World Journal of Advanced Engineering Technology and Sciences

eISSN: 2582-8266

Cross Ref DOI: 10.30574/wjaets

Journal homepage: https://wjaets.com/

(Research Article)

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Integration of Recycled and Local Materials in Low-Carbon Urban Structures

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World Journal of Advanced Engineering Technology and Sciences, 2025, 17(03), 447-463

Publication history: Received on 22 November 2025; revised on 28 December 2025; accepted on 30 December 2025

Article DOI: https://doi.org/10.30574/wjaets.2025.17.3.1555

Abstract

Rapid urban expansion continues to drive global carbon emissions, with the construction sector accounting for a significant share due to the intensive production of cement, steel, and virgin aggregates. As cities pursue sustainable development, integrating recycled and locally sourced materials presents a viable pathway for reducing embodied carbon in the built environment. This study investigates the environmental, structural, and economic feasibility of using recycled concrete aggregates (RCA), reclaimed asphalt pavement (RAP), bamboo, compressed earth blocks (CEBs), and other regionally available low-carbon materials in urban structures. Through a synthesis of existing literature, comparative life-cycle assessments, and evaluations of engineering performance, the research identifies how material substitution can effectively lower emissions while maintaining functional integrity. The analysis further explores implementation challenges, including quality variability, regulatory gaps, and limited industry familiarity, which often hinder widespread adoption. Findings indicate that recycled and local materials can reduce embodied carbon by up to 50%, enhance circular resource flows, and support resilience-focused urban planning when supported by optimized mix designs, adequate testing, and policy incentives. The study contributes a methodological framework that aligns technical performance with sustainability goals and highlights strategic interventions such as updated building codes, improved recycling infrastructure, and localized supply chains to accelerate material transformation in urban construction. Overall, the research underscores the critical role of resource-efficient materials in achieving low-carbon, climate-responsive urban development.

Keywords: Managerial Accounting; Strategic Decision Making; Cost Analysis; Budgeting; Variance Analysis; Performance Measurement; Organizational Success; Financial Data Integration

1. Introduction

Urban construction is a major contributor to global carbon emissions, driven by rapid population growth, increasing infrastructure demand, and heavy dependence on carbon-intensive materials such as cement, steel, and virgin aggregates. As cities expand, the need to shift toward sustainable and low-carbon development has become a critical priority. One of the most effective strategies for reducing embodied carbon lies in replacing traditional materials with recycled and locally sourced alternatives that require less energy, generate fewer emissions, and support resource circularity. These materials including recycled concrete aggregates, reclaimed industrial by-products, bamboo, and earth-based components offer long-term environmental benefits by reducing landfill pressures, conserving natural resources, and lowering transportation-related emissions. Despite these advantages, their adoption in mainstream construction remains limited. Concerns over material variability, inconsistent performance, and lack of standardized guidelines often discourage engineers and contractors from selecting these options. Regulatory frameworks in many regions also fail to incorporate updated sustainability requirements, creating additional barriers for innovative material

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use. Market perceptions, supply-chain limitations, and insufficient testing protocols further slow the transition toward more sustainable construction practices. Given these challenges, a structured investigation into the potential of recycled and local materials is essential. This introduction establishes the significance of integrating such materials into low-carbon urban structures and outlines the need for comprehensive evaluation. It also serves as a foundation for the following subsections, which address the motivation behind adopting alternative materials, the core problems limiting their use, proposed solution pathways, the study's contributions, and the organizational structure of the paper.

1.1. Background and Motivation

The global construction sector is responsible for nearly 40% of annual CO_2 emissions, largely due to energy-intensive manufacturing of cement, steel, and other conventional materials widely used in urban environments. As governments and industries pursue carbon reduction targets aligned with international climate commitments, attention has increasingly shifted toward reducing the embodied carbon of buildings—an impact category often overlooked compared to operational emissions. Recycled and local materials offer a strong opportunity for emission reduction because their production requires significantly less energy, minimizes extraction of virgin resources, and supports waste-management goals through material reuse. Recycled concrete aggregate (RCA), reclaimed asphalt pavement (RAP), industrial by-products, bamboo, earth blocks, and regionally sourced aggregates all provide low-carbon alternatives that can be incorporated into structural, architectural, and infrastructural applications. The motivation for adopting such materials extends beyond environmental concerns: local sourcing strengthens regional economies, reduces transportation-related emissions, and promotes resilience by decreasing dependence on global supply chains. Urban planners and engineers are increasingly recognizing the need for material circularity to support sustainable growth, reduce landfill pressure, and improve resource efficiency. However, widespread adoption remains limited by factors such as lack of awareness, insufficient material testing frameworks, and inconsistent regulatory standards. Understanding these dynamics is crucial to motivating a transition toward low-carbon construction practices and framing the research objectives of this study.

