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Sustainable Materials in Civil Engineering: A Review of Recycled and Recyclable Materials for Construction

Funmilola Deborah Ogunremi[1], Chidera Kingsley Eze[2], Elijah Oluwadara Adetunji[3], Chibuzo Joseph Attah[4], Chiamaka Sandra Ezugwu[4], Moses Adondua Abah*[5], Micheal Abimbola Oladosu[5] and Nathan Rimamsanati Yohanna[5]

[1]*Department of Civil and Environmental Engineering, Faculty of Engineering, University of Lagos*
[2]*Civil Engineering Department of Civil Engineering, School of Computing, Engineering & Digital Technologies, Teesside University, Middlesbrough, United Kingdom*
[3]*Department of Civil Engineering, Faculty of Engineering, Federal University of Technology Akure, Akure, Ondo State, Nigeria*
[4]*Department of Civil Engineering, Faculty of Engineering, University of Nigeria Nsukka, Nsukka, Enugu State, Nigeria*
[5]*ResearchHub Nexus Institute, Nigeria*

ABSTRACT

The construction industry is a significant contributor to environmental degradation, consuming vast resources and generating substantial waste. Sustainable materials in civil engineering can mitigate this impact. This review explores the use of recycled and recyclable materials in construction, highlighting benefits and challenges. Materials like recycled concrete aggregate, fly ash, and reclaimed wood are gaining traction, offering potential for reduced waste and conserved natural resources. Research shows recycled materials like crushed concrete and fly ash can replace traditional aggregates, reducing landfill waste and CO_2 emissions. Recycled asphalt pavement and demolition waste are also viable alternatives. Challenges include ensuring consistent quality and public acceptance. Recyclable materials like steel and glass are widely adopted, while bio-based materials like bamboo and hemp show promise. Case studies demonstrate economic and environmental benefits, but standardisation and policy support are needed for widespread adoption. Effective recycling technologies and design approaches can further enhance sustainability in civil engineering. Sustainable materials offer significant environmental and economic benefits in civil engineering. Widespread adoption requires overcoming technical and societal barriers. Policy support, standardisation, and innovation are key to a more sustainable construction industry.

Keywords: *Sustainable materials, Recycled materials, Civil engineering, Recyclable materials, Construction waste, Green construction, and Environmental impact.*

Introduction

Due to its reliance on traditional materials like cement, steel, and aggregates, the construction industry has long been acknowledged as one of the most resource-intensive industries, placing a heavy burden on the environment [1]. Despite being essential for contemporary infrastructure, the extraction, processing, and disposal of these minerals have a significant negative impact on the environment. Due in significant part to the energy-intensive nature of clinker production and the calcinations process, cement manufacturing alone is responsible for about 8% of the world's carbon dioxide emissions [2]. Similar to how the extraction of natural aggregates causes habitat damage, soil erosion, and the depletion of limited resources, the production of steel uses enormous amounts of energy and contributes to greenhouse gas emissions. These materials have an environmental impact that goes beyond their manufacturing process and includes shipping, use, and final demolition, which results in significant waste from building and demolition. The issue of resource scarcity and environmental degradation is made worse by the fact that this garbage frequently ends up in landfills [3].

The confluence of environmental responsibility and the increasing need for infrastructure gives rise to the urgent need for sustainability in civil engineering. The building industry must balance its contribution to economic growth with its need to reduce environmental damage as urbanisation picks up speed worldwide. In this setting, sustainability necessitates a paradigm change from linear material consumption to circular ways, making it more than just a theoretical goal [4]. Figure 1's depiction of the life cycle of building materials emphasises how crucial it is to take into account each phase, from the extraction of raw materials to their disposal at the end of their useful lives,

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Corresponding Authors: **Moses Adondua Abah**
Email: **m.abah@fuwukari.edu.ng**

when assessing environmental performance. Civil engineering may lower emissions, save resources, and increase built environments' resilience by implementing sustainable methods [5].

