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Research on the Application of Building Materials and the Low-Carbon Management System in Construction Engineering

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Abstract: The low-carbon transformation of the construction industry is a crucial component of achieving sustainable development. Green building materials, characterized by low emissions, low energy consumption, and recyclability, serve as a key material foundation for low-carbon management in construction projects. This paper investigates the application of green building materials and the low-carbon management framework for construction projects, elucidates relevant theoretical foundations, identifies current shortcomings and challenges in management across design, construction, and operational phases, and proposes a comprehensive low-carbon management pathway spanning the entire lifecycle. It also outlines safeguard measures at the standards, technology, and management levels. The research contributes to refining low-carbon management models, fostering deeper integration of green building materials with construction practices, enhancing carbon reduction throughout the entire lifecycle, and providing actionable insights for the industry's low-carbon development.

Keywords: Green building materials; Low-carbon management; Full life cycle; Construction engineering

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1. Introduction

Against the backdrop of increasingly stringent carbon emission regulations, the construction industry, as a major consumer of energy and emitter of carbon, must urgently advance a low-carbon transformation across its entire value chain. Green building materials are integral throughout the entire lifecycle of construction projects and play a crucial role in reducing carbon emissions from material production, construction, and operational maintenance. Currently, low-carbon management in China's construction sector faces challenges such as fragmented approaches, limited practical implementation of green materials, and inadequate coordination mechanisms, all of which hinder overall emission reduction outcomes. This paper addresses these issues by systematically establishing a low-carbon management framework guided by green building principles, clarifying key control priorities and implementation pathways at each stage, thereby holding significant practical value for enhancing low-carbon management standards in the construction sector.

2. Theoretical foundations of green building materials and low-carbon management

2.1. The connotation and low-carbon characteristics of green building materials

Green building materials are environmentally friendly construction materials characterized by low energy consumption, low emissions, and low pollution throughout their entire lifecycle, from raw material sourcing and manufacturing to engineering application and waste recycling. They significantly reduce the environmental burden and carbon footprint of buildings over their entire service life. Compared to traditional building materials, their production process substantially decreases fossil fuel consumption and carbon dioxide emissions; some recycled materials even enable the resourceful utilization of industrial solid waste, cutting carbon emissions at the source. During building operation, green materials enhance thermal performance, improve insulation, ventilation, and environmental purification efficiency, lower energy consumption during the operational phase, and thereby extend the carbon reduction timeline.

Green building materials offer a comprehensive range, including low-carbon cementitious materials, energy-efficient insulation panels, recycled aggregates, eco-friendly decorative materials, and low-carbon steel, which can be widely applied in various construction components such as structural frameworks, building envelopes, and interior finishes. Each type of material emphasizes distinct low-carbon performance characteristics and specific application scenarios, enabling compatibility with diverse regional climate conditions, building functional requirements, and investment budgets. These materials provide robust material support for low-carbon construction management and serve as an indispensable core component in establishing a low-carbon building system.

2.2. Low-carbon management content for the full life cycle of construction projects

Low-carbon management throughout the entire lifecycle of construction projects is grounded in quantitative carbon emission accounting, extending its scope to encompass the entire process, from design and construction to operation, demolition, and waste recycling and treatment. Through technical optimization, standardized management practices, process monitoring, and performance evaluation, it achieves systematic reduction and precise control of carbon emissions at each stage. Key components of the management framework include lifecycle carbon emission accounting, decomposition of emission reduction targets with clear accountability, process control at critical stages, and dynamic evaluation coupled with feedback-driven adjustments of implementation outcomes. This approach emphasizes an integrated management model focusing on source reduction, process-based emission control, and end-of-life recycling, thereby transforming the traditional segmented, fragmented, and extensive approach to project management.

Low-carbon management throughout the entire lifecycle is driven by digital data, breaking down the overall carbon reduction target into specific stages, participating entities, and construction phases, thereby establishing a clear mechanism for responsibility allocation and performance evaluation. By coordinating key elements such as the application of green building materials, optimization of construction organization, equipment operation management, and energy consumption control during operations, effective integration and synergistic implementation of control measures across all phases are achieved.

