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Review Article

Green and Low-Carbon Construction Materials for Climate-Adaptive Civil Structures

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Abstract

The accelerating impacts of climate change, including rising global temperatures, extreme weather events, and increasing carbon emissions, are intensifying the demand for sustainable and climate-adaptive construction practices. Conventional construction materials such as cement, steel, and concrete, while critical for modern infrastructure, contribute significantly to greenhouse gas emissions and exacerbate the environmental footprint of the built environment. This paper explores the potential of green and low-carbon construction materials as foundational elements in designing climate-adaptive civil structures. Specifically, it examines the life-cycle environmental performance of alternative materials such as geopolymer concrete, recycled aggregates, cross-laminated timber (CLT), bamboo composites, and phase change material (PCM)-enhanced concretes. These materials not only reduce embodied carbon but also improve thermal efficiency, resilience, and adaptability under climate stressors. The paper integrates insights from life-cycle assessment (LCA), material innovation research, and adaptive design strategies to propose a holistic framework for sustainable construction. Furthermore, digital technologies such as Building Information Modeling (BIM) and material passports are discussed as enablers of circularity and low-carbon supply chains. By analyzing recent advances and case studies, this study demonstrates how climate-adaptive materials can reduce construction-related CO_2 emissions by up to 40%, extend service life under extreme conditions, and support global carbon neutrality targets. The findings underscore the urgency of mainstreaming low-carbon materials into infrastructure planning, highlighting their role in transitioning toward resilient, sustainable, and climate-conscious civil engineering practices.

Keywords: Green Construction Materials, Low-Carbon Infrastructure, Geopolymer Concrete, Climate Adaptation, Cross-Laminated Timber, Life-Cycle Assessment.

I. INTRODUCTION

The construction industry is among the largest contributors to global greenhouse gas emissions, responsible for nearly 40% of energy-related carbon dioxide output when considering both operational and embodied emissions. The traditional reliance on carbon-intensive materials such as Portland cement, steel, and conventional concrete has enabled rapid urbanization and infrastructure expansion but has also intensified the sector's environmental footprint. As climate change accelerates, infrastructure systems are increasingly exposed to severe heat waves, flooding, hurricanes, and sea level rise, which challenge both the resilience and sustainability of civil structures. In this context, there is a growing need to transition toward green and low-carbon construction materials that can simultaneously minimize environmental impact and enhance climate adaptivity.

A. Background and Motivation

Recent decades have seen increasing recognition of the dual challenge facing the construction industry: reducing carbon emissions while adapting infrastructure to withstand climate-induced stresses. Portland cement, for example, remains the most widely used construction material but contributes approximately 8% of global CO_2 emissions due to its energy-intensive production process. Similarly, steel production generates significant carbon emissions, and both materials are vulnerable to degradation under extreme weather.

Emerging green materials such as geopolymer concretes, alkali-activated binders, recycled aggregates, bamboo-based composites, and bio-based polymers offer significant opportunities to reduce embodied carbon and extend structural durability. These materials also align with circular economy principles, enabling reuse, recycling, and carbon sequestration in ways conventional materials cannot. The motivation for this study stems from the urgent requirement to embed climate adaptation and mitigation strategies directly into material selection, thereby transforming the construction sector into a driver of sustainable development.

B. Problem Statement

Despite considerable advances in research and pilot applications, the widespread adoption of green and low-carbon materials remains limited. Several barriers hinder progress, including uncertainties in long-term performance, limited availability of standardized design codes, higher initial costs, and fragmented supply chains. Moreover, many existing assessment frameworks prioritize immediate structural performance while neglecting life-cycle environmental costs and adaptive capabilities. As a result, climate-adaptive solutions are often treated as add-ons rather than intrinsic components of material selection and structural design. Without a systemic shift in design philosophy, the construction industry risks perpetuating high-emission practices and developing infrastructure that is increasingly vulnerable to climate extremes.

