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Sustainable and Low-Carbon Construction Materials

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ABSTRACT

The construction industry is one of the largest consumers of natural resources and also a major contributor to global carbon dioxide emissions. Conventional construction materials such as ordinary Portland cement, steel, and fired clay bricks require high energy during production and release significant greenhouse gases. In recent years, increasing attention has been given to sustainable and low-carbon construction materials as a means to reduce environmental impacts while meeting the growing demand for infrastructure. This paper presents a comprehensive review of sustainable and low-carbon construction materials, focusing on their sources, properties, production methods, and applications in the construction sector. Materials such as supplementary cementitious materials, geopolymer binders, recycled aggregates, bio-based materials, and low-energy masonry units are discussed in detail. The environmental benefits, technical challenges, and economic aspects associated with these materials are also highlighted. Although many sustainable materials show promising performance, issues related to standardization, durability, large-scale availability, and acceptance by industry practitioners still remain. The review concludes that the integration of low-carbon materials, supported by policy measures and further research, can significantly contribute to reducing the carbon footprint of the construction industry.

KEYWORDS: *Sustainable construction, low-carbon materials, green concrete, recycled materials, embodied carbon*

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INTRODUCTION

The rapid growth of urbanization and infrastructure development has led to an unprecedented demand for construction materials. Buildings, roads, bridges, and other civil engineering structures consume enormous quantities of cement, aggregates, steel, and bricks. According to various studies, the construction sector accounts for nearly 40% of global energy consumption and about 30–35% of carbon dioxide emissions. Among all construction materials, cement production alone contributes approximately 7–8% of total global CO_2 emissions, mainly due to the calcination of limestone and the use of fossil fuels.

With growing concerns about climate change, resource depletion, and environmental degradation, the concept of sustainability has become central to construction practices. Sustainable construction aims to minimize negative environmental impacts while enhancing social and economic benefits throughout the life cycle of a structure. One of the most effective ways to achieve this goal is through the use of sustainable and low-carbon construction materials.

Low-carbon construction materials are those that require less energy during production, generate lower greenhouse gas emissions, or utilize industrial by-products and renewable resources. These materials not only reduce embodied carbon but also help in waste management and conservation of natural resources. However, despite significant research progress, the adoption of such materials in real projects is still limited in many regions, especially in developing countries.

This paper reviews the current state of sustainable and low-carbon construction materials, their types, advantages, limitations, and future potential. The review mainly focuses on materials applicable to concrete and masonry construction, as these are the most widely used in the industry.

CONCEPT OF SUSTAINABILITY AND EMBODIED CARBON

Sustainability in construction is generally defined based on three pillars: environmental, economic, and social sustainability. Environmental sustainability deals with reducing emissions, energy use, and resource consumption. Economic sustainability focuses on life-cycle cost and affordability, while social sustainability considers health, safety, and comfort of

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users.

Embodied carbon refers to the total greenhouse gas emissions associated with a material throughout its life cycle, including raw material extraction, manufacturing, transportation, construction, maintenance, and end-of-life disposal or recycling. Unlike operational carbon, which comes from energy used during building operation, embodied carbon is locked into the structure once it is built.

Reducing embodied carbon is particularly important because a large portion of emissions occurs at the early stages of construction. Therefore, selecting low-carbon materials can result in immediate environmental benefits. Life Cycle Assessment (LCA) is commonly used to quantify embodied carbon and compare different materials.

SUPPLEMENTARY CEMENTITIOUS MATERIALS (SCMs)

Supplementary cementitious materials are industrial by-products or naturally occurring materials that can partially replace ordinary Portland cement in concrete. The use of SCMs is one of the most practical and widely adopted strategies for producing low-carbon concrete, as it directly reduces cement consumption, energy demand, and associated CO_2 emissions. In addition to environmental benefits, SCMs often improve concrete performance in terms of durability, workability, and long-term strength. Their utilization also supports waste valorization and promotes a circular economy within the construction sector.

1. Fly Ash

Fly ash is a finely divided residue generated from the combustion of pulverized coal in thermal power plants. It is primarily composed of silica, alumina, and iron oxides, and exhibits pozzolanic properties. When incorporated into concrete, fly ash reacts with calcium hydroxide released during cement hydration to form additional calcium silicate hydrate (C–S–H) gel. This secondary reaction refines the pore structure and contributes to improved long-term strength and durability.

The replacement of cement with fly ash typically ranges from 15% to 40%, although high-volume fly ash concrete containing more than 50% replacement has also been reported in

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certain applications. Fly ash concrete generally shows lower heat of hydration, which reduces the risk of thermal cracking in mass concrete structures. Improved workability, reduced water demand, and enhanced resistance to sulfate attack and alkali–silica reaction are additional advantages.