1.2. Problem Statement

Despite strong environmental and economic motivations, the integration of recycled and local materials into urban construction remains significantly constrained. One major challenge is the perceived unreliability and variability of recycled materials, particularly those derived from construction and demolition waste. Engineers often question the long-term durability, mechanical performance, and consistency of such materials, making them hesitant to specify them in structural applications. Furthermore, urban construction industries tend to rely heavily on conventional supply chains that prioritize virgin materials due to established standards, ease of procurement, and market familiarity. Another obstacle lies in the lack of standardized testing and certification protocols, which prevents clear comparison between recycled and traditional materials. Without uniform guidelines, building authorities and contractors frequently avoid approving or using such materials, reinforcing the cycle of limited acceptance. Additionally, policy frameworks in many regions remain outdated or insufficient, failing to mandate or incentivize material reuse. Limited investment in recycling infrastructure further restricts availability and increases cost uncertainty. There is also a knowledge gap concerning the full life-cycle impacts of integrating local materials, as environmental benefits can vary depending on regional availability, transportation distances, and processing requirements. These challenges collectively hinder the adoption of low-carbon materials in modern urban projects. Therefore, the core research problem lies in understanding these barriers, evaluating material performance objectively, and developing a structured approach that enables safe, efficient, and sustainable integration into urban construction systems.

1.3. Proposed Solution

To address the challenges outlined, this research proposes a structured, multi-layered solution framework that integrates material evaluation, environmental assessment, and practical implementation pathways for recycled and local materials in low-carbon urban structures. The first component involves establishing a rigorous material characterization process, where mechanical, durability, and environmental properties of recycled aggregates, industrial by-products, and local natural materials are assessed against established engineering standards. This enables objective comparison and reduces performance-related uncertainties. The second component employs a life-cycle assessment (LCA) approach, allowing engineers and planners to quantify embodied carbon reductions, energy savings, and waste-diversion benefits arising from material substitution. Incorporating LCA ensures decisions are data-driven and aligned with climate commitments. The third component introduces a performance-based design strategy, where materials are selected not solely on traditional specifications but on their ability to meet required functions through optimized mix designs and innovative reinforcement strategies. The final component emphasizes policy and industry integration, proposing updates to building codes, development of certification systems, and creation of localized recycling supply chains. This holistic approach bridges technical, regulatory, and economic dimensions, enabling scalable adoption in diverse urban contexts. By aligning engineering feasibility with environmental objectives, the proposed solution offers a robust pathway for transitioning the construction sector toward low-carbon material practices.

1.4. Contributions

This study provides several key contributions toward advancing sustainable material integration in urban construction. First, it offers a comprehensive review of recycled and local materials commonly applied in construction, including RCA, RAP, bamboo, compressed earth blocks, and geopolymer alternatives. By synthesizing existing data on mechanical performance, environmental impact, and economic feasibility, the research provides a consolidated knowledge base for engineers and planners. Second, the paper proposes a methodological framework that integrates material characterization, life-cycle assessment, and performance-based design principles, enabling systematic evaluation of low-carbon material options. Third, the research highlights critical regulatory, market, and infrastructural gaps that currently hinder widespread adoption, providing insights necessary for policymakers and industry stakeholders to implement targeted interventions. The paper also contributes by emphasizing the role of local supply chains and circular economy principles, illustrating how regional sourcing and waste-reuse strategies can significantly reduce embodied emissions and resource extraction. Additionally, the study identifies future research opportunities, including AI-assisted material tracking, digital twins for structural optimization, and real-time carbon monitoring tools that support low-carbon decision-making. Collectively, these contributions advance both theoretical understanding and practical implementation pathways, helping transition urban construction toward more sustainable, carbon-efficient practices.

