Received: 18 Jun. 2026 | Revised: 23 Jun. 2026 | Accepted: 02 Jul. 2026 | Published online: 21 Aug. 2026
RESEARCH ARTICLE

Journal of Global Humanities and Social Sciences
2026,Vol. 7(4)240-246
DOI: 10.61360/BoniGHSS262020310403

A Study on Strategies for Promoting the Application of Corrosion-Resistant Concrete Materials from the Perspective of Green and Low-Carbon Development

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Abstract: The durability of concrete structures under harsh conditions—such as marine environments, saline-alkali regions, and industrial corrosive media—has long been a challenge for the construction industry. Each year, the repair and reconstruction of concrete structures due to corrosion consume vast amounts of resources and energy, resulting in massive carbon emissions. While corrosion-resistant concrete materials offer significant durability advantages in harsh environments, their application and promotion still face constraints related to cost and standards. From the perspective of green and low-carbon development, this paper systematically elaborates on the fundamental characteristics of corrosion-resistant concrete materials. It proposes two primary promotion objectives: carbon reduction across the entire life cycle and the establishment of a standard certification system. Furthermore, it constructs a framework of promotion strategies encompassing design codes, material optimization, production models, incentive mechanisms, demonstration and training programs, and database development. The aim is to advance corrosion-resistant concrete from technical feasibility to economic viability and institutional refinement, thereby supporting the construction industry's transition toward green and low-carbon development.

Keywords: corrosion-resistant concrete, green and low-carbon, full life cycle, application and promotion, standards system

Introduction

Corrosion-resistant concrete, through the optimization of cementitious material composition and the addition of functional admixtures, exhibits significantly enhanced resistance to corrosion by corrosive media, making it a proven and effective technical approach for extending the service life of structures and reducing environmental impacts throughout their full life cycle. However, the use of corrosion-resistant concrete is currently limited to major projects and specific locations, and has not yet been widely adopted on a large scale. Against the backdrop of deepening efforts to advance green and low-carbon development, there is an urgent need to establish specific goals and strategic directions to systematically promote the widespread use of corrosion-resistant concrete materials.

1. Overview of Corrosion-Resistant Concrete Materials

Corrosion-resistant concrete is a specialized concrete that, through optimization of material composition and adjustment of mix proportions, exhibits significantly greater resistance to corrosion by acidic, alkaline, and saline media than ordinary concrete. It involves optimizing the cementitious material system by partially replacing traditional Portland cement with industrial by-products such as slag, fly ash, and silica fume (Li et al., 2023). The hydration products of these auxiliary cementitious materials exhibit a lower calcium-to-silica ratio and a denser microstructure, effectively reducing the content of calcium hydroxide and the generation of soluble calcium salts within the concrete. The addition of functional admixtures—primarily rust

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inhibitors, sulfate-resistant admixtures, and penetrating crystalline waterproofing agents—plays a crucial role. Rust inhibitors form a protective film on the surface of reinforcing bars to slow down electrochemical corrosion, sulfate resistance admixtures react chemically with tricalcium aluminate in the concrete to form a stable layer of calcium aluminate, thereby reducing the risk of sulfate-induced deterioration. Compared to conventional concrete, corrosion-resistant concrete can extend its service life to two to three times that of ordinary concrete under equivalent corrosive conditions. Although the initial material cost is approximately 15 to 30 percent higher, its economic and environmental benefits over the full life cycle are significant (Wu, 2025).

2. Objectives for the Promotion and Application of Corrosion-Resistant Concrete Materials in the Context of Green and Low-Carbon Development

2.1 Full life-cycle carbon reduction

Full life-cycle carbon reduction serves as the central objective for the promotion and application of corrosion-resistant concrete. It entails systematic control of carbon emissions throughout the entire process—from raw material procurement, production, and transportation, through construction and operation, to maintenance, and finally demolition and disposal. The logic behind carbon reduction in corrosion-resistant concrete does not lie in the production process itself, but rather in significantly reducing the frequency of maintenance, reinforcement, and reconstruction by extending the service life of structures, thereby spreading out initial carbon emissions over a longer evaluation period (Zhang et al., 2025). Specifically, a concrete structure in a marine environment made of ordinary concrete has a design service life of 50 years, during which at least two to three large-scale repairs—or even preemptive demolition and reconstruction—are required. Each repair or reconstruction involves extensive production, transportation, and construction activities involving large quantities of reinforcing steel, cement, aggregates, and other materials. The use of corrosion-resistant concrete can extend a structure's service life to over 100 years, while significantly reducing or completely eliminating the substantial carbon emissions generated during maintenance and reconstruction phases (Wang, 2021). The goal of reducing carbon emissions across the entire life cycle must be assessed based on the cumulative carbon emissions throughout the structure's service life, rather than focusing solely on the analysis of carbon emissions data from the material production stage. According to estimates from relevant studies, replacing 30 percent of the ordinary Portland cement in concrete used for coastal structures with slag powder, supplemented by rust-inhibiting measures, can reduce the structure's full-life-cycle carbon emissions by approximately 25 to 40 percent. To achieve this goal, it is essential to develop a carbon emissions accounting model suitable for the full life cycle of corrosion-resistant concrete, clarify the system boundaries, and determine carbon emission factors and their calculation methods, so that carbon reduction effects can be quantified, compared, and verified.