Figure: 1 Fly Ash

Despite these benefits, the quality and availability of fly ash can vary significantly depending on coal source and combustion conditions. With the gradual shift toward renewable energy and reduced dependence on coal-based power generation, the long-term availability of high-quality fly ash is becoming uncertain in some regions. This has prompted research into alternative pozzolanic materials and beneficiation techniques for low-grade fly ash.

2. Ground Granulated Blast Furnace Slag (GGBS)

Ground granulated blast furnace slag is obtained by rapidly quenching molten iron slag from blast furnaces in water or steam, followed by drying and grinding. GGBS is a latent hydraulic material that reacts with water in the presence of an activator such as calcium hydroxide from cement hydration. It can replace Portland cement in concrete at levels ranging from 30% to 70%, depending on performance requirements.



Figure: 2 Ground Granulated Blast Furnace Slag (GGBS)

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Concrete containing GGBS generally exhibits lower permeability, improved resistance to chloride ingress, and enhanced durability in aggressive environments such as marine and industrial conditions. The lighter color of GGBS-based concrete also helps reduce heat absorption, which can be beneficial in hot climates. From an environmental perspective, the embodied carbon of GGBS is significantly lower than that of Portland cement, as it is derived from an industrial by-product.

One of the main limitations of GGBS is its slower early-age strength development, particularly at low curing temperatures. This can pose challenges in fast-track construction projects where early strength gain is critical. Proper curing practices and optimized mix design are therefore essential to fully realize the benefits of GGBS concrete.

3. Silica Fume

Silica fume is an ultra-fine amorphous silica by-product obtained during the production of silicon and ferrosilicon alloys in electric arc furnaces. Due to its extremely small particle size and high silica content, silica fume exhibits very high pozzolanic reactivity. It is commonly used in high-performance and high-strength concrete to enhance mechanical properties and durability.



Figure: 3 Silica Fume

The incorporation of silica fume leads to a dense microstructure by filling voids between cement particles and reacting rapidly with calcium hydroxide. This results in significantly improved compressive strength, reduced permeability, and enhanced resistance to chemical attack and abrasion. Typical replacement levels of silica fume are relatively low, usually in the range of 5% to 10% by weight of cement.

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However, the use of silica fume is limited by its higher cost, limited availability, and handling difficulties such as dust generation and reduced workability. The need for chemical admixtures, particularly superplasticizers, is common when silica fume is used in concrete mixes. As a result, silica fume is generally reserved for specialized applications where superior performance is required rather than for mass concrete construction.

Table 1: Typical CO_2 Emissions of Cement and SCMs

Material	Approximate CO_2 Emissions (kg CO_2/ton)
Ordinary Portland Cement	850–900
Fly Ash	20–30
GGBS	50–70
Silica Fume	30–40

4. Geopolymer and Alkali-Activated Materials

Geopolymer materials are emerging as a promising alternative to Portland cement-based binders. They are produced by activating alumino-silicate rich materials such as fly ash or slag using alkaline solutions.

Geopolymers can reduce CO_2 emissions by up to 60–80% compared to conventional cement. They exhibit good mechanical strength, chemical resistance, and fire resistance. Moreover, they make effective use of industrial waste materials.

However, the use of alkaline activators such as sodium hydroxide and sodium silicate raises concerns related to cost, safety, and environmental impact. Lack of standardized mix design methods and limited field applications are also major barriers for widespread adoption.

5. Recycled Aggregates and Construction Waste Utilization

Construction and demolition waste constitutes a significant portion of solid waste generated worldwide. Recycling this waste into aggregates helps in reducing landfill burden and conserving natural aggregates.

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Recycled concrete aggregates (RCA) are obtained by crushing old concrete structures. These aggregates can be used in non-structural and, in some cases, structural concrete. However, recycled aggregates generally have higher water absorption and lower strength due to adhered mortar.

Proper processing techniques and quality control can improve the performance of recycled aggregate concrete. The use of recycled aggregates can reduce embodied energy and promote circular economy in the construction sector.

BIO-BASED AND NATURAL CONSTRUCTION MATERIALS

Bio-based and natural construction materials are derived from renewable biological resources and have gained renewed interest due to their low embodied carbon, biodegradability, and reduced dependence on energy-intensive industrial processes. These materials were widely used in traditional construction practices before the advent of modern cement-based systems. In the present context of climate change and sustainability, bio-based materials are being re-evaluated and improved using modern engineering and treatment techniques to meet contemporary performance requirements. Their ability to sequester carbon, provide thermal comfort, and support local economies makes them attractive alternatives for sustainable construction.

