Volume 10, Issue 11, November – 2025 International Journal of Innovative Science and Research Technology
ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25nov955

Concrete to Composites: Exploring Sustainable Alternatives for a Resilient Construction Industry

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Publication Date: 2025/11/24

Abstract: The construction industry has a vital role to play in human progress but has historically consumed an unparalleled share of raw materials and has been a major source of energy use, resource depletion, and greenhouse gas emissions. The carbon dioxide (CO2) generated from conventional concrete and cement in most buildings, has had catastrophic and irreversible impacts on the environment. With global concerns about environmental degradation while encouraging a path toward sustainability, more research has been devoted to investigating sustainable and eco-friendly materials in construction. This study comprehensively reviews conventional and sustainable construction materials—namely concrete, steel, wood, composites, and alternatives (bamboo, engineered wood, polymer concrete, cement-stabilized rammed earth, bamboo Fiber geopolymer, recycled composites, optimized concrete mixes, and waste steel slag). Key mechanical properties regarding the materials—compressive strength, tensile strength, and flexural strength—are analysed, as well as the environmental properties—renewability, recyclability, and energy efficiency. Laboratory exploration, life cycle assessments, and comparative evaluations provide evidence for both the performance and environmental sustainability benefits of these sustainable materials. This study also emphasizes the critical need to reorient the research agenda for construction materials, shifting focus from mechanical performance only to considerations of environmental sustainability in keeping with global initiatives (i.e., Millennium Development Goals or MDGs). This paper also looks at future directions such as the role of nanotechnology, biotechnology, and building certification systems (i.e., LEED) in supporting green construction. In general, this study provides helpful information for architects, engineers, and building policy makers as it will be useful in future development of sustainable building concepts that seek to create a greener and more resilient built environment.

Keywords: *Sustainable Construction, Green Building Materials, Concrete Alternatives, Bamboo, Sustainability, Resilient Built Environment.*

How to Cite: Mahadeva M.; Vikas C. (2025). Concrete to Composites: Exploring Sustainable Alternatives for a Resilient Construction Industry. *International Journal of Innovative Science and Research Technology*, 10(11), 1225-1231. https://doi.org/10.38124/ijisrt/25nov955

I. INTRODUCTION

The construction sector holds an important position in global development, supplying the critical need for infrastructure in terms of housing, mobility, and economic growth. While the construction industry also is one of the most resource-heavy and emissions-producing industries in the world, it consumes a variety of materials and energy sources to do so. It should also be noted that the primary materials within traditional materials (e.g., concrete, cement, etc.) are critical components of construction today and a significant contributor to negative environmental impacts due to their emissions. Cement production and cement itself generates almost 8% of the global climate gas emissions today - sustainability of this material is arguably questionable for the future. Cement is a by far the primary component of construction, as it is an economical and very adaptable material with good strength properties. However, production of cement (and concrete production) requires a large amount of energy and accounts for substantial global carbon emissions. The extraction of raw materials (sand, gravel, limestone, etc.) required for conventional concrete continues to draw down those natural resources and has negative environmental consequences. Now, additionally, climate change, resource depletion, and sustainability will all be key parts of the construction industry's immediate need for alternative (effective technology) and reduction of environmental impacts, continuing to provide structurally sound designs and safety. Consequently, increasing numbers of researchers and engineers are utilizing composite materials and other sustainable alternatives such as geopolymer concrete, recycled aggregate and Fiber reinforced composites that offer performance and lower carbon footprints while effectively harvesting industrial and natural waste.

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25nov955

Sustainable alternatives along with its performance characteristics and durability can provide the construction industry a more sustainable and resilient future while striving for economic viability and environmental consequences while contributing long-lasting performance of structural performance.