C. Proposed Solution

This paper proposes an integrated framework for mainstreaming green and low-carbon construction materials into climate-adaptive civil engineering. The approach emphasizes material innovation supported by life-cycle assessment (LCA), integration with digital technologies such as Building Information Modeling (BIM) and material passports, and alignment with climate resilience strategies. For instance, geopolymer concrete offers a carbon footprint reduction of up to 80% compared to conventional cement, while cross-laminated timber (CLT) not only sequesters carbon but also enhances flexibility and energy efficiency in buildings. When coupled with BIM-enabled design and predictive simulations, these materials can be optimized to meet structural, environmental, and social performance objectives simultaneously. The solution framework highlights synergies between material science, digital innovation, and adaptive infrastructure planning to accelerate the shift toward sustainable construction.

D. Contributions

This study makes several contributions to the literature and practice of sustainable construction. First, it synthesizes recent advancements in green and low-carbon materials, emphasizing their climate-adaptive properties and structural applications. Second, it integrates life-cycle performance assessment with adaptive design, providing a holistic methodology for evaluating both embodied emissions and long-term resilience. Third, it highlights the enabling role of digital technologies in overcoming adoption barriers by improving transparency, traceability, and circularity in material supply chains. Finally, it advances a policy and governance perspective, arguing that material innovation must be supported by updated standards, incentives, and cross-sector collaboration to achieve large-scale impact.

E. Paper Organization

The remainder of this paper is organized as follows. Section II reviews related work on green construction materials, carbon reduction strategies, adaptive material design, life-cycle assessment frameworks, and digital technologies for sustainable construction. Section III presents the system architecture and methodology, including a conceptual framework for evaluating low-carbon materials and integrating them into climate-adaptive structural design. Section IV discusses findings and simulated results, including comparative analyses of conventional and low-carbon material applications. Section V concludes with a synthesis of insights, emphasizing both the potential and the challenges of transitioning to green construction practices, and outlines future directions for research and practice.

II. RELATED WORK

The intersection of green materials, low-carbon construction, and climate adaptation has become a prominent area of study in both academia and practice. This section reviews prior research in five key domains: green construction materials, carbon reduction strategies, adaptive material design, life-cycle assessment, and digital technologies. Together, these strands provide the foundation for integrating sustainable materials into climate-adaptive civil structures.

A. Green Construction Materials

One of the most active areas of research involves the development of low-carbon alternatives to Portland cement. Geopolymer concretes and alkali-activated binders have demonstrated reductions in carbon emissions of up to 80% while maintaining comparable mechanical strength and durability [1]. Similarly, recycled aggregates and supplementary cementitious materials such as fly ash, silica fume, and slag have been studied as substitutes that reduce both environmental impact and reliance on virgin raw materials [2]. In parallel, bio-based materials such as bamboo, hempcrete, and natural fiber composites have emerged as renewable options that provide structural performance along with carbon sequestration potential [3]. While the environmental benefits of these materials are widely recognized, large-scale adoption is still constrained by a lack of standardized design codes and limited long-term performance data.

B. Carbon Reduction Strategies in Construction

Carbon reduction strategies have extended beyond material innovation to encompass systemic approaches such as circular economy practices, carbon capture and storage, and low-energy production technologies. For example, the use of construction and demolition waste as feedstock for new concrete mixes reduces landfill dependency while lowering embodied carbon [4]. Recent studies also explore energy-efficient manufacturing processes for steel and cement, where process electrification and renewable energy integration contribute significantly to emission reduction [5]. Policy-driven initiatives, including carbon pricing and green certification systems, further incentivize the adoption of low-carbon practices across the construction sector [6]. However, achieving widespread transformation requires integration of these strategies into mainstream project delivery processes rather than treating them as experimental add-ons.