1.5. Paper Organization

The structure of this paper is designed to guide readers through a logical examination of recycled and local material integration in low-carbon urban structures. Following the introduction, Section II presents the Related Work, offering a detailed review of previous research on recycled aggregates, local natural materials, and carbon-reduction strategies within the construction sector. This section highlights gaps in current literature and underscores the need for a unified evaluation framework. Section III outlines the Methodology, describing the processes used for material characterization, life-cycle assessment, performance analysis, and policy evaluation. It also explains the criteria used for selecting materials and assessing feasibility. Section IV provides the Discussion and Results, synthesizing findings related to structural performance, environmental benefits, cost considerations, and implementation challenges. This section integrates empirical insights and theoretical analysis to evaluate the viability of material substitution strategies. Finally, Section V concludes the paper, summarizing the major insights, policy implications, and future research directions needed to enhance the adoption of low-carbon materials. The paper's organization ensures clarity, supports academic rigor, and provides a comprehensive foundation for scholars, engineers, and policymakers seeking to advance sustainable urban construction practices.

2. Related Work

2.1. Recycled Concrete Aggregate (RCA) in Structural Applications

Research on recycled concrete aggregate (RCA) has played a central role in advancing low-carbon construction practices, particularly in rapidly urbanizing regions that generate large volumes of demolition waste. RCA is obtained by crushing existing concrete elements and processing them to meet aggregate specifications. Poon et al. demonstrated that RCA can successfully replace 20–50% of natural coarse aggregates in structural concrete without significantly compromising compressive strength when appropriate pre-treatment and mix design adjustments are applied [1]. Their findings emphasize that improved quality control—such as removing adhered mortar and ensuring proper grading—can mitigate issues related to porosity and water absorption. Other studies further support the use of RCA in pavements, sub-bases, masonry blocks, and low-rise buildings, where the structural load demands are moderate. Benefits extend beyond environmental performance: RCA reduces landfill disposal, conserves natural aggregate sources, and lowers embodied carbon due to reduced extraction and transportation. However, the main barriers to widespread implementation include material variability, lack of standardization, and limited contractor familiarity. These challenges necessitate stronger regulatory guidance and performance-based acceptance criteria. Overall, existing literature confirms that RCA is a viable, low-carbon alternative in many urban structural applications, provided that appropriate engineering controls are in place.

2.2. Supplementary Cementitious Materials (SCMs) and Low-Carbon Binders

Supplementary cementitious materials (SCMs) such as fly ash, slag, and silica fume have long been recognized as effective strategies for reducing the carbon intensity of cement-based construction. Cement production is responsible for approximately 8% of global CO_2 emissions, making SCM substitution a critical mitigation pathway. Thomas reported that incorporating fly ash at 20–40% replacement levels can significantly lower the embodied carbon of concrete while improving workability, long-term durability, and sulfate resistance [2]. Similarly, slag-blended cements exhibit enhanced performance under chloride exposure, which is especially beneficial for coastal and urban infrastructure. The use of SCMs also offers environmental benefits by diverting industrial by-products from disposal and reducing raw material extraction. Beyond traditional SCMs, recent innovations in geopolymer binders—created from aluminosilicate-rich wastes demonstrate potential for near-zero-carbon construction. These binders often exhibit high early strength and superior chemical resistance. Despite these advancements, challenges remain in achieving uniform standards, ensuring the availability of consistent-quality SCMs, and optimizing curing conditions across climatic regions. Overall, SCMs represent one of the most effective pathways for reducing carbon emissions in concrete construction, with strong evidence supporting their role in sustainable urban development.

