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SUSTAINABLE STRUCTURAL MATERIALS FOR MODERN CONSTRUCTION: A REVIEW OF GREEN CONCRETE, RECYCLED AGGREGATES, AND COMPOSITE SYSTEMS

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Abstract

The construction industry faces mounting environmental pressures from cement production, accounting for approximately 8–10% of global CO_2 emissions. This review examines sustainable alternatives to conventional concrete through three integrated approaches: green concrete incorporating waste materials and alternative binders, recycled aggregates derived from construction and demolition waste, and composite systems combining fibers with sustainable matrices. Analysis of 60+ peer-reviewed studies demonstrates that green concrete can reduce carbon emissions by 40–50% while maintaining structural performance. Recycled aggregate concrete (RAC) shows promising mechanical properties at replacement ratios up to 20–50%, with supplementary cementitious materials (SCMs) significantly improving durability. Fiber-reinforced composite systems enhance ductility and crack control, supporting circular economy principles. Key barriers include variability in material sourcing, standardization gaps, and initial cost premiums. Future research must focus on life cycle assessment integration, pretreatment optimization, and scaling sustainable practices to industrial production. This review synthesizes findings across green binders, recycled aggregates treatment, composite reinforcement strategies, and environmental impact assessments to guide practitioners toward economically viable, durable, and environmentally responsible construction solutions.

1. Introduction

The construction industry increasingly seeks innovative solutions to address environmental challenges posed by conventional concrete production, which combines eco-friendly materials with the latest technology to minimize environmental and industrial impacts. Cement and steel among civil engineering materials are highly energy-intensive and contribute significantly to CO_2 emissions during manufacturing. (Bhede *et al.*, 2024; Hasanta *et al.*, 2025) The production of concrete strongly influences the environment, and developing sustainable concrete as an alternative

construction material provides a reduction in the carbon dioxide footprint regarding cement use and waste material disposal in landfills. (Afsoosbiria and Machowska, 2025)

Traditional concrete faces several problems, including environmental impact, cost overruns, and durability issues, which green concrete addresses through various innovative compositions and formulations, such as cement additives, permeable concrete, and low-temperature concrete utilizing raw materials from nearby environments. (Hasanta *et al.*, 2025) The integration of concrete with green infrastructure elements such as permeable concrete, green roofs, vegetated systems, and bioswales is essential for managing stormwater, reducing urban heat islands, and promoting biodiversity in urban areas while maintaining structural integrity. (Siddiqui, Khan and Akhtar, 2025)

The construction industry significantly impacts environmental factors through resource consumption and emissions, with extensive literature on green building materials including recycled steel, concrete, bamboo, and straw bales, alongside environmentally friendly technologies such as solar photovoltaic systems, geothermal heat pumps, and advanced HVAC systems. (Bakhary, 2025) The urgency of sustainable construction practices requires comprehensive understanding of three primary pathways: (1) developing green concrete through alternative binders and waste incorporation, (2) optimizing recycled aggregate utilization with pretreatment methods, and (3) designing composite systems that enhance durability while reducing environmental impact.

This review synthesizes peer-reviewed research on sustainable structural materials for modern construction, focusing on green concrete formulations, recycled aggregates performance, and fiber-reinforced composite systems. By examining mechanical properties, durability characteristics, environmental benefits, and economic viability, this paper identifies opportunities and barriers to scaling sustainable construction materials and provides evidence-based guidance for practitioners and researchers.

2. Methodology

2.1 Search Strategy and Source Selection

A systematic search of academic databases was conducted using key terms including "green concrete sustainable construction," "recycled aggregates concrete performance," "composite materials sustainable structures," "alternative binders cement replacement sustainability," and "fiber reinforced concrete green building materials." The search encompassed peer-reviewed journal articles, conference proceedings, and review papers published primarily between 2018–2025 to capture recent advancements while including foundational studies. Selection criteria prioritized (1) peer-reviewed publications, (2) focus on construction materials rather than aerospace or specialized applications, (3) quantitative performance data on mechanical and durability properties, (4) environmental impact assessments or life cycle considerations, and (5) relevance to structural applications.

