Adaptability Research on Different Civil Engineering Materials in Marine Environment

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Abstract. This study examines the adaptability of civil engineering materials in marine environments, investigating deterioration laws of five material types under multi - environmental coupling effects. Laboratory accelerated aging and multi - climatic field exposure tests simulate salt spray, freeze - thaw, carbonation etc. Combined with micro - characterization for structural evolution analysis, results show: high - performance concrete has best durability in high - chloride environments; recycled aggregate concrete suits dry - cold and plateau regions; fiber composites perform well but are costly; low - carbon cementitious materials lack sufficient carbonation stability. An adaptability evaluation system is built, offering theoretical support for material selection, full - life cycle design and low - carbon development of coastal and cross - sea engineering.

Keywords: Marine Environment, Civil Engineering Materials, Durability, Adaptability Model.

1. Introduction

With the rapid development of global marine engineering construction, the adaptability of civil engineering materials in marine environments has become increasingly prominent. Marine environments are characterized by high humidity, high salinity and drastic temperature changes, posing severe challenges to the durability and stability of building materials. Statistics show that from 2019 to 2023, the total investment in marine engineering construction in China reached 1.2 trillion yuan, among which coastal infrastructure construction accounted for more than 40%. However, the annual engineering maintenance cost caused by improper material selection exceeded 30 billion yuan, accounting for 8–12% of the total investment [1].

The impacts of marine environments on civil engineering materials are mainly reflected in the coupled effects of chloride ion erosion, carbonation, freeze-thaw cycles, acid rain corrosion and other factors. Traditional cement-based materials often suffer from deterioration such as strength degradation and increased permeability in marine environments, which seriously affects the service life of structures [2]. In recent years, emerging materials including high-performance concrete, recycled aggregate concrete, fiber-reinforced composites and new low-carbon cementitious materials have been gradually applied in marine engineering, but their long-term adaptability still needs systematic evaluation. Currently, the inspection of offshore structures often relies on advanced robotic technologies. However, while these methods effectively capture surface data and structural deformations, they cannot directly assess the intrinsic material degradation mechanisms (e.g., chloride diffusion depth or microstructural evolution). Therefore, research focusing on the fundamental adaptability of construction materials remains the cornerstone of ensuring long-term structural safety [3].

At present, domestic and foreign studies on material performance in marine environments mostly focus on single environmental factors, lacking systematic analysis under the coupling of multi-dimensional environmental stresses. Meanwhile, the correlation mechanism between material microstructure evolution and macroscopic performance degradation is insufficiently understood, making it difficult to provide accurate prediction models for practical engineering. In addition, marine environmental characteristics vary significantly among climatic regions, leading to regional differences in material adaptability, which requires a regional material selection guidance system.

This study aims to reveal the adaptability laws of cement-based materials, high-performance concrete, recycled aggregate concrete, fiber-reinforced composites and new low-carbon cementitious materials in marine environments through systematic experimental research. By establishing a standardized material system, conducting accelerated aging and field exposure tests under multi-dimensional environmental stresses. The research results provide theoretical support for scientific selection, optimal design and full-life cycle reliability assessment of marine engineering materials, and promote the rational application of green building materials in marine environments, with important theoretical significance and engineering application value.

2. Adaptability Tests of Materials under Marine Environmental Stress

The adaptability evaluation of materials under marine environmental stress is implemented through multi-dimensional environmental factor coupling tests, which systematically monitor the mechanical property evolution and durability index changes of each material system. The test design covers typical marine environmental stresses including chloride ion erosion, carbonation, freeze-thaw cycles and acid rain corrosion, adopting a combined strategy of accelerated aging and field exposure [4].

The chloride ion erosion test simulates the high-salinity marine environment. Specimens are immersed in 3.5% NaCl solution, which is replaced monthly to maintain stable concentration. The temperature is controlled at 20±2°C, and the chloride ion diffusion depth and bound chloride ion content are measured regularly. After 12 months of immersion, the chloride ion diffusion depth of cement-based materials reaches 15.8 mm, and the compressive strength retention rate drops to 87.3%. High-performance concrete exhibits excellent chloride ion resistance, with a diffusion depth of only 8.2 mm and a strength retention rate of 93.6%, fully verifying the effectiveness of mineral admixtures in optimizing pore structure[5].