Recyclable and recycled materials offer a viable way to accomplish these objectives. Fly ash, slag, and recycled aggregates are examples of industrial byproducts that are structurally viable and environmentally beneficial when included in construction processes. These materials lessen the total environmental impact of construction projects by diverting waste from landfills and minimising the need for virgin resources. For instance, recycled concrete aggregates have been shown to perform comparably to natural aggregates in certain structural applications, while polymer-based recycled materials offer durability and versatility in non-load-bearing components [6]. Furthermore, recyclable materials such as aluminium and certain plastics can be reintegrated into production cycles, aligning with circular economy principles and minimizing waste generation.

As Figure 1 shows, the construction material life cycle is an evolving structure in which interventions at any stage, whether through recycling, reuse, or improved design, can yield significant environmental benefits. By embracing recycled and recyclable materials, civil engineering can move closer to a future where infrastructure development harmonises with ecological stewardship, ensuring that the built environment supports both human progress and planetary health. In the end, the shift towards sustainable materials in civil engineering is not only a technical but also a cultural and economic.

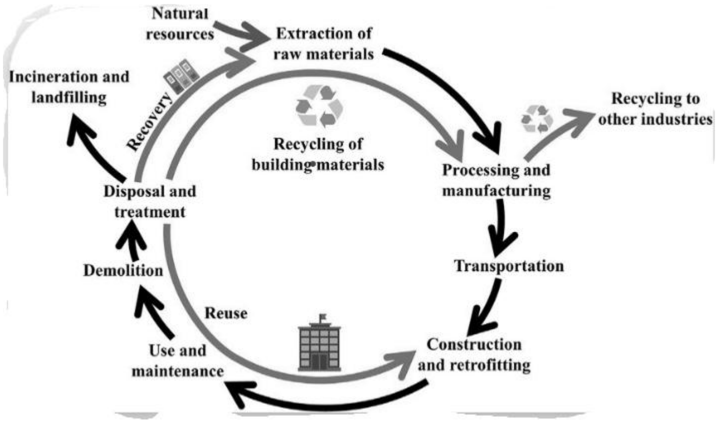

Figure 1. Construction material life cycle
Source: [28]

This review's objective is to assess recyclable and recycled materials in civil engineering critically, with an emphasis on their structural performance and environmental effects. This study aims to emphasise the opportunities and problems related to their adoption by synthesising findings from current studies, especially those published in peer-reviewed journals like Sustainability and Materials. Examining material qualities, life cycle assessments, and case studies that show real-world uses in infrastructure projects are all included in the scope. By doing this, the assessment highlights the twin necessity of guaranteeing durability and safety while furthering sustainable goals.

Types of Sustainable Construction

Materials that not only satisfy structural requirements but also reduce environmental impacts throughout their life cycle are becoming more and more important in civil engineering as a result of the goal of sustainability. Recycled aggregates, industrial byproducts like fly ash and slag, and bio-based materials are some of the most promising categories. Each of these makes a distinct contribution to lowering the environmental impact of building while preserving or even raising performance standards. Table 1 provides a summary of sustainable materials and their sources, highlighting the diversity of options available for integration into modern construction practices.

Table 1. Sustainable materials and sources

Material Category	Examples / Sources	Key Properties / Benefits
Recycled Aggregates	Crushed concrete, masonry rubble, asphalt debris	Reduces demand for virgin aggregates; comparable mechanical strength; lowers CO_2 emissions
Industrial By-products	Fly ash (coal combustion residue), Ground Granulated Blast Furnace Slag (steel industry by-product)	Pozzolanic activity; improves durability and workability; reduces cement demand and carbon footprint
Bio-based Materials	Hempcrete (hemp shiv + lime), bamboo composites, starch/cellulose-based biopolymers	Renewable, biodegradable, carbon sequestration potential; thermal insulation; tensile strength

Sources: [6-8]

Place of natural aggregates in the manufacturing of concrete, road base layers, and other uses. Their use reduces the demand for virgin aggregates, thereby mitigating the environmental degradation associated with quarrying and mining activities. Studies have demonstrated that recycled concrete aggregates (RCA) can achieve comparable mechanical properties to natural aggregates when properly processed, although attention must be paid to issues such as higher water absorption and potential variability in quality [9].