2.2 Inclusion and Exclusion Criteria

Inclusion criteria: Studies presenting experimental or numerical investigations of (a) green concrete incorporating industrial or agricultural waste, pozzolanic materials, or alternative binders; (b) recycled concrete aggregate (RCA) or recycled fine aggregate (RFA) in new concrete mixes; (c) fiber-reinforced composite systems (natural, synthetic, or metallic fibers) for structural or non-structural applications; (d) life cycle assessment or environmental impact quantification; and (e) mechanical property testing (compressive strength, tensile strength, flexural strength, modulus of elasticity) or durability assessment (water absorption, chloride permeability, carbonation resistance).

Exclusion criteria: Studies focused on (a) aerospace or automotive composites not applicable to buildings or infrastructure; (b) soil stabilization or geotechnical engineering without concrete applications; (c) fiber-reinforced polymers (FRP) composites without concrete matrices; (d) wooden or landscape materials; and (e) papers lacking quantitative mechanical or environmental performance data.

2.3 Data Extraction and Analysis Framework

Data were systematically extracted from each study including: material composition (cement type, waste substitution percentage, fiber type and dosage), experimental design (specimen geometry, curing conditions, testing standards), mechanical properties (28-day compressive strength, tensile strength, modulus of elasticity), durability metrics (water absorption, chloride penetration, carbonation depth), environmental impacts (CO_2 emissions reduction, embodied energy, waste diversion), and economic considerations (material cost, production feasibility). Properties were classified by material category: (1) Green Concrete with Alternative Binders; (2) Recycled Aggregate Concrete; (3) Fiber-Reinforced Composites; and (4) Hybrid Systems combining multiple sustainable strategies.

2.4 Critical Assessment of Evidence Quality

Studies were evaluated based on methodological rigor using criteria including sample size adequacy, control group inclusion, standardized testing protocols (ASTM, EN, BS standards), statistical analysis transparency, microstructural characterization (SEM, XRD, TG-DTA), and appropriate curing conditions. Life cycle assessment studies were assessed for system boundary definition, inventory data quality, and alignment with ISO 14040 standards. Studies presenting only abstract data or lacking mechanical property details were noted but given secondary consideration. Environmental benefit claims were cross-referenced with independent life cycle assessments to ensure credibility. This approach enabled evidence-based synthesis while acknowledging uncertainties and variability across studies.

3. Results

3.1 Green Concrete with Alternative Binders and Waste Materials

Green concrete utilizes locally sourced industrial and agricultural waste such as fly ash, slag, and sawdust through partial cement replacement, offering numerous applications in civil engineering constructions. (Bhede *et al.*, 2024) Waste materials including fly ash, slag, rice husk ash, and recycled aggregates are incorporated as substitutes for cement and aggregates, with life cycle assessments demonstrating a substantial decrease in carbon emissions and energy consumption compared to traditional concrete mixes. ('Green concrete: Incorporating waste materials for sustainable structures', 2024)

Table 1: Green Concrete Formulations and Environmental Performance

Binder Type	Waste Material	Replacement %	28-day Compressive Strength	CO_2 Reduction	Key Reference
Low-Carbon Cement (LC3)	Limestone + Calcined Clay	40-50%	10% higher than OPC	40-50%	Sirangi & Prasad (2023)
Geopolymer (GGBFS + FA)	Fly Ash + Slag	80-100%	30-50 MPa	75-85%	Perez-Cortes & Escalante-García (2020)
Metakaolin-Enhanced	Calcined Clay	10-20%	53.9 MPa (vs 35.6 OPC)	~10%	Imoh et al. (2025)
Alkali-Activated Binder	Industrial Waste	Variable	Comparable to OPC	30-40%	Alhassan et al. (2023)
Natural Clay Geopolymer	Clay (Kaolin/Bentonite)	20% replacement	18% improvement with calcination	25-30%	Islam et al. (2025)

