

# Development of Low-Carbon Coatings/Materials and Intelligent Construction Protection Technology

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## 1. Introduction and Scope

Global urbanization continues to accelerate, driving rapid growth in demand for new buildings and infrastructure, as well as further exacerbating natural resource consumption, ecological degradation, and greenhouse gas emissions [1–3]. In this context, the research and application of low-carbon materials and coatings, resource recycling technology, and intelligent construction and protection technology have received widespread attention. At present, urban construction is gradually moving from the traditional resource-based development model to a new stage of coordinated promotion of low-carbon materials, resource recycling, and engineering digitization.

The low-carbon transformation of the built environment is difficult to achieve through a single material or technology, and requires coordinated efforts from multiple aspects such as reducing the amount of cement clinker, developing alternative cementitious materials, utilizing recycled components, optimizing material mix ratios, improving durability, and extending the service life of structures [4–6]. Meanwhile, circular construction is transforming construction and demolition waste, metallurgical by-products, waste plastics, and biomass residues from conventional wastes into recyclable resources with engineerable performance and controllable processing, thereby providing an important pathway for reducing virgin-resource consumption and environmental burdens and promoting the sustainable development of the construction industry [7,8].

Moreover, the development of low-carbon materials should account for both material durability and the long-term performance of structures in service [9]. Chloride ingress, freeze–thaw cycling, friction and wear, and environmental and loading actions such as impact and earthquakes can all degrade material and structural performance [10–13]. It is therefore necessary to integrate the transport of aggressive agents, microscale damage evolution, macroscopic performance deterioration, and service-life prediction, thereby providing a theoretical basis and technical support for improving the in-service reliability of infrastructure [14–16].

At the same time, infrastructure protection is shifting from localized inspection and reactive repair toward intelligent sensing, risk prediction, and proactive maintenance. Technologies such as structural health monitoring, intelligent sensing, computer vision, machine learning, and artificial intelligence can effectively improve the efficiency of defect identification [17,18]. On this basis, by further integrating physical models, probabilistic



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risk analysis, and long-term monitoring data, intelligent evaluation technology is expected to develop into a comprehensive tool that integrates material state perception, structural performance evaluation, and maintenance decision optimization.

Surface and interface engineering further expands the functional boundaries of low-carbon materials and engineering protection. Advanced coatings such as diamond-like carbon films can improve the wear resistance, friction reduction, and protective properties of the substrate with minimal increase in material usage [19,20]. Multiphase composite coatings, graded electrodes, and heterogeneous interface materials can achieve synergistic improvements in mechanical, anti-corrosion, friction, and electrochemical properties through structural design and interface regulation. From this, it can be seen that innovation in low-carbon and resilient materials is gradually shifting from single-component substitution to multiscale collaboration in resource recycling, durability design, functional interfaces, and intelligent management.

In this context, this Special Issue “Development of Low-Carbon Coatings/Materials and Intelligent Construction Protection Technology” includes a total of 17 papers covering solid waste and biomass resource utilization, green cement-based materials, durability degradation and life prediction, advanced functional coatings and energy storage electrodes, as well as infrastructure resilience and intelligent risk assessment. The research objects and technological paths are different, and their common goal is to improve material performance, structural service reliability, and the scientific nature of engineering protection decisions while reducing resource consumption and environmental loads. The following text will summarize and discuss the papers in this Special Issue under four interrelated themes.

## 2. Contributions

### 2.1. Sustainable Utilization and Performance Improvement of Building Materials

One of the important themes of this Special Issue is the high-value utilization of waste resources in building materials and the improvement of the performance of recycled materials. Gao et al. [21] reviewed the application of solid waste-based cementitious materials in recycled mortar. Solid waste such as construction waste powder, slag, and fly ash has the potential to replace some cement, but their activity needs to be improved through thermal activation, carbonation activation, or alkali activation. Moderate addition of solid waste can improve pore structure and durability, while excessive addition can lead to a decrease in strength. Synergistic utilization of multi-source solid wastes, composite activation, and low-energy activation are important development directions for achieving high-performance and low-carbon recycled mortar.

Zhai et al. [22] reviewed the influence of steel slag fine aggregate on the volume stability of cement-based materials. Steel slag has the potential to replace natural fine aggregates, but the continuous hydration expansion of free CaO and free MgO can easily lead to particle damage, crack propagation, and mechanical property degradation. Among them, free CaO mainly affects early stability, while free MgO has a more significant impact on long-term service safety. The engineering application of steel slag fine aggregate should be combined with reasonable dosage control and pre-stabilization treatment to ensure the long-term stability of the material.

Lin et al. [23] analyzed the effects of cellulose ether, stone powder, manufactured sand, polyvinyl alcohol, and bentonite on the properties of premixed mortar. Cellulose ether is a key component in regulating fluidity and water retention, while stone powder and manufactured sand mainly affect strength development. Polyvinyl alcohol can improve crack resistance, while bentonite improves thickening and water retention effects. The article reveals the synergistic mechanism of organic–inorganic composite components and

establishes prediction and optimization methods for mortar flowability, water retention, and compressive strength.