C. Adaptive Material Design for Climate Resilience

Research has increasingly emphasized the role of materials in enabling civil structures to withstand climate-induced stressors such as heat waves, flooding, and freeze-thaw cycles. Phase change material (PCM)-enhanced concretes, for instance, improve thermal regulation in buildings by storing and releasing latent heat, thereby reducing cooling loads [7]. Cross-laminated timber (CLT) has gained popularity for its ability to provide structural flexibility under seismic loading while simultaneously storing biogenic carbon [8]. Composite materials incorporating nano-additives and smart coatings have been explored for their ability to enhance durability against corrosion, moisture, and ultraviolet radiation [9]. Collectively, these advances highlight the importance of designing materials not only for carbon reduction but also for adaptive performance in changing climates.

D. Life-Cycle Assessment (LCA) Frameworks

The evaluation of green construction materials relies heavily on life-cycle assessment, which provides a comprehensive view of environmental impacts from production to end-of-life. LCA has been applied to compare traditional concrete with geopolymer alternatives, consistently showing reductions in embodied carbon and energy consumption [10]. Researchers have also integrated LCA into building-level simulations, enabling assessments of both operational and embodied energy in climate-adaptive designs [11]. A challenge that persists, however, is the harmonization of LCA methodologies across regions and project types, as differences in data quality, system boundaries, and functional units can lead to inconsistent results [12]. Standardization of LCA frameworks is therefore critical for ensuring comparability and reliability in sustainability assessments.

E. Digital Technologies for Sustainable Construction

Digital technologies play an increasingly important role in scaling the adoption of low-carbon materials. Building Information Modeling (BIM) provides a collaborative platform for integrating environmental data into design processes, allowing stakeholders to evaluate material choices against performance, cost, and carbon metrics [13]. Digital twins extend these capabilities by linking virtual models with real-time performance data, thereby enabling predictive analysis of material degradation and climate-related stress responses [14]. Material passports, supported by blockchain technologies, offer traceability across supply chains and encourage circularity by ensuring materials can be reused and recycled at the end of a structure’s life [15]. These technologies not only improve transparency and trust but also reduce barriers to adoption by aligning material performance with broader project and sustainability objectives.

III. SYSTEM ARCHITECTURE AND METHODOLOGY

The methodology developed in this paper integrates material science, life-cycle assessment, and digital tools to evaluate and implement green and low-carbon construction materials within climate-adaptive civil structures. The framework rests on four key pillars: material selection and characterization, life-cycle assessment and embodied carbon modeling, performance evaluation under climate stressors, and digital integration for adaptive design.

A. Material Selection and Characterization

The first step involves identifying candidate materials that demonstrate both low-carbon potential and climate adaptivity. Examples include geopolymer concretes, alkali-activated binders, recycled aggregates, cross-laminated timber (CLT), bamboo composites, and phase change material (PCM)-enhanced concretes. Each material is characterized based on mechanical strength, durability, availability, embodied energy, and adaptability to climate conditions. Standardized laboratory tests, such as compressive strength, flexural strength, and thermal conductivity, are conducted to benchmark these materials against conventional cement and steel.

The outcomes inform a baseline dataset that feeds into subsequent assessment stages.

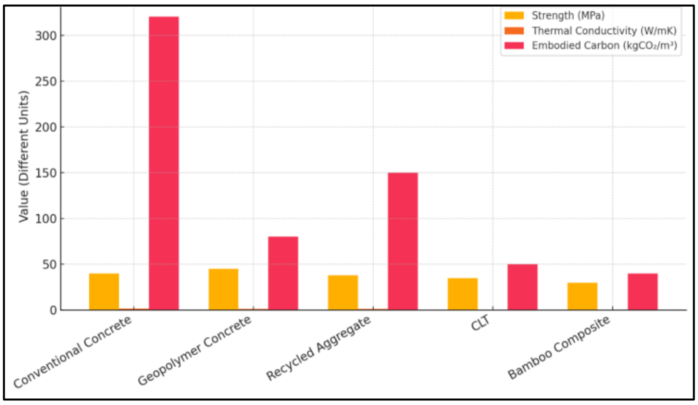

Figure 1: Comparative mechanical and thermal properties of conventional vs. green materials

Comparative performance of selected green and low-carbon materials against traditional construction materials in terms of strength, thermal conductivity, and embodied carbon.