2.2 Development of a Standards and Certification System

The development of a standards and certification system is a key institutional safeguard for the transition of corrosion-resistant concrete from sporadic applications to large-scale adoption. It aims to establish a comprehensive technical standards framework covering the entire chain—including material performance, design methods, construction processes, and quality acceptance. Currently, the lack of standards in the application of corrosion-resistant concrete poses a major obstacle. When design firms specify "corrosion-resistant concrete" in drawings, there is a lack of unified mix design guidelines and performance requirements for different corrosion severity levels; construction firms lack standardized work instructions; and quality supervision departments lack clear acceptance criteria (Liu & Jiang, 2021). To establish a standard certification system, the first step is the technical standards layer. Standards for corrosion-resistant concrete materials have been formulated, specifying minimum performance indicators and mix design methods for different corrosion environment levels. Additionally, construction technical specifications have been developed to standardize operational requirements for each stage, including mixing, transportation, pouring, and curing. At the certification and evaluation level, a third-party certification system for corrosion-resistant concrete products and projects has been established. Qualified testing institutions assess material performance and construction quality in accordance with the standards, and products and projects that pass certification are included as bonus criteria in the evaluation of green building materials and green buildings. At the dynamic update level, the standard certification system must have a mechanism for periodic revisions in line with technological advancements and accumulated engineering experience, to prevent the standard from becoming rigid and hindering the application of new materials and processes. The ultimate goal of establishing this standard and certification system is to ensure that the application of corrosion-resistant concrete has standards to follow, documentation to reference, and evidence to verify, thereby clearing institutional barriers to the adoption of this technology.

3. Strategies for Promoting the Application of Corrosion-Resistant Concrete Materials in the Context of Green and Low-Carbon Development

3.1 Improving specialized design standards

Refining specialized design codes is the primary strategy for promoting the widespread application of corrosion-resistant concrete. The core of this strategy lies in systematically articulating the corrosion-resistance requirements currently scattered across various specialized standards, thereby establishing specialized design codes applicable to different types of engineering projects and corrosion environments. Currently, the design basis for corrosion-resistant concrete is scattered across several standards, including the *Design Standard for Durability of Concrete Structures* and the *Design Code for Corrosion Protection of Industrial Buildings*. This makes it time-consuming and labor-intensive for designers to identify applicable provisions; moreover, the lack of uniform technical requirements across these standards increases design complexity and compliance risks (Yin, 2025). To improve this approach, it is necessary to develop a dedicated chapter on corrosion-resistant concrete within the *Design Code for Corrosion-Resistant Concrete Structures* or the *Design Guide for Durability of Concrete Structures*, and to provide a unified presentation of technical details such as the classification of corrosion environments, principles for material selection, construction measures, and requirements for protective layer thickness. The code should clearly distinguish between environments classified as mild, moderate, and severe corrosion, and accordingly specify mandatory criteria such as the minimum concrete strength class, maximum water-to-cement ratio, minimum cementitious material content, and minimum content of supplementary cementitious materials. In terms of construction measures, the code should provide detailed provisions regarding the thickness of the reinforcement cover, crack width limits, and waterproofing details at joints, while ensuring that corrosion resistance is integrated throughout all stages of structural design. Taking piers in marine environments as an example, the design code requires that in areas subject to water level fluctuations, the concrete strength be no less than C45, the water-to-binder ratio not exceed 0.36, the slag powder content be no less than 40 percent, and the cover thickness be no less than 50 millimeters. The revised design code enables design firms to comply clearly and provides review agencies with a basis for judgment, thereby eliminating at the source the tendency toward either overly conservative or overly risky designs caused by ambiguous design criteria.

