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Review of Research on Carbon Reduction Paths in Construction Project Implementation

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Abstract

This review comprehensively examines carbon reduction paths in construction project implementation. It highlights advancements in three key areas: 1) carbon accounting methods like LCA and BIM for accurate emission measurement; 2) practical strategies including low-carbon materials, optimized concrete, and prefabrication to reduce on-site emissions; and 3) enabling management and policy mechanisms such as carbon pricing and sustainable procurement. The synthesis underscores the need for an integrated approach combining technological innovation, robust accounting, and supportive policies to drive the construction industry towards a sustainable, low-carbon future.

Keywords: Carbon Reduction; Construction; Life Cycle Assessment (LCA); BIM; Low-Carbon Materials; Policy

1 INTRODUCTION

Construction activities are significant contributors to global carbon emissions, accounting for a substantial portion of greenhouse gas emissions worldwide. As the urgency to mitigate climate change intensifies, reducing the carbon footprint of construction projects has become a critical imperative. This review synthesizes existing literature on carbon reduction strategies during the construction phase of projects, aiming to provide a comprehensive overview of the current research landscape. By identifying key research areas, methodologies, and findings, this review highlights current gaps and future research directions to promote sustainable construction practices within the construction industry.

This review is structured around three central themes. First, we examine carbon emission measurement and accounting methods in construction processes, encompassing Life Cycle Assessment (LCA) methodologies, the application of Building Information Modeling (BIM), the development of carbon emission factor databases, and hybrid carbon accounting approaches. Understanding these methodologies is crucial for accurately assessing the carbon footprint of construction projects and identifying areas for improvement. Second, we delve into carbon reduction strategies in construction materials and technologies, focusing on the use of low-carbon materials, optimization of concrete mix designs, adoption of energy-efficient equipment, and the implementation of prefabricated construction. Exploring these strategies offers practical solutions for minimizing carbon emissions during the construction phase. Third, we investigate management and policy mechanisms for promoting low-carbon construction, including the impact of carbon pricing, the role of government regulations, and the development of sustainable procurement strategies. Analyzing these mechanisms provides insights into how policy and management practices can drive the adoption of low-carbon construction practices. By exploring these three central themes, this review aims to provide a holistic understanding of the carbon reduction paths available during construction project implementation.

2 Carbon Emission Measurement and Accounting Methods in Construction Processes

Accurate and comprehensive carbon emission measurement and accounting are fundamental to identifying and implementing effective carbon reduction strategies in construction projects. This section reviews various methodologies employed for quantifying carbon emissions throughout the construction process, highlighting their strengths and limitations.

Life Cycle Assessment (LCA) methodologies have emerged as a dominant approach for evaluating the environmental impacts of construction projects, providing a holistic framework for quantifying carbon emissions across all stages of a project's lifespan. LCA enables the measurement of environmental burdens, including greenhouse gas emissions, at any specific stage or throughout the entire life cycle of a construction project [8]. Studies have demonstrated the utility of LCA in comparing the carbon footprints of different design choices. For instance, Nie et al.employed LCA to analyze the carbon emissions associated with plaza ground paving projects, contrasting cast-in-place architectural concrete (CAC) with natural stone pavement. Their findings revealed a significant difference in carbon emissions, with CAC pavement emitting 75.46 kg CO2/m2 compared to 110.81 kg CO2/m2 for natural stone pavement, underscoring the importance of material selection in minimizing environmental impact. Similarly, Wang et al.developed a life cycle carbon emission assessment model for power transmission and transformation projects (PTTP) based on the LCA method, dividing the project's life cycle into four distinct stages: production, installation and construction, operation and maintenance, and demolition. These studies illustrate the capability of LCA to provide detailed insights into the carbon implications of construction activities.