II. LITERATURE REVIEW

Xintian (2024) [1] Bamboo is known to be a fast-growing, high-yielding renewable resource that also reduces the cost of producing materials. Especially in the Brazilian Amazon, composite materials made from bamboo fibres and geopolymers are frequently used. Studies have proposed that adding bamboo fibres to geopolymers boosts flexural strength by 3.5 times while also providing good durability and resistance to acid exposure. Therefore, geopolymers and natural fibre-reinforced composites as the best potential alternatives to OPC. Pacheco (2013) [2] used a computer model based on the fixed-stock paradigm to study the interactions between population, food production, industrial production, pollution and the consumption of non-renewable resources. As a result, they predicted that during the 21st century the Earth´ s capacity would be exhausted resulting in the collapse of human civilization as we know it. An update of this study was published in 1992. Babu (2023) [3] The utilisation of steel slag not only plays a positive role in waste disposal but also provides resources for the sustainable development of the construction industry. It can replace traditional building materials and can be applied in cement and concrete to reduce environmental pollution. Compared with ordinary steel slag, the treated steel slag has more superior performance. Stabilized steel slag can be used in green building materials to make cementitious materials for concrete, aggregates, and artificial corals. Petchikkan (2024) [4] Steel slag can be stabilised and repurposed for constructing pre-concrete, floor tiles, etc., reducing the need for water and clay. However, it should be noted that steel slag will only show higher strength than pure cement concrete at a later stage under the condition of constant compressive strength at 28 days.

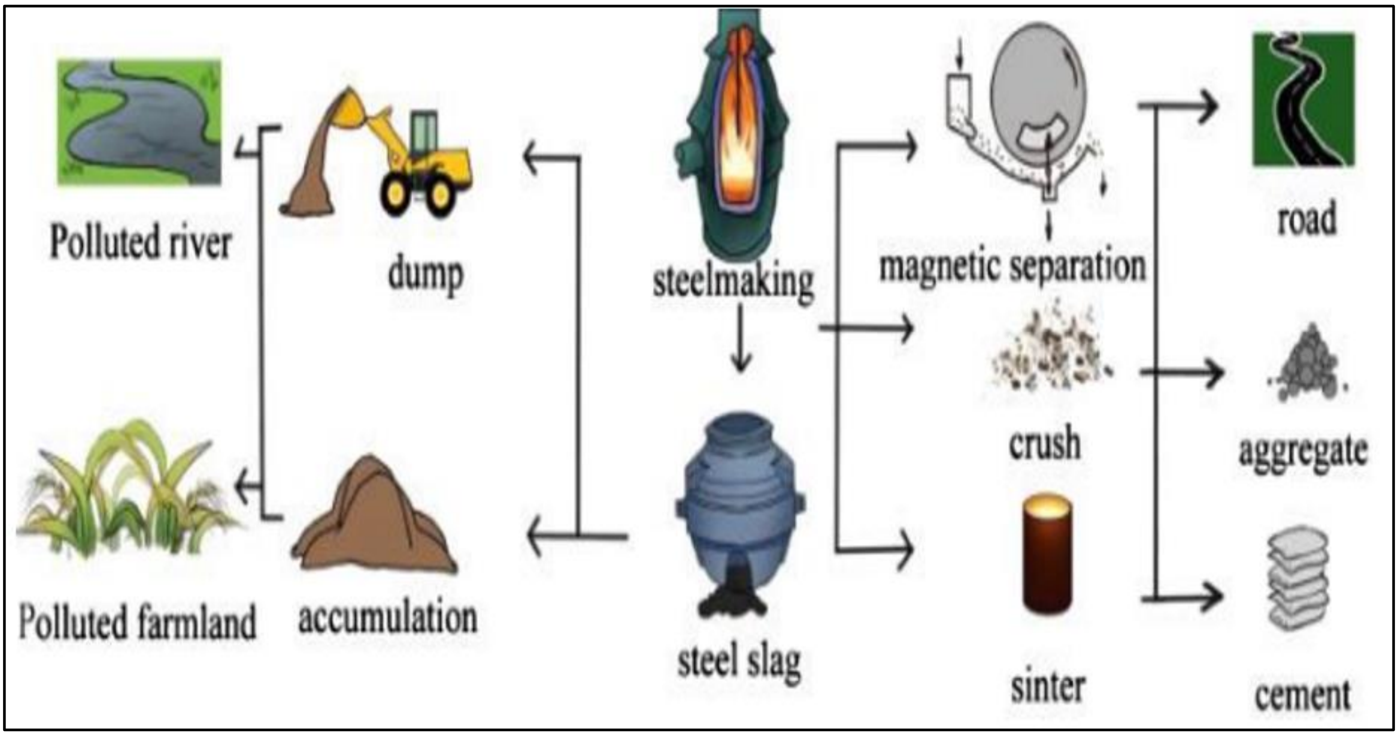

Fig 1 Steel Slag Production and Treatment.
(Source: From net Source)