1. Bamboo

Bamboo is one of the fastest-growing plants in the world, reaching maturity within three to five years, which makes it a highly renewable construction material. It possesses high tensile strength, often comparable to mild steel on a strength-to-weight basis, and exhibits good flexibility, which is advantageous in seismic regions. Traditionally, bamboo has been used for housing, scaffolding, roofing, flooring, and temporary structures, particularly in tropical and subtropical regions.

When properly treated against insects, moisture, and fungal attack, bamboo can be used for both structural and non-structural applications. Modern preservation methods such as chemical treatment, heat treatment, and surface coatings significantly improve its durability and service life. Engineered bamboo products, including laminated bamboo lumber and bamboo composites, have been developed to overcome variability in natural bamboo and to achieve

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uniform mechanical properties. Despite its advantages, challenges such as susceptibility to biological degradation, lack of standardized design codes, and perception of bamboo as a low-cost or temporary material still limit its widespread adoption in mainstream construction.

2. Timber and Engineered Wood

Timber is widely recognized as a sustainable and carbon-negative construction material because it stores carbon absorbed during tree growth. When sourced from sustainably managed forests, timber construction can contribute to long-term carbon sequestration. Conventional timber has been used for centuries in residential and low-rise buildings, offering good strength-to-weight ratio, ease of construction, and aesthetic appeal.

In recent years, engineered wood products such as cross-laminated timber (CLT), glued laminated timber (glulam), and laminated veneer lumber (LVL) have gained popularity. These products are manufactured by bonding layers of wood in specific orientations, resulting in improved strength, dimensional stability, and load-bearing capacity. CLT, in particular, has enabled the construction of mid-rise and even high-rise timber buildings, significantly expanding the application range of wood in modern construction.

However, concerns related to fire resistance, moisture sensitivity, and long-term durability remain important issues. Although engineered timber exhibits predictable charring behavior that can provide fire resistance, appropriate design measures and protective systems are required. Additionally, proper detailing and maintenance are essential to prevent decay and moisture-related problems. Higher initial cost and limited awareness among practitioners can also act as barriers to adoption.

3. Agricultural Waste-Based Materials

Agricultural waste-based materials utilize residues generated from farming and agro-processing activities, thereby reducing waste disposal problems and environmental pollution. Materials such as rice husk ash, coconut shell aggregates, bagasse ash, straw-based panels, and palm oil fuel ash have been investigated for construction applications. These materials can partially replace conventional cement, aggregates, or insulation products, leading to reduced embodied energy and carbon emissions.

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Rice husk ash, for example, exhibits pozzolanic properties and can be used as a supplementary cementitious material when properly processed. Coconut shell aggregates can replace natural coarse aggregates in lightweight concrete, making them suitable for non-structural and low-load applications. Straw-based boards and panels provide good thermal insulation and are often used in prefabricated housing systems.

Despite their environmental benefits, the performance of agricultural waste-based materials can vary significantly depending on source, processing method, and quality control. Long-term durability data, resistance to moisture and biological attack, and lack of standardized specifications are key challenges that need to be addressed. Continued research and pilot-scale applications are essential to establish confidence in these materials for wider construction use.

LOW-CARBON MASONRY AND ALTERNATIVE BUILDING BLOCKS

Conventional fired clay bricks require high energy for kiln firing. Alternative masonry units such as fly ash bricks, compressed stabilized earth blocks, and autoclaved aerated concrete blocks consume less energy and emit lower CO_2.

Fly ash bricks utilize industrial waste and show good strength and durability. Compressed earth blocks use locally available soil and minimal cement, making them suitable for low-cost housing.

CHALLENGES AND LIMITATIONS

Despite the benefits, several challenges limit the adoption of sustainable construction materials. These include lack of awareness among engineers and contractors, absence of clear standards, higher initial cost perception, and uncertainty regarding long-term performance. In some cases, availability of materials is region-specific, which affects large-scale implementation.

FUTURE PROSPECTS

Future research should focus on improving durability, developing standardized guidelines, and conducting large-scale pilot projects. Policy incentives, carbon taxation, and green building certifications can encourage the use of low-carbon materials. Integration of digital tools such as life-cycle assessment software can also support informed decision-making.

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CONCLUSION

This review has presented an overview of sustainable and low-carbon construction materials and their potential to reduce the environmental impact of the construction industry. Materials such as SCMs, geopolymers, recycled aggregates, and bio-based products offer significant reductions in embodied carbon while maintaining acceptable performance. However, technical, economic, and institutional challenges still hinder their widespread use. A combined effort from researchers, industry practitioners, and policymakers is necessary to promote sustainable materials in mainstream construction. With continued innovation and awareness, low-carbon construction materials can play a vital role in achieving sustainable development goals.

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