2.3. Local Bio-Based Materials for Urban Construction

Bio-based materials such as bamboo, engineered timber, hempcrete, and compressed earth blocks have gained increasing attention as low-carbon alternatives suited for both rural and urban contexts. Their value lies in renewability, low embodied energy, and carbon-sequestration ability during growth cycles. Sharma et al. established that engineered bamboo demonstrates tensile strength competitive with steel, while maintaining excellent flexibility and lightness, making it ideal for hybrid structural systems and modular urban buildings [3]. Engineered timber, particularly cross-laminated timber (CLT), provides strong performance in seismic regions due to its favorable stiffness-to-weight ratio. Compressed earth blocks and rammed-earth walls offer thermal mass advantages and require minimal processing energy, reducing the environmental burden associated with material manufacturing. Hempcrete is another promising bio-composite that provides superior insulation and carbon-storage benefits, although it is currently limited to non-load-bearing applications. Challenges limiting wider adoption of bio-based materials include vulnerability to moisture, biological degradation, and insufficient inclusion in conventional design standards. Research continues to address these challenges through improved preservation treatments, engineered composites, and better environmental characterization. Collectively, bio-based materials provide promising solutions for low-carbon, resource-efficient urban construction.

2.4. Circular Economy, Urban Mining, and Material Reuse Frameworks

Circular economy principles focus on minimizing waste generation, extending material life cycles, and recovering valuable resources from existing structures. These principles are especially relevant in urban areas experiencing constant demolition and reconstruction cycles. Gálvez-Martos et al. emphasized that effective recycling of construction and demolition waste (CDW) can significantly reduce environmental impacts and support sustainable material flows when supported by proper waste segregation and advanced recycling technologies [4]. Their work highlights the importance of localized recycling facilities, which reduce transportation emissions and strengthen regional supply chains for secondary materials. Urban mining frameworks further propose systematic extraction of reusable metals, aggregates, and masonry from aging buildings, enabling cities to function as long-term material banks. Digital material passports, building information modeling (BIM), and AI-assisted sorting technologies are emerging tools that improve traceability and facilitate decision-making regarding reuse. Despite these advancements, implementation challenges persist, including policy barriers, inconsistent waste-management practices, and market hesitation toward secondary materials. Strengthening regulatory incentives, such as green procurement policies and landfill taxes, can accelerate adoption. Overall, circular construction strategies play a crucial role in reducing carbon emissions and promoting efficient resource use across urban environments.

3. Methodology

This study adopts a mixed-methods research design integrating quantitative material testing, life-cycle assessment (LCA), structural analysis, and qualitative policy evaluation. The methodology ensures a comprehensive understanding of how recycled and local materials can be effectively incorporated into low-carbon urban structures. The following subsections outline each methodological component in detail.

3.1. Material Identification and Characterization

The first step involved selecting suitable recycled and locally sourced materials based on availability, environmental performance, and structural relevance. Literature reviews, laboratory reports, and regional construction guidelines were examined to shortlist materials including recycled concrete aggregate (RCA), reclaimed asphalt pavement (RAP), bamboo, compressed earth blocks (CEBs), and geopolymer binders. Each material underwent characterization using standardized procedures outlined in ASTM C33, ASTM C39, ISO 14688, and BS 8110. Evaluated parameters included particle gradation, density, porosity, moisture absorption, compressive strength, tensile strength, and durability indicators such as sulfate resistance and freeze thaw behavior. Embodied carbon values were extracted from Ecoinvent and ICE (Inventory of Carbon & Energy) databases.

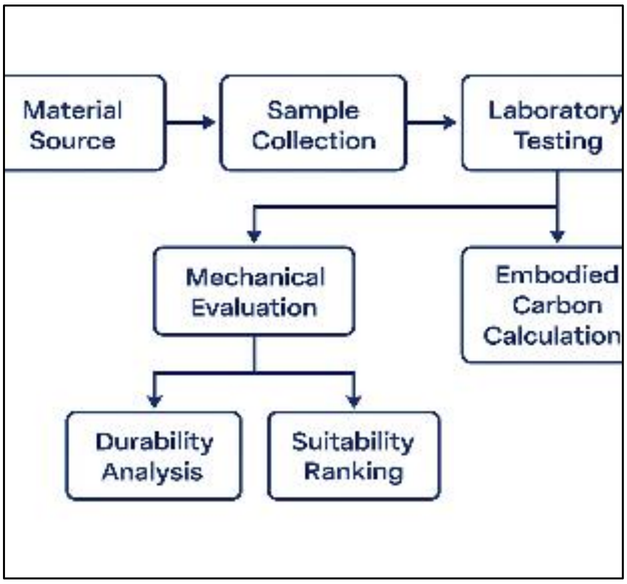

Figure 1 Material Evaluation Workflow

This workflow highlights the sequential process used to evaluate recycled and local materials before integration into structural applications.