2.3. The intrinsic relationship between green building materials and low-carbon management

Green building materials serve as the core material foundation for low-carbon management in construction projects. The selection of materials, their application ratios, construction quality, and operational maintenance standards directly determine a project's overall carbon reduction potential and management effectiveness. The scientific adoption of green building materials with superior low-carbon performance and strong adaptability can significantly reduce embodied carbon emissions and operational energy consumption at the source. Proper application also minimizes construction waste and material performance degradation, serving as a prerequisite and critical foundation for achieving low-carbon management objectives. The low-carbon management system provides institutional and technical safeguards for the efficient and standardized use of green building materials, regulating material usage, storage, maintenance, and recycling throughout

the entire lifecycle to enhance utilization efficiency and performance stability, thereby fully realizing their low-carbon advantages.

The two elements mutually reinforce, are deeply integrated, and develop synergistically. The application of green building materials must be embedded across all lifecycle management stages: material selection during the design phase must closely align with management objectives; their implementation during construction must be incorporated into comprehensive process control; and maintenance during the operational phase must adhere to management requirements while providing feedback for optimization.

3. Existing issues in the application of green building materials and low-carbon management

3.1. Disconnection between building material selection and low-carbon management during the design phase

A core issue prevalent during the design phase is the insufficient scientific rigor and rationality in green building material selection. Designers often prioritize achieving building functions, ensuring structural safety, and controlling project costs during the design process, while paying inadequate attention to critical factors such as the low-carbon performance of materials, carbon emission accounting across the entire lifecycle, and regional climate compatibility. This results in a clear disconnect between material selection and low-carbon management objectives, preventing effective alignment. Some projects blindly adopt expensive, high-end green materials to align with the "low-carbon" concept, neglecting actual functional requirements, construction feasibility, and future operation and maintenance costs. Consequently, these projects face significant implementation challenges and ultimately fail to achieve the intended emission reduction outcomes [1].

Meanwhile, the application of carbon emission quantification assessment tools remains limited during the design phase. Designers lack professional carbon footprint calculation capabilities, making it impossible to conduct multi-dimensional, full-life-cycle comparisons and optimal selections of different building material combinations. Design decisions consequently lack scientific data support. There is insufficient effective coordination and communication mechanisms among various design disciplines, as well as between design, construction, and operation phases.

3.2. Weak process control of green building materials during the construction phase

The construction phase is a critical stage for the application of green building materials and carbon emission control. However, most current projects lack refined, standardized management across the entire lifecycle of green building materials, including transportation, storage, cutting, installation, and maintenance. This results in high material loss rates and inadequate protection measures for finished products, directly leading to performance degradation and failure to fully realize the low-carbon advantages. Construction organization designs fail to optimize work processes and technical arrangements based on the characteristics of green building materials; the use of energy-intensive construction machinery remains high, the resource utilization rate of construction waste is low, green construction measures often remain superficial, and carbon emission control during construction is severely insufficient, lacking effective implementation mechanisms.

The construction phase involves numerous participating entities with complex overlapping processes, yet the responsibilities for low-carbon management remain ambiguous and unclear. The project owner, construction contractor, and supervision unit have failed to establish a coordinated control framework or collaborative advancement mechanism. In some projects, efforts to shorten timelines and reduce costs have led to deliberate simplification of green building material protection measures and unauthorized lowering of construction standards. Compounded by insufficient on-site carbon emission monitoring equipment, limited monitoring coverage, and the absence of real-time data collection and intelligent early-warning systems, the baseline carbon emissions during construction remain unclear, issue rectification is delayed, and operational efficiency is low.

3.3. The collaborative mechanism for full-cycle low-carbon management and control remains inadequate

During the building operation phase, widespread issues include inadequate low-carbon operation and maintenance systems and missing management frameworks. Most buildings lack comprehensive online monitoring systems for energy consumption and environmental conditions, while the operation and control of equipment such as air conditioning, lighting, and ventilation remain crude and lack intelligent optimization. The energy-saving, thermal insulation, and heat-isolation properties of green building materials are not fully utilized to reduce operational carbon emissions; actual operational energy consumption and carbon emissions far exceed design expectations, preventing the long-term realization of the low-carbon benefits of these materials. During the demolition phase, the recycling system for renewable building materials is immature, with inefficient resource utilization channels and insufficient supporting facilities. A significant number of recyclable materials with recovery value is directly discarded, making it difficult to implement effective end-of-life low-carbon control measures with limited impact.