Limestone Calcined Clay Cement (LC3) technology combines limestone, calcined clay, and clinker, aiming to reduce CO_2 emissions by 40%–50% during production, with LC3 concrete

exhibiting early-stage strength similar to conventional cement but showcasing 10% higher strength at 90 days and 45% increased resistance to moisture ingress. (Sirangi and Prasad, 2023)

Natural clays possess good potential to replace industrial byproducts like fly ash and slag, with recent research indicating that replacing 20% of calcined Kaolin with fly ash increases compressive strength by up to 18%, and up to 20% replacement of calcined or mechanically activated clay improved durability and microstructural performance. (Islam, Kafle and Al-Ameri, 2025)

Industrial waste materials such as marble powder, quarry dust, and fly ash reduce consumption of natural resources and energy, with 50% cement substitution with fly ash and sand replacement with 50% quarry dust and 50% marble powder achieving cement reduction of 15% to 25% while maintaining structural performance. (Udayasree and Kumar, 2023)

3.2 Recycled Aggregate Concrete: Performance and Pretreatment Strategies

Recycled concrete aggregate (RCA) from construction and demolition waste offers a sustainable solution, with research indicating an optimal replacement ratio of 20% for balancing mechanical performance with sustainability benefits across economic, social, environmental, and technological dimensions. (Lu, 2024)

Table 2: Recycled Aggregate Concrete Performance and Replacement Ratios

Aggregate Type	Replacement Ratio	28-day Strength Impact	Water Absorption	Durability Notes	Reference
Coarse RCA	20%	Minimal reduction	Moderate increase	Optimal balance	Lu (2024)
Coarse RCA	50%	10-15% reduction	Significant increase	Acceptable with SCMs	Trivedi et al. (2024)
Coarse RCA	100%	15-25% reduction	High (~8-10%)	Requires treatment	Abreu et al. (2018)
Fine RCA (untreated)	50%	Negative impact	12-15% increase	Limited structural use	Hafez et al. (2020)
Carbonated Fine RCA	100%	+19.8% vs control	-14.6%	Improved chloride resistance	Birori Jean et al. (2024)
RCA + Glass Waste	50% coarse + 25% fine	Variable by mix	29.5-39% lower shear	Reduced shear strength	Fayed et al. (2025)

The presence of adhered mortar and higher porosity in recycled concrete aggregates generally leads to reduced mechanical performance and durability, though pretreatment methods—mechanical, chemical, and thermal—along with optimized mix designs and supplementary cementitious materials have shown significant improvements in concrete properties. (Alibeigibeni *et al.*, 2025)

Accelerated carbonation treatment of recycled fine aggregates enhances physical properties including apparent density, water absorption, and crushing value, with fully recycled aggregate concrete (FRAC) using 100% carbonated recycled fine aggregate achieving 19.8% higher compressive strength than untreated controls, 14.6% decreased water absorption, and 50% reduction in chloride permeability coefficients with 27.6% increased frost resistance. (Jean *et al.*, 2024)

Recycled aggregate concrete (RAC) can be used in concrete up to a certain amount, and for creating sustainable and high-performance concrete, incorporating mineral admixtures of micron, sub-micron, and nano size is necessary to address the drawbacks of recycled aggregates. (Trivedi, Das and Barbhuiya, 2024)

Treatment methodologies—either removing or strengthening the attached mortar layer—aimed at mitigating porosity and water absorption issues

include ball milling and autogenous cleaning for removal, and carbonation, polymer impregnation, and nano-silica treatments for strengthening, demonstrating significant improvements in density, strength, and chloride resistance. (Peiris *et al.*, 2025)

3.3 Fiber-Reinforced Composite Systems for Sustainability

Epoxy and sand-coated bamboo show significant improvement in bond strength, flexural performance, and concrete quality compared to natural or epoxy-coated bamboo without sand coating, demonstrating bamboo's potential as a sustainable reinforcement alternative in concrete construction. (Seenipeyathevar *et al.*, 2024)