The carbonation test is carried out in an accelerated environment with 20% CO_2 concentration, relative humidity of 70% and temperature of 20°C. The carbonation depth of each material system shows different development trends with time. The carbonation depth of cement-based materials is linear with the square root of time, and the carbonation coefficient is 2.85 mm/day. The carbonation rate of high-performance concrete is significantly reduced, with a carbonation coefficient of 1.92 mm/day. New low-carbon cementitious materials show rapid carbonation development, with a carbonation depth of 18.7 mm after 24 months, indicating insufficient stability of the alkali-activated system in CO_2 environments.

The freeze-thaw cycle test simulates the temperature variation in high-latitude marine environments, with a cycle temperature range of -18°C to 5°C and one cycle per day. After 300 cycles, significant differences are observed in mass loss rate and strength loss rate among materials. Fiber-reinforced composites perform best, with a mass loss rate of only 0.8% and a strength retention rate of 96.4%. The bridging effect of fibers effectively inhibits microcrack propagation and maintains structural integrity. Recycled aggregate concrete has relatively large freeze-thaw loss due to numerous weak interface zones, with a mass loss rate of 2.5%.

The acid rain corrosion test uses sulfuric acid solution with pH 4.5 to simulate acidic conditions. Specimens are alternately immersed and dried with a 7-day cycle. Acid corrosion mainly causes surface softening and mass loss of materials. After 24 months, the mass loss rate of each material ranges from 1.2% to 3.8%. High-performance concrete and fiber-reinforced materials show better acid corrosion resistance, with mass loss rate controlled within 1.5% [6].

As shown in Table 1, based on multiple performance indicators, a marine environmental adaptability scoring system is established using a 100-point scale, with high-performance concrete as the reference benchmark. The weighting is determined according to the main deterioration mechanisms in marine environments: chloride ion resistance 30%, carbonation resistance 25%, freeze resistance 25%, and acid corrosion resistance 20%.

As shown in Table 1, high-performance concrete achieves the highest comprehensive adaptability score of 88.0, demonstrating excellent overall durability, particularly in chloride ion resistance 94 and carbonation resistance 89. Fiber-reinforced concrete ranks second with a score of 82.8, showing a significant advantage in freeze resistance 96, which aligns with its ability to inhibit crack propagation. Cement-based materials exhibit moderate performance, with a balanced score of 74.8 across all indicators. In contrast, recycled aggregate concrete shows relatively lower durability 70.3, mainly due to weaker interfacial zones affecting its resistance under multiple environmental stresses. Low-carbon cementitious materials obtain the lowest score of 65.5, primarily limited by insufficient carbonation resistance 58.

Table 1. Marine environmental adaptability scores of materials

Materials	Chloride ion resistance score	Carbonation resistance score	Freeze resistance score	Acid corrosion resistance score	Comprehensive adaptability score
Cement-based materials	72	75	78	74	74.8
High-performance concrete	94	89	82	87	88.0
Recycled aggregate concrete	68	73	69	71	70.3
Fiber-reinforced concrete	76	74	96	85	82.8
Low-carbon cementitious materials	65	58	71	68	65.5

Field exposure tests are simultaneously conducted in four typical climatic regions: coastal, hot-humid, dry-cold and plateau, to verify the accuracy of laboratory accelerated test results. The coastal site is located on the coast of Qingdao, 200 meters from the coastline, with an annual average chloride ion deposition rate of 15.2 mg/(m²·d). The hot-humid site is in Sanya, Hainan, with an annual average temperature of 27.8°C and relative humidity of 82%. The dry-cold site is in Hohhot, Inner Mongolia, with an annual average temperature of 6.8°C and annual precipitation of 350 mm. The plateau site is in Lhasa, Xizang, at an altitude of 3650 meters, with large diurnal temperature difference and strong ultraviolet intensity.

Chloride ion erosion is most severe in coastal environments, and the strength retention rate of each material is generally lower than in other environments. Hot-humid environments promote hydration and carbonation, which benefit long-term strength development. Dry-cold environments mainly affect the freeze resistance of materials, and freeze-thaw loss is highly correlated with laboratory test results. The combined effects of ultraviolet radiation and temperature difference in plateau environments have certain impacts on material surfaces, but the overall loss is controllable.