At each stage of the full life cycle, the responsible entities operate relatively independently, with poor information flow and a lack of data sharing. Data on green building materials application, carbon emissions during construction, and energy consumption and carbon emissions during operation are difficult to share, hindering the establishment of a unified data system [2]. Overall management lacks unified standards and specifications as well as a closed-loop evaluation system; control requirements across stages are not aligned, control objectives are inconsistent, and control logic lacks coherence.

4. Establishing a low-carbon management system under the guidance of green building materials

4.1. Low-carbon control strategies at the design stage

With the core objective of reducing carbon emissions throughout the entire lifecycle of construction projects, a scientific and systematic hierarchical selection system for green building materials is established. This system fully incorporates key factors such as the local climate characteristics, building functional requirements, and project investment constraints, comprehensively evaluating multidimensional indicators, including carbon emission intensity, economic cost, durability, and compatibility, to determine the optimal building material combination that precisely aligns material selection with low-carbon management goals.

By introducing professional carbon emission accounting and simulation tools, we conduct full-life-cycle carbon footprint assessments and multi-scenario comparisons for various design solutions and building material combinations, providing scientific and quantifiable data support for design decisions. A multi-disciplinary collaborative design platform is established to integrate the design requirements of architecture, structural engineering, mechanical and electrical systems, and interior decoration, while aligning construction processes and operational management practices in advance to ensure effective communication between design and subsequent phases.

4.2. Low-carbon management strategies for the entire construction phase

The optimization of construction organization and design requires the development of targeted and highly operational specialized construction plans for green building materials. Management requirements for all stages, including material transportation routes, storage methods and conditions, installation procedures, and cutting and processing specifications, should be clearly defined to minimize secondary handling and material waste while maximizing the actual utilization rate of green building materials. The scientific selection of low-energy-consumption and low-emission construction machinery and equipment, together with the vigorous promotion of green construction techniques such as prefabricated construction and dry methods, can effectively strengthen the comprehensive management of construction dust, noise, and wastewater, increase the resource recovery rate of construction waste, and comprehensively reduce carbon emissions and

environmental impacts throughout the construction process.

A dynamic carbon emission monitoring and intelligent early-warning system covering the entire construction process should be established, with strategically arranged monitoring points used to collect real-time key data, including building material usage, equipment energy consumption, and on-site carbon emissions. Scientifically defined warning thresholds can enable the timely identification, correction, and rectification of anomalies. Critical indicators, such as the quality of green building material application, material loss rates, and emission reduction effectiveness, should also be incorporated into the construction performance evaluation system. In addition, the control responsibilities of all parties involved, including the project owner, contractor, and supervisor, should be clearly defined to establish a tiered and closed-loop management framework [3].

4.3. Long-term low-carbon management strategy for the operational phase

A low-carbon operation and maintenance management system that closely aligns with the performance characteristics of green building materials should be established. The online monitoring system for building energy consumption, environmental parameters, and equipment operating conditions should be improved, while intelligent regulation and automation technologies should be utilized to optimize the operational modes of air conditioning, lighting, and ventilation systems. These measures can fully leverage the core advantages of green building materials in thermal insulation, energy efficiency, and environmental sustainability, thereby continuously reducing energy consumption and carbon emissions during the operational phase.

A carbon emission ledger and a regular evaluation mechanism should also be established during the operational phase to support the continuous analysis and in-depth mining of monitoring data. Operation and maintenance strategies, together with control measures, should be dynamically optimized and adjusted based on actual operational data, thereby achieving refined and intelligent operation and maintenance management. In addition, an information feedback and reverse optimization mechanism linking the operational phase with the design and construction phases should be developed. Key data, including building material usage status, energy consumption performance, emission reduction effectiveness, and operation and maintenance issues, should be fed back in real time to the earlier design and construction stages. This process can provide a scientific basis for subsequent material selection and construction process optimization, thereby establishing a closed-loop low-carbon management model for the operational phase.