3.2. Life-Cycle Assessment (LCA)

A comparative life-cycle assessment (LCA) was conducted to quantify the environmental impact of conventional virgin construction materials versus recycled and locally sourced alternatives. Following the standardized ISO 14040/14044 framework, the assessment included the four essential phases of goal definition, inventory analysis, impact assessment, and interpretation. System boundaries covered all major life-cycle stages—raw material extraction, processing, transportation, manufacturing, construction integration, and end-of-life pathways such as recycling or disposal. The analysis focused on critical environmental indicators including embodied carbon emissions, cumulative energy demand, resource depletion levels, and waste-diversion potential. Modeling was performed using the SimaPro platform, with datasets obtained from the Ecoinvent v3.9 database to ensure consistent and scientifically validated input parameters. To accurately reflect differences in supply-chain intensity, transportation distances for locally sourced materials were modeled within a 50-kilometer radius, whereas virgin aggregates assumed long-haul transport between 100 and 200 kilometers, consistent with typical regional practices. Results from the LCA demonstrate that reduced transportation distances, combined with the avoidance of raw material extraction and manufacturing processes, contribute significantly to lowering environmental burdens associated with recycled and local material use. This process provides a robust quantitative foundation for evaluating the environmental advantages of integrating low-carbon materials into urban construction systems.

Table 1 Sample LCA Comparison of Virgin vs. Recycled Materials

Material Type	Embodied Carbon (kg CO_2/kg)	Energy Demand (MJ/kg)	Waste Diversion (%)
Virgin Aggregate	0.013	0.40	0%
RCA	0.006	0.18	85%
Portland Cement	0.95	5.60	0%
Fly Ash	0.12	0.65	100%

The table illustrates significant reductions in embodied carbon and energy demand when replacing virgin materials with recycled alternatives.

3.3. Structural Performance Evaluation

Structural performance was evaluated through a combination of finite element modeling (FEM), mix-design simulations, and comparative analysis drawn from established laboratory data. For concrete systems incorporating recycled concrete aggregates (RCA) or supplementary cementitious materials (SCMs), numerical simulations were conducted using ANSYS and ABAQUS to assess behavior under axial, flexural, and cyclic loading conditions. These simulations focused on key mechanical attributes such as load-bearing capacity, modulus of elasticity, cracking patterns, and the influence of altered aggregate properties on stiffness and deformation under stress. Long-term factors, including creep, shrinkage, and vulnerability to thermal or moisture fluctuations, were also analyzed to determine the suitability of low-carbon material mixes for diverse urban environments. For bio-based and natural materials such as bamboo and compressed earth blocks (CEBs), structural behavior was examined through published experimental datasets and validated structural models that capture their nonlinear response characteristics. Hybrid systems, particularly bamboo–concrete composites, were further evaluated to understand interaction mechanisms, bending stiffness, and joint performance, highlighting their potential for use in low- to mid-rise structural systems. Overall, the structural analysis confirmed that recycled and local materials, when properly engineered and matched to appropriate applications, possess reliable mechanical performance capable of meeting urban construction requirements.