Correlation analysis between mechanical properties and durability shows that the initial porosity of materials is significantly negatively correlated with environmental adaptability, with a correlation coefficient of -0.87. The correlation coefficient between chloride ion diffusion coefficient and compressive strength retention rate is -0.76, proving the key role of compactness in marine environmental adaptability. Although fiber incorporation has limited improvement on impermeability, it significantly enhances the toughness and integrity of materials under composite environmental stresses. The positive effect of mineral admixtures becomes more obvious during long-term service, and the performance advantage of high-performance concrete becomes increasingly prominent over time.

3. The Impact of Ocean Erosion

As one of the harshest service conditions for civil engineering materials, the marine environment features complex and variable characteristics and unique erosion mechanisms. According to the China Marine Engineering Construction Development Report, by 2023, the total number of marine engineering structures in China has exceeded 15,000, among which key infrastructures such as bridges, wharves and offshore wind power platforms have service performance directly related to engineering safety and economic benefits. The erosion characteristics of marine environments are mainly reflected in the coupled effects of high salt spray concentration, drastic temperature and humidity changes, strong ultraviolet radiation and mechanical scouring [7].

The chloride ion concentration in marine atmospheric environment is usually 0.1–10 mg/L, much higher than 0.01–0.1 mg/L in inland areas. As the main cause of steel corrosion in concrete, chloride ions penetrate into materials through diffusion, convection, electromigration and other transport mechanisms, destroying the passive film on steel surfaces and triggering electrochemical corrosion. Periodic temperature and humidity changes intensify thermal expansion and contraction, generating thermal stress concentration inside materials and providing preferential channels for chloride ion penetration. The relative humidity in marine environments remains 75%–95% all year round. High humidity promotes water migration and accumulation in material pores, providing necessary reaction media for chemical erosion [8].

Seawater has a complex chemical composition, containing sulfate, magnesium, bicarbonate and other corrosive ions besides chloride ions. Sulfate ions react with calcium hydroxide and calcium aluminate in cement hydration products to form expansive gypsum and ettringite, causing chemical erosion and expansion damage. Magnesium ions react with calcium hydroxide to form magnesium hydroxide, reducing the alkalinity of pore solution and further weakening corrosion resistance. Bicarbonate ions participate in carbonation, reacting with calcium hydroxide to form calcium carbonate, lowering the pH value of concrete pore solution and creating acidic conditions for steel corrosion.

Biological erosion in marine environments cannot be ignored. Marine microorganisms such as sulfate-reducing bacteria can metabolize hydrogen sulfide and other corrosive substances, accelerating biochemical degradation of materials. Attachment and growth of algae, shellfish and other marine organisms form biofilms on material surfaces, changing local pH and oxygen concentration, forming differential corrosion cells and inducing localized corrosion. Mechanical wear caused by wave impact and tidal action increases surface roughness, providing a larger reaction area for chemical erosion [9].

Table 2. Main characteristic parameters of marine erosion environment

Environmental factors	Parameter range	Erosion Mechanism	Degree of impact
Chloride ion concentration	0.1-10 mg/L	Steel bar de-passivation, electrochemical corrosion	high
Relative humidity	75%-95%	Water migration, chemical reaction medium	mid
Temperature change	-5℃-45℃	Thermal stress, material fatigue	mid

As shown in Table 2, Regional differences in marine environments significantly affect the erosion degree and mode of materials. High temperature and humidity in tropical marine environments accelerate chemical reaction rates, while frequent freeze-thaw cycles in polar marine environments affect material performance mainly through physical damage. In coastal tidal flats, materials undergo wet-dry cycles due to tidal range, and chloride ion concentration and crystallization pressure become the main destructive factors. Under high pressure and low temperature in deep-sea environments, the elastic modulus and toughness of materials change, affecting their load resistance. In tropical marine environments, the combined effects of high temperature, humidity and strong ultraviolet radiation should be comprehensively considered, and material selection should balance chemical stability and physical durability [10].

4. Summary

This study systematically evaluates the adaptability of five typical civil engineering materials in marine environments, reveals the performance evolution laws and deterioration mechanisms of different materials under complex environmental stress coupling, and provides important theoretical support and practical guidance for marine engineering material selection and structural design. Based on 24-month long-term service data and multi-scale micro-mechanism analysis, a material adaptability evaluation system and regional selection strategy with engineering practical value are formed.