Yan et al. [24] developed a biomass functional monomer-modified polycarboxylate superplasticizer using renewable raffinose as a functional monomer. Research has shown that this polycarboxylate superplasticizer can enhance the dispersibility of cement particles, improve the fluidity and flow retention of cement paste, delay early hydration, and optimize the microstructure of the hardened cement paste, thereby improving the compressive and flexural properties of mortar.

Song et al. [25] prepared a triisopropanolamine-modified polycarboxylate cement grinding aid. Research has shown that this grinding aid can reduce particle agglomeration, optimize particle-size distribution, improve grinding efficiency, improve cement paste fluidity, and promote hydration reactions, thereby enhancing the early and later strength of mortar and providing a reference for the development of high-performance and environmentally friendly cement grinding aids.

Zhou et al. [26] studied the effect of waste wood fibers on the properties of lightweight mortar. The results indicate that an appropriate amount of wood fiber can improve interfacial bonding, suppress crack propagation, and enhance the mechanical and thermal insulation properties of mortar. However, excessive dosage can easily lead to fiber aggregation and interface defects, reducing the overall performance of the material. Therefore, the dosage of wood fibers should be reasonably controlled.

Li et al. [27] studied the effects of recycled coarse aggregate replacement rate and freeze–thaw cycles on the frost resistance of recycled aggregate concrete. The results indicate that recycled aggregates increase the initial defects of concrete and exacerbate freeze–thaw damage, with the degree of damage increasing as the replacement rate and number of freeze–thaw cycles increase. The old interfacial transition zone is a weak point for crack initiation and propagation. The study also established a freeze–thaw damage prediction model based on the relative dynamic modulus of elasticity, which can better describe the degradation law of material properties.

Yang et al. [28] studied the improvement effect of waste polypropylene fibers on the frost resistance of recycled aggregate concrete. The results indicate that waste polypropylene fibers can slow down mass loss and the degradation of stiffness and strength by bridging cracks, optimizing pore structure, and improving interfacial properties, thereby enhancing the frost resistance and durability of recycled aggregate concrete. It is also pointed out that using a comprehensive evaluation of relative dynamic modulus of elasticity and strength loss can more accurately reflect the freeze–thaw resistance.

Yu et al. [29] reviewed the application of Microbially Induced Calcium Carbonate Precipitation (MICP) technology in the reinforcement and seepage control of fractured rock masses. Research has shown that MICP can fill cracks, improve strength, and reduce permeability by generating calcium carbonate. Its repair effect is influenced by factors such as bacterial strains, environmental conditions, and construction processes. The article believes that optimizing mineralization pathways, selecting bacterial strains, and improving construction processes are key to promoting the engineering application of MICP.

## 2.2. Durability Degradation, Transport Processes, and Intelligent Maintenance Decision-Making

For the long-term safe service of infrastructure, durability research is gradually expanding from material degradation mechanisms and aggressive-medium transport simulations to intelligent defect detection, performance degradation prediction, and life-cycle maintenance decision-making. Ji et al. [30] established a numerical model for macroscopic chloride ion diffusion in concrete based on the peridynamic differential operator (PDDO). Research has shown that this model can simulate the chloride ion transport process under

complex boundary and material defect conditions, revealing that internal defects accelerate the migration of chloride ions to the surface of reinforcing steel, increasing the risk of steel bar corrosion. It can provide a reference for concrete durability evaluation and service-life prediction.

Zhang et al. [31] studied the pavement distress identification and aging damage mechanism of asphalt pavement in municipal landscape roads. The results indicate that the shadow removal method based on SpA-Former can improve the accuracy of crack detection. Asphalt aging, temperature changes, and freeze–thaw cycles are the main causes of transverse crack formation. The study combines intelligent image recognition with material performance analysis, providing a reference for pavement distress detection and life-cycle maintenance.

### 2.3. Advanced Functional Coatings, Hierarchical Electrodes, and Interface Control

Regarding the optimization of material surface structure and improvement of interface function, this Special Issue explores the implementation path of enhancing the performance of composite coatings and energy storage electrodes from the aspects of particle-size regulation, hierarchical structure construction, and electrochemical activation. Qi et al. [32] prepared Ni–Co–Y<sub>2</sub>O<sub>3</sub> composite coatings and studied the effect of Y<sub>2</sub>O<sub>3</sub> particle size on coating properties. The results indicate that particle size and particle-size combinations can regulate the microstructure, hardness, tribological performance, and corrosion resistance of coatings. Reasonable optimization of particle size can help achieve a synergistic improvement in the comprehensive performance of coatings.