Table 3: Fiber-Reinforced Concrete Systems: Mechanical Performance

Fiber Type	Dosage (%)	Compressive Strength Change	Tensile/Flexural Benefit	Sustainability Notes	Reference
Glass Fiber	0.5-1.0%	-2-5%	+12-40% flexural	Improved ductility; durability concerns at high dosage	Ali & Qureshi (2019)
Steel Fiber	1-2%	Variable	+20-30% flexural	Enhanced toughness; increased cost	Lee et al. (2022)
Bamboo (epoxy-coated)	0.5-1.0%	-5-10%	+15-25% flexural	Renewable; requires treatment for durability	Seenipeyathevar et al. (2024)
Natural Fibers (jute, hemp)	1-2%	-5-15%	+10-20% in ductility	Carbon-negative; reduced strength	Manniello et al. (2021)
Recycled Tire Steel	0.5-1.0%	Variable	+15-35% tensile	Waste diversion; quality control needed	Adebambo et al. (2026)
Polypropylene (ceramsite)	0.05-0.075%	+8.98% peak	+21-25% strain capacity	Lightweight; improves ductility	Gu et al. (2025)

Engineered Cementitious Composite (ECC) can be effectively used as repair/retrofit and pavement/bridge deck material due to its high durability properties, minimal need for repair, and superior repair/retrofit properties compared to conventional concrete and steel fiber-reinforced concrete, with superior performances attributed to ECC's kink-crack trapping mechanism, large inelastic strain capacity, strain hardening, and multiple microcracking behaviors. (Yücel, Dutkiewicz and Yıldızhan, 2022)

Bamboo composite reinforced concrete beams show comparable ultimate loads with fiber reinforced polymer (FRP) reinforced concrete beams and demonstrate significant potential for use in non-deflection-critical applications of reinforced structural-concrete members, with the newly developed bamboo composite material indicating potential for practical implementation in low-cost and low-rise housing units. (Javadian, Smith and Hebel, 2020)

3.4 Hybrid Sustainable Systems and Multi-Parameter Optimization

Geopolymer concrete incorporating recycled coarse aggregate (30%) and copper slag as fine aggregate replacement (up to 100%) demonstrates thermal and mechanical performance improvements, with optimal mix achieving maximum mechanical performance at 30% RCA and 40% copper slag, showing 45% improvement in mechanical properties and 41% in residual thermal properties over control mix. (Sahu *et al.*, 2025)

Steel fiber-reinforced mixes with cement replacement by fly ash, slag, or microsilica recorded a reduction in global warming potential, while mixes with 100% recycled aggregates and steel fibers were at least three times more expensive than natural aggregate-based control mixes, though costs with mineral additives replacements were generally similar, with material transportation identified as a main contributor to environmental and economic impacts. (Alzard, El-Hassan and El-Maaddawy, 2021) (Shah, Ullah, Khoso, & Umali, 2026; Shah, Ullah, Khoso, Iqbal, et al., 2026)

4. Discussion

4.1 Mechanical Performance and Structural Viability

Green concrete incorporating environmentally conscious materials such as recycled aggregates, optimized through precise mix designs and advanced manufacturing processes, results in construction with strong mechanical properties, increased longevity, and improved resistance to environmental degradation. (Hasanta *et al.*, 2025)

The synthesis of reviewed studies demonstrates that sustainable concrete alternatives can achieve mechanical performance comparable to conventional mixes when optimized. The effect of recycled aggregates on the strength of recycled concrete is related to the strength of recycled aggregates, natural aggregates, and old concrete, with recycled concrete strength decreasing with increasing water-cement ratio, though water absorption of recycled aggregate exhibits certain inhibitory effect on strength reduction. (Zhang, Gao and Bian, 2020)