The results show that high-performance concrete exhibits the best comprehensive adaptability in marine environments. Through the synergistic effect of mineral admixtures and microstructure optimization, the chloride ion diffusion coefficient of high-performance concrete is reduced by 62% compared with ordinary cement-based materials, and the compressive strength retention rate remains 88%–92% even in harsh marine environments. Its dense pore structure effectively slows down chloride ion penetration, and the strengthened interfacial transition zone significantly improves the integrity and durability of materials. From the engineering perspective, high-performance concrete is especially suitable for key components with high durability requirements such as cross-sea bridges, offshore wind power foundations and wharf structures. Although the initial investment cost is 15%–25% higher than ordinary concrete, its excellent long-term performance significantly reduces full-life cycle maintenance costs.

As a representative green building material, recycled aggregate concrete shows acceptable adaptability under specific marine environmental conditions. Although its initial mechanical properties are slightly lower than those of natural aggregate concrete, the performance degradation rate is controllable in dry-cold and plateau marine environments, with a compressive strength retention rate of 75%–82%. The main deterioration mode of recycled aggregate concrete is preferential failure at the new-old mortar interface, and its marine environmental adaptability can be effectively improved through interface strengthening and mix proportion optimization. Considering its remarkable environmental benefits and cost advantages, recycled aggregate concrete is recommended for non-critical structural parts or temporary marine engineering to achieve coordinated development of economic benefits and environmental protection.

Fiber-reinforced composites show unique performance characteristics in marine environments. Their lightweight, high-strength properties and excellent corrosion resistance make them irreplaceable in special application scenarios. Although they maintain good structural integrity under acid rain and freeze-thaw coupling, high material cost and fiber-matrix interface degradation limit large-scale application. The study finds that chemical dissolution of glass fiber in high-alkali environments and attenuation of interfacial bonding force are the main factors affecting the long-term performance of composites. Fiber-reinforced composites are recommended for upper structures of offshore platforms, light floating structures and weight-sensitive special engineering parts, and their service life can be improved through surface protection and fiber modification technologies.

As an important technical path to achieve carbon peaking and carbon neutrality in the construction industry, new low-carbon cementitious materials are gradually showing application potential in marine environments. The alkali-activated slag system has good chemical stability in high-chloride environments, but insufficient durability in carbonation environments needs to be solved through surface protection or cementitious system optimization. Fly ash-based geopolymer materials have a three-dimensional network structure with good seawater erosion resistance, but slow early-strength development and sensitivity to environmental humidity. Pilot application of low-carbon cementitious materials is recommended in marine engineering parts with relatively stable environments to accumulate experience and lay a foundation for large-scale promotion.

Based on the differentiated characteristics of different marine environmental regions, a regional material selection strategy is proposed. In high-salt spray coastal environments, high-performance concrete combined with surface protection is recommended to ensure long-term structural safety. In temperate marine environments, recycled aggregate concrete and optimized cement-based materials can meet general engineering requirements. In polar marine environments, emphasis should be placed on freeze-thaw resistance, and fiber-reinforced composites have obvious advantages. In tropical marine environments, the combined effects of high temperature, humidity and strong ultraviolet radiation should be comprehensively considered, and material selection should balance chemical stability and physical durability.

To further improve the adaptability of materials in marine environments, technical optimization is suggested in the following aspects. At the material design level, attention should be paid to precise regulation of microstructure, and the intrinsic marine erosion resistance of materials should be improved through nano-modification and multi-scale reinforcement strategies. In terms of surface protection, high-performance coating materials and surface modification technologies should be developed, and an integrated design concept of material-protection system should be established. In construction technology, construction quality, especially the compactness and curing quality of key parts, should be strictly controlled to ensure the realization of design performance.

From the perspective of engineering full-life cycle management, a performance-based maintenance strategy for marine engineering structures is recommended. Through regular inspection and condition monitoring, the trend of material performance degradation can be grasped timely, realizing the transformation from passive maintenance to active maintenance. Meanwhile, the construction of marine environmental material standard system should be strengthened, and material performance evaluation methods and engineering application specifications should be improved to provide technical support for industrial development .

The material adaptability evaluation system and prediction model constructed in this study provide an important tool for scientific selection of marine engineering materials, but still need verification and improvement on a larger time scale and more environmental conditions. Future research should focus on the impact of climate change on marine environmental characteristics and develop a new generation of marine engineering materials adapting to future environmental conditions. Through continuous technological innovation and engineering practice, the technology of marine engineering materials will be promoted to a higher level, providing solid material and technical support for the construction of a marine power.

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