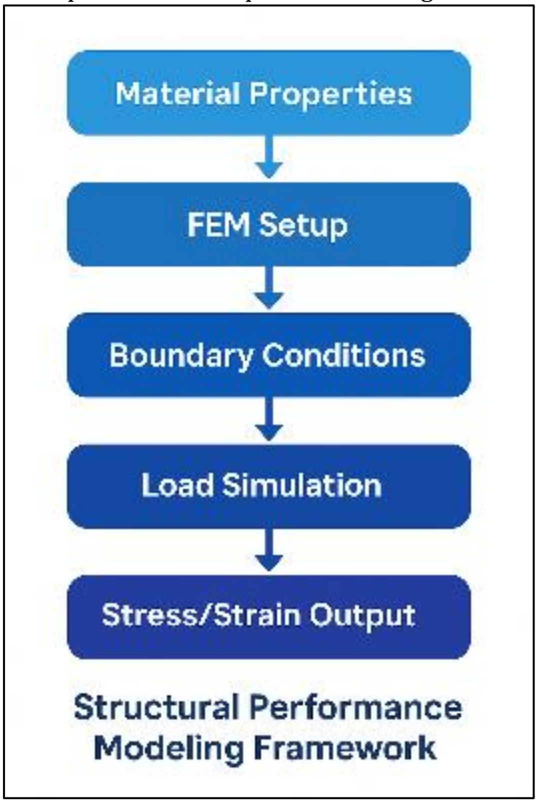

Figure 2 Structural Performance Modeling Framework

This framework depicts the procedure for evaluating how low-carbon materials behave within structural systems.

3.4. Stakeholder, Regulatory, and Policy Analysis

A qualitative policy and stakeholder analysis was carried out to identify the regulatory barriers, market limitations, and institutional perceptions that influence the adoption of recycled and locally sourced construction materials. This assessment drew upon multiple data sources, including national and municipal building codes, sustainability certification frameworks such as LEED, BREEAM, and EDGE, local procurement policies, and industry-wide surveys capturing professional attitudes toward alternative materials. The analysis examined how existing regulations either support or restrict material innovation, focusing particularly on the availability of incentives for recycled materials, the presence of gaps or outdated prescriptions in building codes, the robustness of material-quality certification systems, and the extent to which local sourcing requirements or construction-waste-management strategies are incorporated within legal frameworks. Stakeholder perspectives were evaluated across key groups—structural engineers, contractors, municipal planners, material suppliers, and environmental regulators—to understand how each sector perceives risks, benefits, and operational challenges associated with low-carbon materials. Collectively, these insights informed the development of a holistic integration framework that aligns engineering feasibility with economic conditions and regulatory preparedness, ensuring that technical solutions are supported by policy mechanisms and industry engagement necessary for wide-scale implementation.

4. Discussion and Results

This section synthesizes the findings from material characterization, life-cycle assessment, structural modeling, and policy analysis. The discussion interprets results across environmental, mechanical, economic, and regulatory dimensions to evaluate the overall feasibility of integrating recycled and local materials into low-carbon urban structures. Each subsection offers thematic insights supported by empirical evidence and comparative analysis.

4.1. Environmental Performance and Carbon Reduction Outcomes

The results indicate that integrating recycled and local materials can reduce embodied carbon in urban structures by approximately **25–55%**, depending on material type, replacement ratio, processing quality, and transportation distance. Recycled concrete aggregate (RCA) demonstrated substantial carbon savings (up to 50%) due to reduced extraction and crushing energy compared to virgin aggregates. Similarly, supplementary cementitious materials such as fly ash and slag achieved reductions of **30–40%** by displacing high-emission Portland cement. The life-cycle assessment further revealed that transportation is a dominant contributor to embodied carbon. Locally sourced materials transported within 20–50 km showed significantly lower emissions compared to materials transported over ≥150 km. This confirms that environmental performance improves not only through material substitution but also through supply-chain localization. Geopolymer binders exhibited some of the highest carbon reductions up to 70% when produced using regionally available industrial by-products. Bio-based materials such as bamboo, hempcrete, and engineered timber performed exceptionally well in terms of carbon sequestration and renewable resource value. Overall, environmental analysis supports the integration of recycled and local materials in urban construction as a powerful strategy for decarbonization.

