bonding performance of materials are two core factors determining the repair effectiveness, requiring a balance between early strength development and long-term stability.

In terms of mechanical properties, early strength determines the emergency repair capability, with focus on monitoring compressive and flexural strength at 2h, 6h, 1d, and 3d. For tidal zones, the 6h compressive strength is required to be ≥ 15 MPa, and the 1d compressive strength ≥ 30 MPa. Long-term stability examines strength evolution at 28d, 90d, and 180d, requiring that the strength retention rate from 28d to 180d is not less than 90%, ensuring no strength regression occurs [19].

Interfacial bonding performance is key to ensuring the monolithic behavior of old and new concrete. The splitting tensile bond test is used to characterize the normal tensile capacity of the interface, while the slant shear bond test more closely represents the complex stress state of marine structures. High-performance repair materials should achieve a wet bond strength of no less than 2.0 MPa on saturated surface-dry substrates, with the ideal failure mode being cohesive failure within the old concrete substrate rather than failure along the interface. Marine engineering practice has shown that repair materials treated with polymer modification and fiber reinforcement composite treatment can achieve interfacial bond strength exceeding 4.5 MPa, with failure modes consistently being cohesive failure within the substrate.

3.3. Interfacial Microstructure and Characterization

The microstructural characteristics of the interfacial transition zone (ITZ) between old and new concrete directly influence the bond performance and long-term stability of the repaired structure. Therefore, microscopic testing techniques are needed to reveal the interfacial bonding mechanism and evaluate modification effects: scanning electron microscopy coupled with energy dispersive spectroscopy is used to observe the micromorphology and elemental distribution at the interface, analyzing the formation and bonding status of hydration products; backscattered electron imaging combined with image analysis enables quantitative characterization of interfacial porosity, pore size distribution, and structural compactness, clarifying the distribution patterns of micro-defects; nanoindentation techniques are employed to

determine the micromechanical properties of each phase at the interface, assessing their strength and toughness characteristics. C-(N)-A-S-H gel with a low calcium-to-silicon ratio can enhance the chemical stability of geopolymer interfaces, reducing interfacial deterioration caused by marine ion erosion. The bridging effect of basalt fibers can reduce the porosity in the ITZ by 15%–20%, significantly improving interfacial compactness. These methods corroborate each other, providing a systematic microscopic theoretical basis for interface strengthening and material optimization [20].

4. Conclusions and Future Perspectives

The rehabilitation of concrete structures in marine environments represents a complex systems engineering challenge, necessitating the simultaneous optimization of rapid constructability, long-term durability, robust interfacial bonding, and adaptability to harsh conditions. Despite the niche successes of traditional systems (e.g., rapid-hardening composites, polymer-modified materials) and the promising erosion resistance of emerging green solutions (e.g., geopolymers, microbial-induced mineralization), significant bottlenecks persist. These include the inherent trade-off between early strength and long-term performance, pervasive interfacial weaknesses, insufficient adaptability to extreme scenarios, and a critical lack of scientific life-cycle prediction models. Consequently, current engineering practices remain overly reliant on empirical methods rather than predictive science.

Future advancements must be strategically anchored in four pillars: "Green, Intelligent, Integrated, and Long-lasting." Fundamental research should prioritize elucidating performance evolution mechanisms under multi-factor coupling and establishing micro-mechanism-based life prediction models to shift decision-making from empirical judgment to scientific forecasting. Material innovation should focus on low-carbon cementitious systems, autonomous self-healing concretes, and intelligent materials capable of real-time sensing of strain and chloride ingress. Concurrently, construction methodologies must integrate Digital Twins, BIM, robotics, and 3D printing to achieve precision and automation, while nano-reinforcement and advanced interface agents should be employed to ensure seamless monolithic integration of old and new concrete.

Ultimately, these initiatives aim to cultivate an intelligent repair ecosystem spanning the entire lifecycle—from material design to construction and maintenance. By fostering multidisciplinary convergence and systematic innovation, this approach will provide robust support for the long-term safety and resilience of marine infrastructure, effectively

transitioning the field towards a paradigm of predictive, sustainable, and high-performance engineering.

Abbreviations

SAC	Sulfoaluminate Cement
MPC	Magnesium Phosphate Cement
AFT	The Prolific Formation of Ettringite
GGBS	Ground Granulated Blast-furnace Slag
C-S-H	Calcium Silicate Hydrate
MPC	Magnesium Phosphate Cement
MGO	Magnesium Oxide
PCM	Polymer-modified Cementitious Materials
IPN	Interpenetrating Network
UV	Ultraviolet
AWA	Anti-washout Admixtures
NDC/NDM	Non-dispersible Concrete/Morta
MICP	Microbial-induced Calcite Precipitation
ITZ	Interfacial Transition Zone

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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