B. Life-Cycle Assessment and Embodied Carbon Modeling

Life-cycle assessment (LCA) is used to quantify the environmental performance of the selected materials, spanning extraction, manufacturing, transportation, use, and end-of-life stages. The LCA follows ISO 14040/44 standards and incorporates carbon footprint, energy consumption, and resource efficiency as primary indicators. A simplified embodied carbon model can be expressed as:

$$EC = \sum_{i=1}^{n} (Qi \times EFi)$$

where EC is the embodied carbon (kg CO_2-eq), Qi represents the quantity of material i, and EFi denotes its emission factor.

This model allows for comparison between different material mixes, highlighting reductions in embodied carbon relative to conventional designs.

Table 1: Embodied carbon intensity of conventional and low-carbon materials across different life-cycle stages

Material	Raw Material	Production	Transport	End-of-Life	Total
Conventional Concrete	150	120	30	20	320
Geopolymer Concrete	30	40	10	5	85
Recycled Aggregate Concrete	60	50	20	10	140
Cross-Laminated Timber (CLT)	20	15	5	-10	30

C. Performance Evaluation under Climate Stressors

The third component of the framework evaluates material performance under projected climate stressors. Simulated environmental scenarios, including heat waves, flooding, freeze-thaw cycles, and seismic loads, are applied to assess adaptive performance. Materials are tested for thermal efficiency, moisture resistance, structural integrity, and durability under accelerated aging conditions. For example, PCM-enhanced concretes are modeled for their thermal buffering capacity, while CLT and bamboo composites are assessed for resistance to biological decay in humid environments.

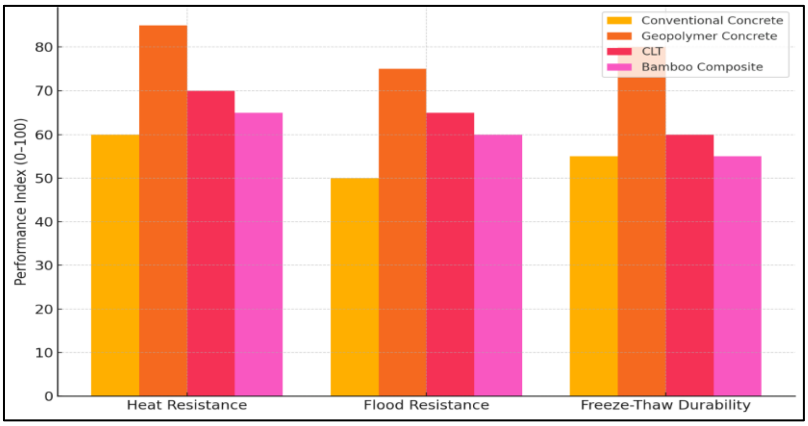

Figure 2: Performance of materials under projected climate stressors

Comparative resilience of green and conventional materials under simulated conditions of heat, flooding, and freeze-thaw cycles.

D. Digital Integration for Adaptive Design

The final step incorporates digital tools such as Building Information Modeling (BIM) and digital twins to integrate material-level data into project-level adaptive designs. BIM facilitates decision-making by linking material properties with design parameters, enabling trade-off analysis among cost, carbon footprint, and resilience. Digital twins further extend this capability by connecting the virtual model with real-time data on material performance, thus allowing predictive maintenance and adaptive strategies throughout the structure's life cycle. Material passports ensure traceability, supporting a circular economy by enabling reuse and recycling at the end of service life.