RCA inclusion is a key component of sustainable construction solutions because life cycle assessments verify that it greatly reduces energy consumption and greenhouse gas emissions when compared to traditional aggregates [10]. It has long been known that industrial by-products, especially fly ash and ground granulated blast furnace slag (GGBS), can improve concrete's performance and sustainability.

Because of its pozzolanic qualities, fly ash, a fine powder produced from burning coal, can partially substitute cement in concrete compositions. This replacement enhances workability and long-term strength development while lowering the carbon footprint related to cement manufacture. Fly ash's usefulness can be further expanded by recycling it into lightweight aggregates, which have both structural and environmental advantages, according to recent life cycle studies [11]. In a similar vein, GGBS, a by-product of the production of iron and steel, helps create high-performance concretes that are more durable, less permeable, and more resistant to chemical attack. It has been demonstrated that adding slag to geopolymer concretes significantly lowers carbon emissions without compromising structural integrity, highlighting slag's importance in sustainable building [12].

A new area of sustainable building is bio-based materials, which provide renewable substitutes made from natural and agricultural resources.

This category includes materials that combine ecological advantages with functional adaptability, such as hempcrete, bamboo composites, and bio-polymers [13]. Hempcrete, produced from hemp shiv and lime, provides excellent thermal insulation and carbon sequestration potential, while bamboo offers high tensile strength and rapid renewability, making it suitable for structural applications in certain contexts. Bio-polymers derived from starch or cellulose are increasingly being explored for use in coatings, adhesives, and lightweight composites. These materials not only reduce reliance on non-renewable resources but also align with circular economy principles by enabling biodegradability and recyclability. Research has highlighted that bio-based materials can significantly lower embodied energy and carbon emissions compared to conventional options, though challenges remain in scaling production and ensuring consistent performance [14].

Mechanical and Durability Performance

The acceptability of sustainable building materials in civil engineering practice is largely dependent on their mechanical and durability performance [14]. Engineers must make sure that recycled and recyclable materials satisfy structural requirements, withstand deterioration, and retain long-term stability under a variety of service situations, even if environmental benefits are crucial. Using data from recent experimental and analytical research, this section looks at three interconnected factors: *strength, durability, and long-term behaviour*. The mechanical and durability indices of recycled aggregates, industrial byproducts, and bio-based materials are contrasted with traditional standards in Figure 2's comparative performance chart [15].

Strength

When assessing building materials, strength is still the most important factor, especially in structural applications where load-bearing capacity is crucial. Because of their greater porosity and weaker interfacial transition zones (ITZ), recycled aggregates made from crushed concrete and masonry waste frequently have lower compressive strengths than natural aggregates. However, research has demonstrated that recycled concrete aggregates (RCA) can attain compressive strengths within 10–20% of conventional concrete with appropriate processing, such as removing adherent mortar and optimising grading [16]. By improving pore structure and encouraging secondary hydration reactions, the use of additional cementitious materials such as fly ash or slag, further improves strength development [17]. Through pozzolanic action, fly ash can increase long-term strength when utilised in place of some of the cement. The matrix becomes denser as a result of its tiny particles reacting with calcium hydroxide to produce more calcium silicate hydrate (C-S-H). Despite slower early-age strength development, research shows that concretes with 20–30% fly ash replacement frequently outperform control mixes in terms of compressive strength after 90 days [18]. In a similar vein, ground granulated blast furnace slag (GGBS) improves flexural and compressive strength, especially in blended systems with a slag percentage of 40–60%. Slag is a favoured constituent in high-performance concretes because of its latent hydraulic qualities, which support the development of robust strength.

Durability

When fly ash is used in place of some of the cement, it can boost long-term strength through pozzolanic action. Its microscopic particles react with calcium hydroxide to create more calcium silicate hydrate (C-S-H), which makes the matrix denser. According to study, concretes containing 20–30% fly ash substitution often beat control mixes in terms of compressive strength after 90 days, despite slower early-age strength development [19]. Similarly, in blended systems with a slag proportion of 40–60%, ground granulated blast furnace slag (GGBS) enhances flexural and compressive strength. Because of its latent hydraulic properties, which promote the development of strength, slag is a preferred component in high-performance concretes.