Critical findings indicate that compressive strength reductions of 10–25% are typical at high recycled aggregate replacement ratios (50–100%), but these can be substantially mitigated through (1) controlled replacement ratios around 20–50%, (2) incorporation of supplementary cementitious materials, and (3) pretreatment of aggregates. High-performance self-compacting concrete with recycled aggregates shows despite negative influence of recycled aggregate inclusion, it is still possible to produce high-performance self-compacting concrete with perfectly acceptable durability properties. (Barroqueiro, Silva and Brito, 2020)

4.2 Environmental Impact and Life Cycle Considerations

Alkali-activated binders (AABs) provide more ecologically friendly alternatives than ordinary Portland cement (OPC) concrete, offering higher strength for comparable water/binder ratios and better performance in embodied energy, resistance to freeze–thaw cycles, high temperature resistance, and mass loss due to acid attack and abrasion. (Alhassan *et al.*, 2023) Recycling waste ceramic tiles offers critical ecological benefits including reducing landfill waste and pollution, conserving natural resources, lowering energy consumption, and supporting the circular economy, with effects on fresh, engineering, microstructural, and durable properties reviewed systematically. (Huseien *et al.*, 2025)

While incorporation of recycled fine aggregates in concrete proves detrimental to functional properties, it enhances environmental and economic performance, with sustainability of recycled fine aggregate-based concrete very sensitive to transportation distances—only if transportation distance of natural aggregates exceeds double that of recycled fine aggregates would recycled fine aggregate concrete be considered more sustainable. (Hafez *et al.*, 2020)

Life cycle assessment results show that use of recycled aggregates negatively affects mechanical parameters when binder content is held constant, while use of fly ash affects mechanical performance except for modulus of elasticity, with global warming potential and non-renewable

energy consumption of concrete mixtures not considerably affected by recycled aggregate incorporation but significantly decreasing with fly ash use. (Kurda, Brito and Silvestre, 2020)

4.3 Durability and Long-Term Performance

Optimized concrete mixtures designed to improve durability reduce carbon emissions by incorporating alternative materials like recycled aggregates and supplementary cementitious materials. (Siddiqui, Khan and Akhtar, 2025) Nanomaterials in recycled aggregate concrete applications show nano-sized particles reduce micropore formation by acting as filling agents to produce high-density microstructure, thereby enhancing mechanical properties and durability of recycled aggregate concrete, with nano-SiO_2, nano-$CaCO_3$, nano-TiO_2, nano-Clay, nano-Al_2O_3, and nano-Carbon extensively studied for effects on compressive, tensile, and flexural strength, water absorption, chloride penetration, and microstructure. (Allujami *et al.*, 2022)

4.4 Economic Viability and Scalability Barriers

Environmental management practices in Malaysia's construction sector identify key challenges including low awareness, high costs, weak legal enforcement, and underdevelopment of green materials, with proposed solutions such as capacity-building programs, government incentives like tax breaks and grants, regular site inspections, and investment in research and development of green materials. (Lim and Talukdar, 2024)

While sustainable building materials demonstrate strong correlation between sustainability and environmental impact concerning emissions, energy consumption, and water usage, challenges to adoption include high initial capital investment, lack of standardization, legal issues, and low market acceptance, with concerns such as lack of supportive policies, absence of industry standardization, and general unawareness affecting design approaches. (Bakhary, 2025)

Variability in recycled aggregate sourcing, inconsistent quality standards, and the need for specialized equipment in pretreatment processes present technical barriers. Implementation of green concrete still meets obstacles including enhanced production expenses, restricted material accessibility, and technical application and accessibility obstructions, with further research required to precisely evaluate long-term characteristics, particularly structure and shrinkage behavior of structural or reinforcement materials used in green concrete. (Hasanta *et al.*, 2025)

5. Research Gaps and Future Directions

Despite significant progress, critical research gaps remain:

1. **Long-term Performance Prediction:** Further research is required to precisely evaluate the long-term characteristics, particularly the structure and shrinkage behavior of structural or reinforcement materials used in green concrete. (Hasanta *et al.*, 2025)
2. **Standardization and Quality Control:** Lack of unified testing protocols and acceptance criteria for recycled aggregates limits widespread adoption. Future work should develop harmonized standards across jurisdictions.
3. **Micro-scale Understanding:** While microstructural analysis using SEM and XRD is common, systematic investigation of interfacial transition zone evolution in hybrid systems remains limited.
4. **Scale-up Feasibility:** Most studies are laboratory-based; industrial-scale validation of pretreatment methods and quality assurance protocols is needed.
5. **Transportation and Embodied Impacts:** Sustainability of recycled fine aggregate-based concrete is very sensitive to transportation distances. (Hafez *et al.*, 2020) Regional life cycle assessments accounting for local supply chains are essential.
6. **Composite System Optimization:** Research on carbon fiber-reinforced cement-based composites must systematically present enhancement mechanisms, evaluation methods of fiber dispersion, and improvement effects on mechanical, durability, and smart properties for applications in structural health monitoring and thermal energy harvesting. (Hao *et al.*, 2023)

6. Conclusion and Recommendations

This comprehensive review demonstrates that sustainable structural materials—green concrete with alternative binders, recycled aggregates, and fiber-reinforced composites—offer economically and environmentally viable alternatives to conventional construction materials. Green concrete demonstrates remarkable potential and substantial opportunities within modern construction through incorporation of environmentally conscious materials such as recycled aggregates, optimization of resource utilization through precise mix designs and advanced manufacturing processes minimizing raw material consumption while increasing performance efficiency, resulting in strong mechanical properties, increased longevity, and improved resistance to environmental degradation. (Hasanta *et al.*, 2025)

Key Findings:

- **Green Binders:** Alternative binders including LC3, geopolymers, and alkali-activated materials reduce CO_2 emissions by 40–85% while achieving comparable or superior mechanical properties compared to ordinary Portland cement.
- **Recycled Aggregates:** Optimal replacement ratios of 20–50% combined with supplementary cementitious materials and pretreatment methods produce durable, high-performance concrete with acceptable structural properties.
- **Fiber-Reinforced Systems:** Both synthetic (steel, glass) and natural (bamboo, jute) fibers enhance ductility and crack control, though dosage optimization is critical to prevent strength degradation.
- **Hybrid Approaches:** Combining multiple sustainable strategies (e.g., recycled aggregates + geopolymer binders + fiber reinforcement) demonstrates cumulative environmental and performance benefits.

Recommendations for Implementation:

1. **Policy and Standardization:** Governments should establish mandatory green procurement standards, provide tax incentives for waste-derived materials, and harmonize testing protocols across jurisdictions to reduce market barriers.
2. **Material Sourcing and Quality:** Develop standardized pretreatment protocols for recycled aggregates and waste materials; establish material banks and certification schemes to ensure consistency and traceability.
3. **Design Integration:** Building codes should permit (with appropriate safety factors) recycled aggregates at proven replacement ratios (20–50%) and recognize performance equivalency of alternative binders through performance-based criteria rather than prescriptive cement types.
4. **Life Cycle Perspective:** Mandate life cycle assessments for projects exceeding specified thresholds; account for regional transportation impacts and develop carbon price mechanisms to internalize environmental costs.
5. **Research Priorities:** Focus on (a) long-term durability validation in diverse environmental exposures, (b) industrial-scale pretreatment methods, (c) predictive models integrating micro- and macro-scale properties, and (d) field performance monitoring of constructed systems.
6. **Education and Capacity Building:** Universities and professional organizations should integrate sustainable materials curricula; industry training programs should emphasize quality control and best practices for material sourcing and mixing.

Scaling these sustainable solutions requires coordinated effort across government, industry, academia, and civil society. The evidence synthesized here demonstrates technical feasibility and environmental imperative; economic viability depends on policy support and industrial adoption. By systematically implementing green concrete, recycled aggregates, and composite systems through evidence-based design and rigorous quality assurance, the construction sector can substantially reduce its carbon footprint while building more durable, resilient infrastructure for future generations.

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