Lv et al. [33] constructed a CuCo<sub>2</sub>O<sub>4</sub>/nickel–cobalt–sulfide hierarchical electrode and studied the effect of electrodeposition time on its energy storage performance. The results indicate that the hierarchical structure can increase active sites and promote ion transport. By optimizing the electrodeposition time, the specific capacitance, rate performance, and cycling stability of the electrode can be improved.

Liu et al. [34] prepared an electrochemically activated ZnCo-LDH/NCS hierarchical electrode (EA ZnCo-LDH/NCS), and systematically analyzed the effects of activation conditions and synergistic effects of different components on energy storage performance. Research has shown that hierarchical architecture and electrochemical activation can synergistically improve electrode reaction kinetics, enhance specific capacitance, rate performance, and cycling stability, providing a reference for the design of high-performance energy storage electrodes.

### 2.4. Infrastructure Resilience and Intelligent Risk Assessment

In the face of sudden disasters such as impacts, earthquakes, and landslides, infrastructure security needs to coordinate the design of protective materials and energy-dissipating structures, structural vulnerability analysis, and intelligent prediction of regional disasters, in order to achieve a transition from passive disaster resistance to risk identification, active protection, and resilience enhancement. Gao et al. [35] studied the impact response characteristics of EPS and EPE foams and soil–lightweight foam composite protective layers. The results indicate that EPE has better stress wave attenuation and energy absorption capabilities, making it suitable as an impact-resistant protective material. The performance of composite protective layer is affected by the thickness of foam and the proportion of soil, so the structural design should be optimized according to the engineering needs.

Chen et al. [36] established a comprehensive seismic assessment system for bridges that considers seismic hazard, structural vulnerability, and damage risk. Research has shown that side piers and bearings are weak areas for seismic resistance in bridges. Therefore, it is necessary to focus on strengthening bearings, unseating-prevention devices, and seismic

isolation and energy dissipation designs, providing a reference for seismic reinforcement and resilience enhancement of bridges.

Wang et al. [37] studied the applicability of conditioning factors and prediction models in landslide susceptibility mapping. The results indicate that introducing dynamic factors can improve the accuracy of landslide susceptibility prediction, and different factor combinations and models have a significant impact on the evaluation results. The study screened for better dynamic factor expression methods and prediction models, providing a reference for landslide risk identification and regional disaster prevention and reduction.

Overall, the 17 papers in this Special Issue cover multiple directions, including solid waste resource utilization, material performance regulation, durability improvement, functional interface design, and infrastructure risk assessment. Related studies have shown that the development of green engineering materials not only relies on the high-value utilization of waste resources, but also requires strengthened regulation of pore structure, interfacial characteristics, transport processes, and damage evolution, combined with intelligent detection, service-life prediction, and risk analysis, to achieve synergistic improvement of material performance, structural safety, and environmental benefits.

### 3. Conclusions and Outlook

This Special Issue showcases the latest research progress in solid waste resource utilization, green cementitious materials, functional additives, durability improvement, advanced coatings and energy storage electrodes, and infrastructure risk assessment. The included papers comprehensively adopt methods such as material testing, microscopic characterization, numerical simulation, statistical analysis, machine learning, and probabilistic risk analysis, extending from material composition, microstructure, transmission and damage processes to structural safety and regional disaster assessment, reflecting the deepening cross-integration between material science, civil engineering, surface engineering, and intelligent analysis technology.

In the future, research on green building materials should balance resource utilization efficiency and long-term service performance [5,7,38]. For solid waste such as steel slag, recycled aggregates, and waste fibers, the focus should be on addressing issues such as raw material fluctuations, interface defects, volume stability, and durability, and improving performance stability through pretreatment, composite activation, and synergistic proportioning. Biomass additives and green grinding aids need to be strengthened in terms of large-scale preparation, system adaptability, and long-term performance verification, in order to promote the transformation of achievements into engineering applications.

Durability research should strengthen the connection between micromechanisms, accelerated testing, numerical simulation, and actual service environments, focusing on freeze–thaw, salt erosion, chloride ion transport, material aging, and crack propagation, and improve evaluation indicators and life prediction methods [39,40]. Coatings, electrodes, and other functional materials should further optimize their interface structure, component coordination, and preparation parameters to achieve coordinated improvement of multiple properties.

In the field of infrastructure security, intelligent detection and risk assessment should develop from a single identification model to a comprehensive decision-making system, integrating computer vision, physical models, probability analysis, real-time monitoring and maintenance data to improve the ability to identify, predict and warn of disasters and long-term deterioration risks [17,41,42].

The Guest Editors expect this Special Issue to further promote cross-disciplinary collaboration in fields such as materials science, coating engineering, civil and geotechnical engineering, and data science. Through collaborative promotion of low-carbon material

development, durability design, intelligent risk assessment, and full life-cycle management, related research is expected to gradually shift from single material or performance optimization to systematic solutions that balance resource recycling, long-term safety, and engineering resilience, thereby reducing primary resource consumption and repetitive maintenance, as well as improving the reliability and sustainability of infrastructure throughout the service life.

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