To summarize, the use of sustainable construction materials not only addresses environmental problems, but also helps to the production of healthier, more energy-efficient, and longer-lasting structures. The building sector encourages sustainable methods, conserves natural resources, and reduces the environmental effect of construction operations by adopting recovered wood, recycled metal, bamboo, recycled glass, rammed earth, and hempcrete. Satyam (2020) [5] The authors believe that the real problem concerning construction materials research is not so much the time between discovery and market use but instead the huge amount of materials research knowledge already generated that is not used by the construction industry. Part of problem relates to the conservative nature of the construction industry that in general chooses low-cost solutions. An excellent proof of that comes from the fact that 31 years after Professor Roger Lacroix coined the expression "high performance concrete-HPC", still only 11% of the concrete ready-mixed production corresponds to the HPC strength class target. Kumar and Kumar [6]. The construction of buildings by using rammed-earth, adobe, and other earthen materials is considered as the best evergreen material. These materials have benefits in costs, aesthetics, acoustics and heat insulation, and low energy consumption. However, few limitations include weak

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25nov955

earthquake wearing forces. But still, strength can be increased by adding bamboo, canes as beams and pillars for an extra 2024. Sathiparan and Saha (2021) [7]. Sustainable Concrete Mixtures Green concrete is designed to reduce environmental impact by incorporating alternative materials that replace traditional Portland cement and natural aggregates. Commonly used supplementary cementitious materials (SCMs) include Fly Ash: A byproduct from coal combustion, which can enhance workability and durability. Ground Granulated Blast Furnace Slag (GGBS): A byproduct from steel manufacturing, known for its ability to improve long-term strength and resistance to aggressive environments. Rice Husk Ash (RHA): An agricultural waste product that, when processed, can contribute to the pozzolanic properties of concrete. Incorporating these materials not only reduces the carbon footprint of concrete but also promotes the recycling of industrial and agricultural byproducts. Gomez, C and Salgado (2018) [8]. The study by Gomez and Salgado (2018) presents a comprehensive life cycle assessment (LCA) of cement-stabilized rammed earth (CSRE) to evaluate its environmental performance as a sustainable construction material. The research aims to provide insights into the potential benefits and challenges associated with the use of CSRE in the construction industry. By analysing various stages of the material's life cycle, including raw material extraction, production, construction, and end-of-life scenarios, the study assesses key environmental indicators such as global warming potential, energy consumption, and resource depletion. The findings contribute to the growing body of knowledge on sustainable building materials and offer valuable information for decision-makers in the construction sector seeking environmentally friendly alternatives.

➢ *Applications of Sustainable Alternatives in Civil Engineering*

Fig 2 Applications of Sustainable Alternatives in Civil Engineering
(Source: Google)

➢ *Applications of Sustainable Construction Materials*

Sustainable construction materials have a variety of applications in contemporary building processes and respond to the dual demands of structural and environmental. The following encapsulate the key uses:

- *Bamboo and Engineered Wood Products*

✓ Implemented within structural frames, scaffolding, roofs, floors, and walls.
✓ Engineered wood products (e.g. cross-laminated timber-CLT) are growing in use in mid- and high-rise construction as they provide a high strength to weight ratio.
✓ More applicable for low carbon construction practices, particularly to prefabricated modular systems.

- *Polymer Concrete*

✓ Utilized in precast products, pavements, bridge decks, and chemical resistant construction.
✓ Offers better chemical resistance and longevity than traditional concrete.
✓ Suited for very hostile environments for infrastructure projects like sewage systems and industrial floors.

- *Cement-Stabilized Rammed Earth*

✓ Utilized for walls, foundations, and low-rise residential or community buildings.
✓ Provides both thermal mass and a natural way of regulating indoor temperature, thus decreasing energy use.

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25nov955

- ✓ Generally applied for sustainable housing in areas where there is abundant soil resource.