5. Measures to ensure the effective operation of the low-carbon management system

5.1. Improving the standard system for green building materials and low-carbon management

Comprehensive standards for green building materials, low-carbon performance evaluation criteria, and technical specifications for engineering applications should be established. Carbon emission accounting methods, testing procedures, certification requirements, and evaluation tiers for green building materials should be unified to provide clear and consistent guidelines for material selection, on-site acceptance, and quality control. In addition, low-carbon management technical regulations and administrative measures covering the entire lifecycle of construction projects should be developed. These regulations should specify control indicators, operational procedures, assessment methods, and responsible entities for each phase, including design, construction, operation, and demolition, thereby enhancing the standardization, normalization, and institutionalization of low-carbon management practices.

Differentiated implementation guidelines and control measures should also be developed according to various building types and regional climate characteristics to improve the applicability and operability of the standards. Furthermore, a comprehensive evaluation mechanism for green building material application and low-carbon management should be established. Key indicators, including building carbon emission intensity, material recycling rates, operational energy consumption levels, and emission reduction effectiveness, should be incorporated into the project assessment system, thereby strengthening the binding and mandatory nature of standard enforcement.

5.2. Establish a digital low-carbon management and control technology platform

By leveraging digital technologies such as Building Information Modeling (BIM), the Internet of Things (IoT), big data, and cloud computing, an integrated digital solution for low-carbon management throughout the entire lifecycle of green building materials and construction projects can be established. The platform should consolidate fundamental data related to the production, transportation, application, and performance of green building materials, together with critical metrics, including carbon emissions during construction and energy consumption and carbon emissions during operation. This integration can enable comprehensive data interoperability, information sharing, and visual management across all stages of the project lifecycle. In addition, the platform should incorporate core functionalities such as scenario simulation analysis, real-time data monitoring, intelligent early-warning alerts, emission reduction effectiveness evaluation, and carbon footprint calculation, thereby enabling the dynamic tracking of carbon emission trends in construction projects and providing precise, real-time data support for low-carbon management decision-making.

A full lifecycle traceability system for green building materials should also be established to enable comprehensive tracking and traceable management throughout the entire process, including manufacturing, transportation, on-site acceptance, application, and waste recycling. Such a system can ensure compliance with low-carbon performance standards and maintain controllable application processes. Furthermore, digital construction simulation, energy consumption modeling, and carbon emission prediction technologies should be promoted to optimize project designs, enable precise control during construction, and facilitate intelligent operational adjustments. These measures can significantly enhance the accuracy, efficiency, and responsiveness of low-carbon management.

5.3. Improve the multi-party collaborative management and talent support mechanism

A low-carbon collaborative management mechanism involving multiple stakeholders, including construction, design, contracting, supervision, and operation entities, should be established. The respective rights, responsibilities, workflows, and evaluation criteria of each party in low-carbon management should be clearly defined. In addition, a communication platform for regular consultations, problem coordination, and information sharing should be created to effectively break down information barriers and eliminate collaboration bottlenecks. A management system that combines incentives with constraints should also be implemented by directly linking low-carbon management outcomes to project awards, corporate credit ratings, and project payment settlements, thereby fully motivating all participating units and personnel to proactively and responsibly fulfill low-carbon management requirements.

The development of a comprehensive talent cultivation system for interdisciplinary professionals should also be strengthened through the establishment of an integrated mechanism that combines institutional education, corporate training, and industry collaboration. Specialized training programs focusing on green building material performance, low-carbon management theories, digital operational skills, and carbon emission accounting methodologies should be conducted to comprehensively enhance practitioners' professional capabilities and overall competence. Furthermore, an industry platform for technical exchange and knowledge dissemination should be established, with regular seminars on low-carbon management technologies, experience-sharing activities, and achievement exhibitions organized to promote the widespread adoption of advanced low-carbon management technologies and green building material application cases throughout the industry [4].

6. Conclusion

The large-scale application of green building materials and the establishment of a low-carbon management system covering the entire lifecycle serve as crucial drivers for advancing the low-carbon transformation of the construction industry. Building on a review of relevant theories, this paper identifies current challenges in application and management during the design, construction, and operational phases, and proposes a comprehensive low-carbon management framework that

spans the source, process, and long-term operational stages.

Disclosure statement

The author declares no conflict of interest.

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