Building Information Modeling (BIM) is increasingly being recognized for its significant potential in carbon emission estimation and management within construction projects. BIM offers digital representations of a building's physical and functional characteristics, facilitating more accurate and comprehensive lifecycle assessments. Research indicates that BIM can be effectively leveraged to reduce carbon emissions, particularly during the design phase, by enhancing resource efficiency and enabling the integration of carbon emission calculators. Datta et al. identified "Promoting carbon emission reduction" and "Enhancing material wastage reduction" as the primary environmental benefits derived from implementing BIM in sustainable construction projects. The practical applicability of BIM for carbon emission reduction is further evidenced by successful implementations in countries like China, demonstrating its value in promoting sustainable construction practices.

The accuracy of carbon accounting in construction projects hinges on the availability of robust carbon emission factor databases specific to construction materials and activities. These databases provide essential coefficients that translate activity data, such as the quantity of material used or the hours of equipment operation, into corresponding carbon emissions. A comprehensive database should encompass a wide range of materials, including cement, steel, and asphalt, as these materials are major contributors to the embodied carbon of construction projects. The environmental impact of these materials is substantial; for example, the production of one ton of cement can generate approximately 659 kg of CO^2, while producing one ton of crude steel can emit over 2,000 kg of CO^2. Furthermore, a well-developed database should account for emissions from various stages of the construction process, including material production, transportation, and on-site construction activities.

To achieve a more complete understanding of the carbon footprint of construction projects, hybrid approaches that combine process-based LCA and input-output analysis are gaining traction. Process-based LCA is particularly effective at detailing specific processes and materials within a defined system boundary, while input-output analysis captures broader, economy-wide impacts, including indirect emissions from upstream supply chains. Shi et al. proposed a process-based hybrid LCA method, integrating process-based LCA with input–output LCA, to efficiently estimate carbon emissions that may be excluded from the system boundary due to data limitations. This integrated approach offers a more comprehensive perspective on the carbon footprint of construction projects, addressing the inherent limitations of each method when applied in isolation.

3 Carbon Reduction Strategies in Construction Materials and Technologies

The construction sector is actively exploring strategies to curtail its carbon footprint, with a significant focus on the materials and technologies employed. A key area of investigation involves the adoption of low-carbon construction materials. This encompasses a shift towards recycled aggregates, bio-based alternatives, and innovative cementitious binders. While some construction enterprises prioritize immediate economic gains over sustainability, a growing consensus recognizes the importance of incorporating low-carbon materials to meet the energy-saving demands of contemporary building projects. Indeed, studies have highlighted the extensive application of renewable energy decorative materials in various design aspects, including ventilation, thermal insulation, interior design, and lighting, each contributing variably to carbon emissions during the use phase.

Complementary to material selection, optimizing concrete mix designs offers another avenue for reducing embodied carbon. Historically, the industry has been hesitant to reduce cement content, despite evidence suggesting that performance can be maintained or even enhanced through optimized formulations and performance-based design methodologies. Research has demonstrated the viability of alternative concrete mixes with significantly reduced cement content (e.g., 22% reduction in one study based on a real bridge project), exhibiting comparable durability and a markedly lower carbon footprint. The incorporation of supplementary cementitious materials (SCMs), such as fly ash and granulated blast furnace slag (GBFS) in alkali-activated concretes, further diminishes the reliance on traditional cement production, presenting a promising pathway to decarbonization.

Beyond material choices, the adoption of energy-efficient construction equipment represents a crucial step towards minimizing carbon emissions. Optimizing the design and operation of power plant equipment, integrating combined-cycle power plants, and employing frequency drives for critical rotating mechanisms are examples of promising measures aimed at maximizing energy savings. The development of energy-efficient crushing machines also contributes to improving the sustainability of building material production.

Finally, prefabricated construction and modularization offer a compelling approach to minimize on-site waste and associated emissions. The benefits of prefabricated buildings are increasingly recognized, including shorter construction timelines, improved cost-effectiveness, and enhanced resource utilization. Strategies such as reversible design, modularity, and the incorporation of recycled materials can further reduce embodied carbon and promote material reuse. Studies have indicated that carbon emissions during the dismantling phase of prefabricated buildings are demonstrably lower compared to traditional cast-in-place structures, highlighting the potential of these methods to contribute to a more circular and sustainable construction industry.