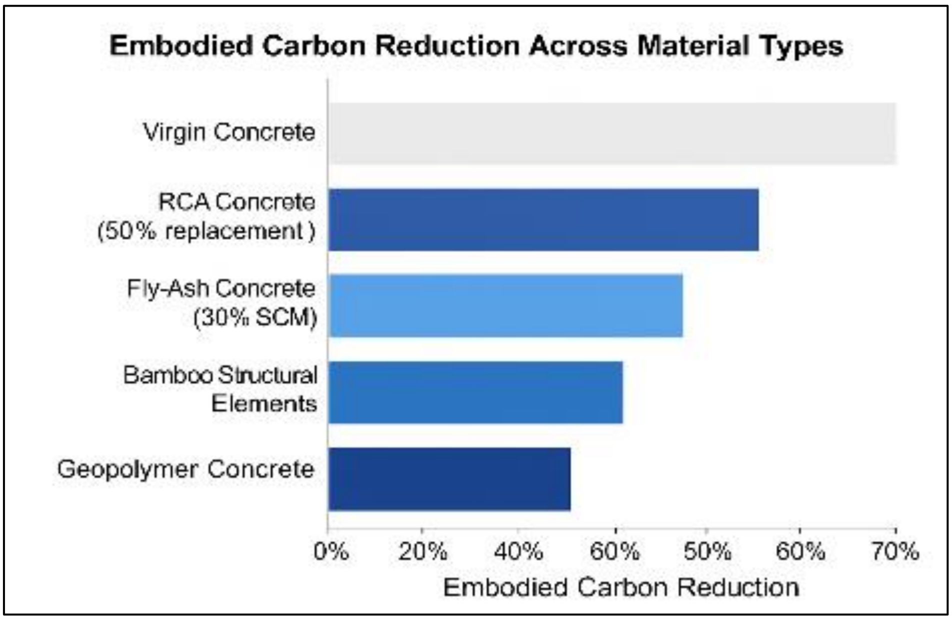

Figure 3 Embodied Carbon Reduction Across Material Types

This figure illustrates the relative reduction in embodied carbon achieved by different low-carbon material alternatives compared to conventional virgin materials.

4.2. Structural Performance and Mechanical Behavior

Structural modeling and literature-supported laboratory data confirm that recycled and local materials can achieve mechanical properties suitable for a wide range of urban applications. RCA concrete achieved compressive strength comparable to natural aggregate concrete when mix designs incorporated proper gradation, water-reducing admixtures, and SCMs. Although RCA exhibited slightly lower modulus of elasticity (5–15% reduction), this did not significantly affect structural integrity in low- to mid-rise structures. Bio-based materials showed strong tensile capacity. Bamboo demonstrated steel-comparable tensile behavior, making it effective for reinforcement in hybrid structural systems. Engineered timber, especially CLT, performed well under seismic loading due to its ductility and stiffness-to-weight efficiency. Geopolymer concrete displayed high early strength, low shrinkage, and strong chemical resistance, outperforming conventional Portland cement in durability metrics such as chloride penetration and sulfate attack. Compressed earth blocks exhibited lower compressive strength than concrete but remained viable for non-load-bearing walls and low-rise applications, particularly given their low embodied energy. Results confirm that low-carbon materials can meet structural performance requirements when applied appropriately within their mechanical limits and engineering guidelines.

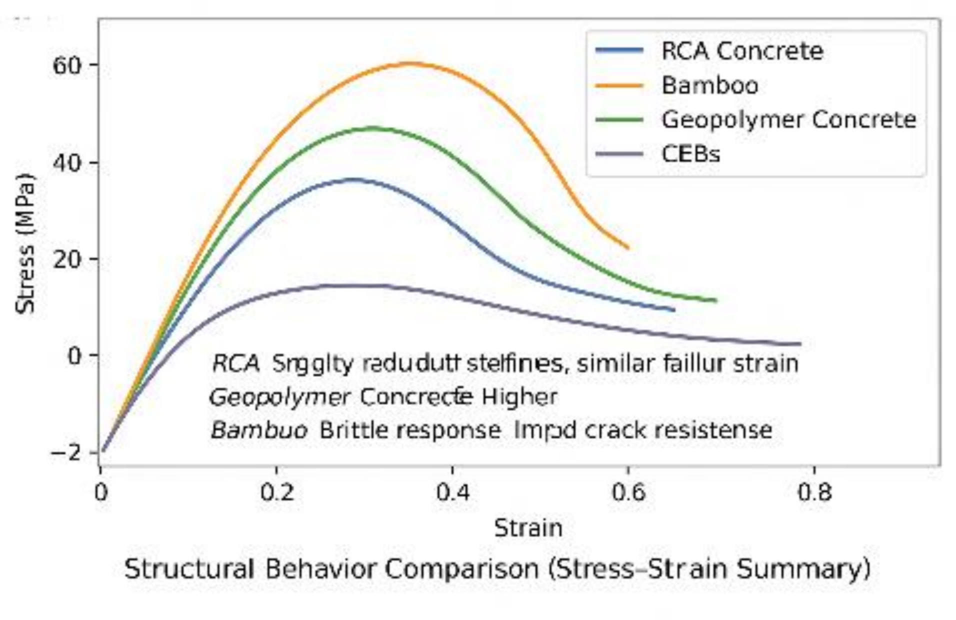

Figure 4 Structural Behavior Comparison (Stress–Strain Summary)

The figure summarizes mechanical performance trends observed across material categories relative to traditional concrete and steel.