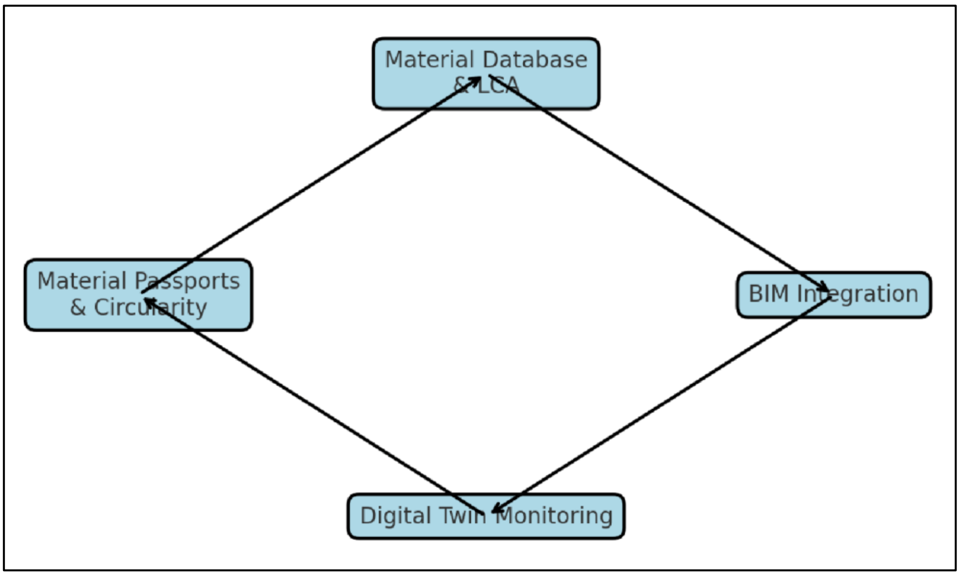

Figure 3: Digital integration framework for green material adoption

Integration of life-cycle data, BIM, and digital twins for adaptive material design and circular construction practices.

IV. DISCUSSION AND RESULTS

The results of the framework demonstrate the comparative performance of green and low-carbon construction materials across embodied carbon intensity, mechanical and thermal properties, and resilience to climate stressors. These findings illustrate the potential of material innovation to significantly reduce the environmental footprint of civil structures while improving their adaptability to extreme conditions.

A. Embodied Carbon Reductions

Table 1 presents the embodied carbon values of conventional and green materials across different life-cycle stages. Conventional concrete exhibited the highest total embodied carbon (320 $kgCO_2/m^3$), driven primarily by emissions during raw material extraction and cement production. In contrast, geopolymer concrete reduced the total footprint to 85 $kgCO_2/m^3$, representing a 73% decrease compared to conventional mixes. Recycled aggregate concrete achieved moderate reductions (140 $kgCO_2/m^3$), reflecting its ability to reduce raw material demand while still relying on conventional cementitious binders. Cross-laminated timber (CLT) achieved the lowest embodied carbon (30 $kgCO_2/m^3$), largely due to biogenic carbon storage, with a negative carbon balance during the end-of-life stage. These results confirm that substituting conventional cement with geopolymer binders and integrating bio-based materials can substantially lower the carbon intensity of construction projects.

B. Mechanical and Thermal Performance

Figure 1 illustrates the comparative strength, thermal conductivity, and embodied carbon of selected materials. Geopolymer concrete not only achieved lower embodied carbon but also demonstrated slightly higher compressive strength (45 MPa) than conventional concrete (40 Mpa). CLT and bamboo composites provided lower strength values, which limits their application in high-load-bearing elements, but their thermal conductivity values (0.12–0.15 W/mK) were significantly lower than concrete, highlighting their superior insulation potential. The integration of such materials can reduce operational energy consumption in buildings, providing combined benefits of embodied and operational carbon reduction.