Long-term behavior

The strength profile of bio-based materials is more complicated. For example, hempcrete's comparatively low compressive strength (usually between 1 and 3 MPa) makes it unsuitable for load-bearing applications. Instead of structural capability, its value is found in insulation and carbon sequestration [20]. In contrast, bamboo exhibits tensile strengths that are on par with mild steel, which makes it appropriate for reinforcing in specific situations. According to studies, bamboo has favourable strength-to-weight ratios and tensile strengths above 200 MPa, making it a potential substitute for low-rise structures [21]. Although their unpredictability and sensitivity to environmental conditions continue to be issues, bio-polymers can achieve modest compressive and flexural strengths depending on formulation. The strength profile of bio-based materials is more complicated. For example, hempcrete's comparatively low compressive strength (usually between 1 and 3 MPa) makes it unsuitable for load-bearing applications. Instead of structural capability, its value is found in insulation and carbon sequestration. In contrast, bamboo exhibits tensile strengths that are on par with mild steel, which makes it appropriate for reinforcing in specific situations. According to studies, bamboo has favourable strength-to-weight ratios and tensile strengths above 200 MPa, making it a potential substitute for low-rise structures [21]. Although their unpredictability and sensitivity to environmental conditions continue to be issues, bio-polymers can achieve modest compressive and flexural strengths depending on formulation.

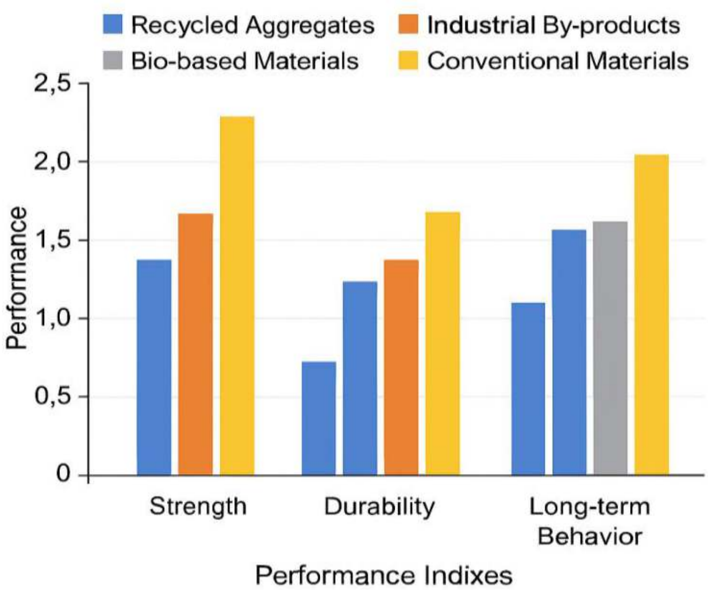

Figure 2. Performance comparison chart
Source: *[11]*

Figure 2 illustrates a comparative chart of mechanical and durability performance indices for recycled aggregates, industrial by-products, and bio-based materials relative to conventional benchmarks. Recycled aggregates demonstrate moderate strength and durability, with long-term behaviour requiring careful mix design. Industrial by-products such as fly ash and slag consistently outperform conventional materials in durability and long-term stability, while bio-based materials excel in environmental performance but present limitations in strength and durability. The chart underscores the complementary nature of these materials, suggesting that hybrid approaches such as combining recycled aggregates with fly ash or slag offer the most balanced performance profile.

Environmental and Economic Assessment

Incorporating sustainable materials into civil engineering requires consideration of their economic and environmental effects in addition to their mechanical performance. Two essential methods that help engineers and policymakers measure the wider effects of material decisions are life cycle assessment (LCA) and cost-benefit analysis (CBA) [22]. These approaches offer a comprehensive understanding of sustainability that takes into account emissions, waste production, resource usage, and long-term financial viability. Table 2 provides a comparative perspective for evaluating recycled aggregates, industrial byproducts, and bio-based materials by summarizing important environmental impact indicators used in life cycle assessment (LCA) research [23].