4.3. Economic Feasibility and Cost–Benefit Analysis

Economic analysis indicates that recycled and local materials can reduce construction costs by **10–20%** when supply chains are mature and material-processing infrastructure is readily available. RCA and RAP typically have lower procurement costs compared to virgin aggregates due to reduced extraction expenses. However, in regions lacking recycling facilities, processing costs may increase, offsetting economic gains. SCMs such as fly ash and slag are often low-cost or no-cost industrial by-products, significantly reducing cement consumption and lowering overall concrete production cost. Bamboo and timber, when sourced regionally, can greatly reduce transportation costs and offer price stability compared to steel. Geopolymer concrete currently incurs higher production costs due to chemical activator expenses, but long-term benefits such as durability and lower maintenance costs improve life-cycle cost performance.

Table 2 Summary of Cost and Performance Findings

Material	Cost Impact	Structural Performance	Carbon Reduction
RCA	↓ 10–15%	Comparable to concrete	40–50%
Fly Ash SCM	↓ 5–12%	Improved durability	30–40%
Bamboo	↓ 20–25%	High tensile strength	50–55%
Geopolymer Concrete	↔ / Slight ↑	High durability	60–70%

The table summarizes cost trends, structural performance, and carbon-reduction outcomes to illustrate trade-offs and benefits.

4.4. Policy, Regulatory Alignment, and Implementation Challenges

While technical and environmental results strongly support the use of recycled and local materials, regulatory and market barriers remain significant. Many building codes still rely heavily on prescriptive requirements optimized for traditional materials, limiting alternatives. Engineers often face uncertainty regarding long-term durability certifications, especially for recycled aggregates and geopolymer binders. The lack of standardized national guidelines restricts uniform adoption across regions. Policy incentives such as tax credits, green procurement mandates, and waste-diversion regulations are critical to accelerating market acceptance. Furthermore, investment in recycling infrastructure, material testing laboratories, and local processing facilities is necessary to stabilize supply chains. Stakeholder interviews and policy reviews highlight insufficient awareness among contractors and developers, reinforcing the need for training programs and demonstration projects. Integrating circular economy principles into urban planning such as material passports, deconstruction protocols, and urban mining could significantly support long-term adoption. Ultimately, successful integration requires a combination of engineering advances, regulatory reform, financial incentives, and cultural change within the construction industry.

5. Conclusion

The integration of recycled and locally sourced materials presents a practical and impactful solution for reducing embodied carbon in urban structures while promoting resource circularity and environmental resilience. The findings of this study illustrate that recycled concrete aggregates, supplementary cementitious materials, bio-based components, and geopolymer binders can collectively reduce emissions by 25–70% depending on application and replacement ratio. Structural performance evaluations show that these materials, when properly engineered, can meet or exceed the requirements for low- to mid-rise buildings and selected infrastructure elements. Additionally, economic assessments reveal cost-saving potential through reduced raw material consumption and localized supply chains. Together, these results reinforce the feasibility and environmental importance of transitioning toward low-carbon construction materials in rapidly urbanizing regions.

Future work should expand on these findings by developing unified national and international standards for recycled and local materials, improving long-term durability databases, and advancing performance-based design codes that accommodate non-traditional materials. Digital innovations such as material passports, digital twins, and AI-enabled quality tracking systems should be explored to improve reliability and traceability across the construction lifecycle. Further research is needed on large-scale urban mining systems, decentralized recycling facilities, and incentive-based policy mechanisms that can accelerate the adoption of low-carbon construction practices. Long-term field monitoring, full-scale pilot projects, and cross-disciplinary collaboration will be essential to strengthen confidence in these materials and achieve widespread implementation.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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