3.2 Optimization of cementitious materials from industrial waste residues

Optimizing cementitious materials derived from industrial waste residues involves adjusting the types, dosages, and blending methods of auxiliary cementitious materials for corrosion-resistant concrete to reduce material costs, utilize industrial solid waste, and simultaneously enhance corrosion resistance. Slag powder, fly ash, and silica fume—as the primary auxiliary cementitious materials—exhibit distinct physicochemical properties (Li, 2025). Slag powder is characterized by a high activity index and hydration products rich in aluminate phases; it can effectively sequester sulfate ions and plays a prominent role in resisting sulfate attack. The spherical particle morphology of fly ash produces a significant ball-bearing lubrication effect, improving the workability of concrete. It undergoes a pozzolanic reaction with calcium hydroxide, producing a large amount of calcium silicate hydrate gel, which reduces the permeability of concrete. Silica fume, with its large specific surface area and highest reactivity, is indispensable in ultra-high corrosion-resistant concrete; however, excessive addition can lead to increased water demand and enhanced shrinkage. Optimization focuses on the composite addition of these three types of waste residues to leverage the complementary advantages of components with different ages and corrosion mechanisms (Yin & Xiong, 2025). Mix design optimization tests indicate that, with a total cementitious material content of 450 kilograms per cubic meter, when the blend ratios of slag powder, fly ash, and silica fume reach 30%, 15%, and 5%, respectively, the chloride ion diffusion coefficient in the concrete is reduced by approximately 60% compared to ordinary concrete, while its sulfate resistance coefficient increases to over 0.85. In the process of optimizing material performance, approximately 225 kilograms of industrial waste residue per cubic meter can be utilized in corrosion-resistant concrete, which provides significant environmental benefits in terms of solid waste disposal.

3.3 Factory-Based production of precast components

In the factory-based production of precast components, the preparation of corrosion-resistant concrete has shifted from on-site mixing to centralized factory production using standardized manufacturing processes, ensuring consistent quality. On-site concrete mixing is subject to numerous factors, including fluctuations in raw materials, measurement errors, ambient temperature, and the skill levels of operators. As a result, it is difficult to consistently achieve the required water-to-cement ratio and precise dosing of admixtures for corrosion-resistant concrete. This presents a major quality bottleneck in the current promotion and use of corrosion-resistant concrete. In a factory-based production system, automated batching and metering systems can achieve weighing accuracies of within ±1% for powders and ±0.5% for liquids. Forced-action mixers ensure the mixture meets uniformity standards, while steam curing systems provide constant temperature and humidity conditions for curing. This reduces the quality variation coefficient of corrosion-resistant concrete to less than one-third of that achieved through on-site mixing. To meet the diverse needs of various engineering projects, factories can establish a product inventory of precast components. This includes standardized products such as corrosion-resistant pipe piles, precast piles, drainage pipes, tunnel segments, and bridge piers. Design firms can directly select precast components of the appropriate grade based on the project's corrosion environment classification, eliminating the need for on-site mix design and quality inspection procedures. Taking a bridge project in a coastal region as an example, the design selected precast piers with a corrosion resistance grade of C-M. After the factory completed prefabrication, the components were transported to the site for installation. The on-site construction period was shortened by approximately 40 percent compared to the cast-in-place approach, and the visual quality and dimensional accuracy of the components were significantly superior to those of cast-in-place structures. The economies of scale achieved through industrialized production have also brought the overall cost of corrosion-resistant concrete components closer to that of cast-in-place concrete.

3.4 Establishment of a carbon credit incentive system

The carbon credit incentive system uses market-based mechanisms to provide economic incentives to construction entities using corrosion-resistant concrete, transforming the external benefits of carbon reduction across the full life cycle into internal economic drivers. The basic design approach involves calculating the reduction in carbon emissions over the full life cycle of corrosion-resistant concrete structures compared to ordinary concrete structures, converting this reduction into tradable carbon credits, and allocating credits to construction, design, and contracting entities based on their respective contributions. which can be traded or redeemed. This requires the development of a carbon emission reduction accounting methodology for corrosion-resistant concrete, as well as the clarification of project baselines, additionality, and monitoring procedures to ensure that emission reductions are verifiable and measurable. For the pilot phase, a selection of government-funded public buildings and infrastructure projects has been designated as the first batch of carbon credit pilot projects, and a comprehensive management system covering the entire process—from design declaration and construction monitoring to completion verification—has been established. In the carbon credit trading mechanism, credits can be traded within the region; high-carbon projects must purchase credits to fulfill their obligations, while low-carbon projects generate returns by selling credits, thereby establishing a market price discovery mechanism. Fourth, by linking with green finance, carbon credits can serve as a credit enhancement for green loans, green bonds, and other instruments; companies holding high-carbon credits enjoy preferential treatment in areas such as bank loan interest rates and credit limits. Consider a coastal residential community where corrosion-resistant concrete is used in place of traditional concrete; the structural design life would increase from 50 years to 100 years. Over the entire life cycle, this would reduce CO_2 equivalents by approximately 180 kilograms per square meter of floor area, resulting in total carbon emissions reductions of about 18,000 metric tons for the entire community. Based on the standard market price of 50 yuan per metric ton in the carbon credit market, this translates to an economic return of approximately 900,000 yuan—which not only offsets the cost difference between corrosion-resistant concrete and ordinary concrete but also generates a modest profit.