Life cycle assessment (LCA)

LCA is a standardised methodology for assessing how a process or product affects the environment at every stage of its life cycle, from the extraction of raw materials to disposal at the end of its useful life. When it comes to building materials, life cycle assessment (LCA) aids in measuring emissions, energy use, water consumption, and ecological degradation related to manufacture, transportation, use, and demolition. The basis for performing LCA is provided by the ISO 14040 and 14044 standards, which provide uniformity and comparability among studies [24].

For example, LCA studies show that recycled aggregates have major environmental benefits. RCA reduces embodied energy and greenhouse gas emissions by keeping building and demolition waste out of landfills and minimising the need to obtain virgin aggregate. [25] conducted a comparative life cycle assessment (LCA) and discovered that RCA concrete reduced CO_2 emissions by up to 30% when compared to conventional concrete, mainly because it avoided quarrying and had shorter transportation distances. However, regional logistics, pollution levels, and processing techniques all affect the environmental advantages.

Slag and fly ash are examples of industrial by-products that do well in life cycle assessments. When utilised as a partial substitute, fly ash, a byproduct from the combustion of coal, lessens the environmental impact of cement manufacture. The most carbon-intensive ingredient in cement, clinker, is less necessary thanks to its pozzolanic action. Slag, which comes from the production of steel, improves durability and adds to low-carbon concrete formulas, increasing service life and lowering emissions associated with maintenance. In comparison to regular Portland cement mixes, slag-blended concretes obtained a 40% reduction in global warming potential, according to a study by [26].

Bio-based materials provide special benefits for the environment, especially when it comes to renewability and carbon sequestration. For instance, hempcrete contributes to negative carbon emissions throughout its life cycle by continuing to absorb CO_2 after installation. Bamboo offers a low-impact substitute for conventional steel and wood because of its quick growth rate and low resource requirements. However, LCA studies warn that transportation, treatment, and cultivation methods have a significant impact on the environmental performance of bio-based goods. Sustainable sourcing and certification are essential since uncontrolled harvesting or chemical-intensive processing can counteract ecological benefits [28].

Cost–benefit analysis

Due to cheaper material and transportation costs, recycled aggregates usually provide cost benefits, particularly when supplied locally. Nevertheless, extra processing to satisfy quality requirements could raise starting costs. According to CBA research, using RCA in non-structural applications or in conjunction with additional cementitious ingredients that improve performance makes it economically advantageous. Long-term positive net benefits are further enhanced by lower landfill costs and longer service life [25].

As industrial byproducts, fly ash and slag may have transportation and quality control expenses. However, their capacity to increase durability and lower cement usage results in significant long-term savings. Slag-blended concrete structures frequently have longer service lives and require less maintenance, which lowers lifecycle costs. Slag-based concretes produced a 15–20% decrease in overall project costs over a 50-year horizon, taking into account fewer repairs and energy savings, according to a study by [24].

The economic profile of bio-based materials is more complex. Because hempcrete and bamboo require specialised labour and have limited supply chains, their initial costs may be higher. Over time, though, these expenses may be mitigated by their minimal maintenance needs and insulating qualities. For example, the strength-to-weight ratio of bamboo lowers installation and transportation costs, while hempcrete cuts heating and cooling costs. CBA models indicate that bio-based materials become economically viable when environmental externalities such as carbon pricing or sustainability incentives are included in the analysis [23].

Table 2. Environmental impact indicators

Indicator	**Description**	**Units**	**Relevance to Sustainable Materials**
Global Warming Potential (GWP)	Total greenhouse gas emissions over life cycle	kg CO_2-equivalent	Lower for fly ash, slag, hempcrete
Embodied Energy	Total energy consumed during production	MJ/kg	Reduced in recycled aggregates
Water Footprint	Water used across life cycle stages	liters/kg	Lower in bio-based materials
Acidification Potential	Emissions contributing to acid rain	kg SO_2-equivalent	Reduced in slag-blended concretes
Eutrophication Potential	Nutrient runoff causing water body degradation	kg PO_4-equivalent	Minimal in bamboo and hempcrete
Resource Depletion	Consumption of non-renewable resources	kg or MJ	Lowest in recycled and bio-based