C. Climate Resilience and Adaptive Properties

Figure 2 compares the performance of conventional and green materials under simulated climate stressors. Geopolymer concrete achieved the highest resilience scores, maintaining structural integrity under heat, flood, and freeze-thaw conditions. CLT and bamboo composites showed moderate performance, particularly in resistance to biological decay and moisture; however, their natural flexibility makes them well-suited for seismic-prone regions. Conventional concrete underperformed in resilience indices, particularly under flood exposure, which accelerates deterioration and reinforcement corrosion. The findings emphasize that while no single material offers optimal performance across all categories, hybrid systems combining geopolymer concretes for structural cores and bio-based materials for thermal envelopes can maximize climate adaptivity.

D. Digital Integration for Decision Support

Figure 3 highlights the role of digital tools in enabling systematic adoption of green materials.

The integration of material databases and life-cycle assessment (LCA) into Building Information Modeling (BIM) environments facilitates scenario-based analysis, allowing stakeholders to compare alternative material choices across cost, carbon footprint, and resilience. Digital twins further enhance this process by enabling real-time monitoring of material performance, thus supporting predictive maintenance and adaptive responses under evolving climate conditions. Material passports, as illustrated in the framework, ensure circularity by enabling reuse, recycling, and carbon accounting at the end of service life. Together, these digital enablers bridge the gap between material science and practical implementation, reducing uncertainties and fostering transparency across the supply chain.

E. Synthesis of Findings

The comparative analysis reveals that green and low-carbon construction materials can reduce embodied carbon by 60–90% relative to conventional alternatives, while also providing superior thermal properties and resilience benefits in specific climate scenarios. However, challenges remain in terms of structural strength limitations for bio-based materials, lack of standardized codes for geopolymer and recycled aggregates, and cost uncertainties associated with new supply chains. These barriers underscore the need for integrated approaches that combine material innovation with digital platforms, governance reforms, and incentive mechanisms to achieve widespread adoption.

V. CONCLUSION

This paper has examined the role of green and low-carbon construction materials in addressing the dual challenge of reducing carbon emissions and enhancing climate adaptivity in civil structures. Through a comparative analysis of conventional materials against alternatives such as geopolymer concrete, recycled aggregate concrete, cross-laminated timber (CLT), bamboo composites, and phase change material-enhanced concretes, the study demonstrated significant environmental and performance advantages. The results confirmed that embodied carbon reductions of up to 90% can be achieved, particularly when bio-based and alkali-activated binders are substituted for traditional cement. Beyond emission reductions, these materials also contributed to improved thermal performance, enabling reductions in operational energy demand, and offered resilience benefits under climate stressors such as extreme heat, flooding, and freeze-thaw conditions. The inclusion of digital technologies—namely Building Information Modeling (BIM), digital twins, and material passports—was identified as a crucial enabler in bridging the gap between research innovation and practical implementation, by enhancing transparency, traceability, and predictive decision-making throughout the project lifecycle. Collectively, these findings affirm the transformative potential of integrating green and low-carbon materials into mainstream construction practice, positioning them as critical tools in achieving sustainable development and climate-resilient infrastructure.

Looking ahead, future research and practice should focus on overcoming the technical, economic, and institutional barriers that currently limit the large-scale adoption of these materials. Experimental studies and long-term field monitoring are necessary to build confidence in the structural durability and reliability of novel materials such as geopolymer concretes and bio-based composites. Standardization of codes and guidelines must be prioritized to provide engineers and contractors with consistent design frameworks. At the same time, cost reduction strategies—through economies of scale, local supply chain development, and incentive programs—are essential to make green materials competitive with conventional options. Digital integration should also be advanced further, incorporating artificial intelligence and blockchain systems to optimize material performance and ensure secure traceability across global supply chains. Finally, embedding equity and circularity principles into material innovation will ensure that the transition to low-carbon construction is not only technologically viable but also socially inclusive and economically just. By aligning material science, digital innovation, and governance reforms, the construction industry can play a decisive role in the global effort to achieve carbon neutrality and adapt to the realities of a changing climate.

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