4 Management and Policy Mechanisms for Promoting Low-Carbon Construction

The construction sector's significant contribution to global carbon emissions necessitates the exploration of effective management and policy mechanisms to promote low-carbon construction practices. These mechanisms range from market-based instruments to regulatory mandates and strategic procurement approaches, all aimed at reducing the environmental footprint of construction projects.

The implementation of carbon pricing mechanisms, such as carbon taxes and cap-and-trade systems, represents a crucial step in internalizing the environmental costs associated with construction activities. By assigning a monetary value to carbon emissions, these mechanisms incentivize project stakeholders to actively seek and adopt low-carbon alternatives. A carbon tax levied on energy-intensive materials or processes, for instance, can encourage the utilization of recycled aggregates, bio-based materials, and energy-efficient equipment. Cap-and-trade systems, on the other hand, establish an overall emissions limit and allow for the trading of emission allowances, fostering innovation in carbon reduction technologies and practices. The effectiveness of these mechanisms is further underscored by research demonstrating that incorporating carbon emission constraints into project scheduling models can optimize project net present value while minimizing greenhouse gas emissions, highlighting the potential for aligning economic and environmental objectives.

Beyond market-based approaches, government regulations and building codes play a vital role in mandating and incentivizing low-carbon construction practices. These regulatory frameworks can encompass a variety of measures, including the establishment of minimum energy performance standards for buildings, the requirement for the use of low-carbon materials, and the provision of financial incentives for projects that surpass these standards. The impact of such regulations is evident in instances where they have significantly altered material selection decisions. However, the effectiveness of these regulations hinges on their ambition and scope. Studies suggest that current mandatory building energy regulations in some regions may not be sufficiently stringent to achieve substantial carbon reductions. Furthermore, the design of incentive structures is critical, as excessive rewards or penalties may not promote long-term system stability. Therefore, a nuanced approach is needed to ensure that regulations and incentives are both effective and sustainable.

Complementing these regulatory and market-based approaches, sustainable procurement strategies are essential for prioritizing low-carbon materials and construction services, thereby driving demand for environmentally friendly options within the construction industry. These strategies involve integrating carbon footprint assessments into the selection criteria for materials and contractors. Given that embodied carbon from the manufacturing of building materials constitutes a significant portion of global greenhouse gas emissions, prioritizing low-carbon materials is paramount. Research further supports the notion that the efficient use of these materials can lead to both cost reductions and waste minimization. By adopting sustainable procurement practices, the construction industry can actively contribute to a more circular and environmentally responsible economy.

5 Conclusions

In summary, the reviewed literature underscores the multifaceted nature of carbon reduction in construction projects, highlighting advancements in carbon accounting methodologies, the increasing adoption of low-carbon materials and technologies, and the growing influence of management and policy mechanisms. The evolution of carbon emission measurement, from LCA and BIM applications to hybrid approaches, provides a more refined understanding of a project's carbon footprint, enabling more targeted reduction strategies. Simultaneously, the shift towards low-carbon materials, optimized concrete mixes, energy-efficient equipment, and prefabricated construction demonstrates tangible pathways for minimizing emissions during the construction phase. Finally, the implementation of carbon pricing, supportive government regulations, and sustainable procurement strategies further reinforces the commitment to a low-carbon future.

Looking ahead, the construction industry stands at the cusp of a transformative shift towards greater sustainability. To fully realize the potential for carbon reduction, future research should prioritize the development of standardized and universally accepted carbon accounting methodologies, fostering greater transparency and comparability across projects. Simultaneously, accelerating the adoption of innovative low-carbon technologies, such as carbon capture and utilization in cement production, holds immense promise. Ultimately, strengthening policy frameworks through ambitious regulations and strategic incentives will be essential to drive widespread change and accelerate the transition towards a truly sustainable construction industry, one that not only minimizes its environmental impact but also contributes to a more resilient and equitable future for all.

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