Sources: *[15-17]*

Challenges, Standards, and Future Outlook

The shift to sustainable building materials is laden with difficulties that go beyond technical performance into the legislative, economic, and cultural spheres, as [28] point out. The unpredictability of recycled aggregates, which frequently show variable quality due to variations in source composition and processing techniques, is one of the most enduring problems. This results in uncertainty regarding mechanical and durability consequences [1-3]. Because engineers need predictable performance to guarantee safety and dependability in structural applications, this unpredictability makes standardisation efforts more difficult [4]. Despite their well-known pozzolanic and hydraulic qualities, industrial by-products like fly ash and slag have supply chain stability and regional availability issues. Fly ash output has decreased in many areas due to the closure of coal-fired power plants, raising questions regarding its long-term availability [5-6]. Although slag is widely available in nations that produce steel, its worldwide scalability is limited in areas lacking substantial metallurgical industries [7-8]. Furthermore, as contamination or incorrect processing might impair performance, the environmental advantages of these materials depend on strict quality control [9-10]. The difficulties associated with bio-based materials are distinct. Although hempcrete, bamboo, and bio-polymers are commended for their potential for carbon sequestration and renewability, their mechanical constraints and vulnerability to biological deterioration continue to prevent widespread use [10-12]. For example, bamboo needs to be chemically treated to withstand insect and fungal attacks, which raises concerns about environmental trade-offs [13-14]. Because of its low compressive strength, hempcrete can only be used in non-load-bearing applications, and bio-polymers frequently have durability issues when the climate changes [15]. These difficulties are made worse by the lack of harmonised standards. While sustainable alternatives frequently lack thorough requirements, conventional materials benefit from decades of regulated specifications. Standards for recycled aggregates differ greatly between jurisdictions, which leaves contractors and designers in the dark [16, 17]. Global interoperability is hampered by the differences in acceptable limits and performance standards between ASTM and EN criteria for fly ash and slag [18, 19]. With new standards emphasising thermal and environmental performance over structural integrity, bio-based materials are still mostly outside of official codes [21, 22]. These difficulties are made worse by the lack of harmonised standards. While sustainable alternatives frequently lack thorough requirements, conventional materials benefit from decades of regulated specifications. Standards for recycled aggregates differ greatly between jurisdictions, which leaves contractors and designers in the dark [23, 24]. Global interoperability is hampered by the differences in acceptable limits and performance standards between ASTM and EN criteria for fly ash and slag [25, 26]. With new standards emphasising thermal and environmental performance over structural integrity, bio-based materials are still mostly outside of official codes (Jones *et al*., 2020; Pittau *et al*., 2020).

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Sustainable materials in civil engineering have a bright future, but systemic reform is needed. The performance envelope of sustainable choices is being expanded by advances in material science, such as nano-modified recycled aggregates and tailored bio-composites [21-23]. Data-driven decision-making is made possible by digital tools like life cycle optimisation software and Building Information Modelling (BIM), which enable engineers to assess economic and environmental effects in real time [24]. Adoption will be accelerated by policy frameworks that include circular economy concepts, green procurement requirements, and carbon pricing [25-27]. Infrastructure development priorities are also changing as sustainability, resilience, and climate adaptation intersect. According to [25, 26], materials that reduce emissions, conserve resources, and survive extreme conditions are increasingly seen as necessities rather than choices. Building with sustainable materials will become increasingly necessary as climate threats worsen, spurring innovation and investment throughout the building industry [27]. The industry can overcome obstacles and realise the full potential of recycled, recyclable, and bio-based materials through focused standards, supportive legislation, and educational reform. Rethinking construction as a regenerative process in line with planetary boundaries is more important for the future than just replacing traditional materials [26, 27].

Conclusion

The adoption of sustainable materials in civil engineering is crucial for reducing the industry's environmental footprint. Recycled and recyclable materials like crushed concrete, fly ash, and reclaimed wood offer significant benefits, including reduced waste, conserved resources, and lower CO_2 emissions. Overcoming challenges like quality consistency and public acceptance is key. Policy support, standardisation, and innovation will drive widespread adoption, paving the way for a more sustainable construction industry that balances economic growth with environmental responsibility, ensuring a greener future for generations to come, with reduced waste and pollution.

Conflicts of Interest

All authors declare that they have no conflict of interest associated with this research article.

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