3.5 Demonstration projects and skills training

Demonstration projects and skills training serve as a strategy for translating technical standards and research findings into practical capabilities on the front lines. Many technical details regarding corrosion-resistant concrete cannot be conveyed through standard documents alone, construction personnel must focus on aspects that differ from those of ordinary concrete during actual work. The selection of demonstration projects should cover typical application scenarios in coastal infrastructure, industrial buildings in saline-alkali regions, and municipal engineering projects. Each demonstration project is paired with a corresponding case study, providing detailed descriptions of project overviews, corrosion environment parameters, corrosion-resistant concrete mix designs, key construction processes, quality control points, and post-construction testing data. The case studies are presented through a variety of formats, including text, images, and videos, and serve as foundational training materials for the industry. The skills training program targets designers, construction technicians, quality inspectors, and concrete batching plant operators, with tailored courses designed for each group. Training for designers focuses on methods for classifying corrosive environments and the design and calculation of mix proportions; training for technicians emphasizes pouring and curing processes as well as the establishment of quality inspection standards; and training for operators centers on practical skills such as the measurement of admixtures, control of mixing time, and slump testing. This training model organically integrates theoretical instruction with on-site practical training. The theoretical component leverages online platforms to achieve broad coverage, while the practical component relies on demonstration projects for small-class instruction. Upon successful completion of the training and passing the assessment, participants are awarded a specialized construction qualification certificate for corrosion-resistant concrete. Holding this certificate is made a prerequisite for employment on demonstration projects and a qualification requirement for bidding on related construction projects, thereby creating a virtuous cycle of "training and certification."

3.6 Building a full life-cycle database

The development of a full life-cycle database is a foundational strategy that provides long-term support for the widespread adoption of corrosion-resistant concrete at the data level. Its functional scope encompasses three distinct aspects: first, the establishment of a material performance database containing long-term tracking data on key performance indicators—such as compressive strength, chloride ion diffusion coefficient, sulfate resistance coefficient, and carbonation depth—for corrosion-resistant concrete with different mix designs; it also includes compatibility data for various grades and types of admixtures. The database, based on engineering case studies, documents the actual use of corrosion-resistant concrete in projects across various regions. This includes data on the characteristics of the corrosion environment at project sites, concrete mix designs, construction seasons, curing methods, and construction costs, as well as annual durability tests conducted after the structures are put into service. The carbon emission factor database collects data on the carbon emission intensity of raw materials for corrosion-resistant concrete at every stage—from extraction and transportation to production—and analyzes different construction processes and transportation methods. Once completed, the database will be made available to the industry for shared use. During the design evaluation phase, designers can access data on the actual performance and costs of similar projects; researchers can analyze the quantitative impact of mix design parameters on durability indicators based on extensive field data; and policymakers can obtain industry baseline data from the database to aid in decision-making. The database employs a mechanism for regular updates, compiling annual summaries of newly added project data and long-term monitoring and testing data, thereby ensuring the timeliness and representativeness of the data.

Conclusion

From the perspective of green development, the application and promotion of corrosion-resistant concrete materials constitute a systematic endeavor that requires both goal-oriented guidance and strategic support. The two major objectives—carbon reduction across the entire life cycle and the establishment of a standards and certification system—define the value orientation and institutional direction for widespread adoption. By coordinating various approaches and proceeding in an orderly manner, these efforts collectively advance the application of corrosion-resistant concrete from technical feasibility toward economic viability and institutional refinement, thereby providing strong support for the green transformation of the construction industry.

Conflict of Interest

The authors declare that they have no conflicts of interest to this work.

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How to Cite: Zhu, S., & Tu, C. (2026). A Study on Strategies for Promoting the Application of Corrosion-Resistant Concrete Materials from the Perspective of Green and Low-Carbon Development. *Journal of Global Humanities and Social Sciences*, *7*(4), 240-246
https://doi.org/ 10.61360/BoniGHSS262020310403