- *Bamboo Fiber Geopolymer Composites*

- ✓ Used in panels, blocks, or light-weight structural components.
- ✓ They offer high mechanical strength and low environmental impact.
- ✓ They are especially effective in seismic construction because of their flexibility and toughness.

- *Recycled Composites and Industrial By-Products*

- ✓ Composites made from waste materials such as recycled plastic, fly ash, or steel slag.
- ✓ They may be used in concrete mixes, road construction, pavements and non-structural applications.
- ✓ They divert waste from a landfill while optimally improving concrete-like durability, strength, and fire protection.

- *An Optimized Concrete Mixture*

- ✓ Primarily used for the ultra-high-performance (UHP) and high-strength applications like bridges, high-rise buildings, and heavy-duty pavements.
- ✓ Uses supplementary cementitious materials (SCMs) such as fly ash, silica fume, or, slag to optimize durability and carbon footprint.

- *Green-Building Certification Compatibility*

- ✓ Sustainable materials are prevalent in LEED certified projects and other green-building platforms.
- ✓ Provide sustainability and other criteria that are important for LEED certification-compliance, such as energy efficiency, recyclability, sustainability and less impact on the environment.

➢ *Key Insights from Comparative Analysis:*

- *Mechanical Performance:*

Bamboo fibre geopolymer and polymer concrete demonstrate superior mechanical properties compared to traditional rammed earth or recycled composites.

- *Environmental Impact:*

Materials like rammed earth, bamboo, and recycled composites offer significant ecological benefits, including lower embodied energy and carbon footprint.

- *Application Versatility:*

Optimized concrete mixtures and polymer concrete are suitable for high-performance structural applications, whereas bamboo and rammed earth are more appropriate for low- to medium-rise construction.

- *Trade-off:*

No single material perfectly balances high strength and environmental sustainability: selection depends on project requirements, structural demands and ecological goals.

Table 1 Comparison of Sustainable Construction Materials: Properties, Benefits, Applications, and Limitation

Material	Compressive Strength	Tensile Strength	Flexural Strength	Environmental Benefits	Typical Applications	Limitations
Bamboo / Engineered Wood	Moderate to High	Moderate	Moderate	Renewable, low carbon footprint, biodegradable	Structural frames, flooring, roofing, partition walls	Sensitive to moisture and pests; requires treatment
Polymer Concrete	High	Moderate	High	Resistant to corrosion, durable, reduces cement usage	Precast components, pavements, bridge decks	Higher material cost; limited workability without additives
Cement-Stabilized Rammed Earth	Low to Moderate	Low	Low to Moderate	Uses local soil, low embodied energy, carbon-friendly	Walls, foundations, low-rise residential buildings	Lower mechanical strength; needs moisture protection
Bamboo Fiber Geopolymer	High	High	High	Reduces cement usage, renewable fiber, recyclable	Panels, blocks, lightweight structural elements	Processing complexity; requires specialized mix design
Recycled Composites (Plastic, Fly Ash, Steel Slag)	Moderate to High	Moderate	Moderate	Reduces waste, reuses industrial by-products	Pavements, non-structural elements, concrete mixes	Variable quality depending on source materials
Optimized Concrete Mixtures (with SCMs)	High	Moderate	High	Reduced cement content, improved durability, lower carbon footprint	Bridges, high-rise buildings, heavy-duty pavements	Requires careful mix design; may need curing control

(Source: From Net Source)

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25nov955

➤ *Conventional Concrete*

Conventional concrete is the most used construction material worldwide, made from cement, water, and aggregates such as sand and gravel. Despite its widespread use, it has significant environmental impacts, mainly due to the high carbon emissions associated with cement production. It is durable and versatile but contributes substantially to resource depletion and pollution. As the demand for infrastructure grows, the drawbacks of conventional concrete have led researchers and engineers to seek more sustainable options. This shift aims to balance performance needs with environmental responsibilities.

➤ *Environmental Issues*

The production of conventional concrete generates a large amount of carbon dioxide, a major greenhouse gas contributing to global warming. Additionally, the extraction of raw materials like sand and gravel causes habitat destruction and resource depletion Concerte manufacturing also consumes significant energy and water, further straining environmental resources. Waste from concrete production and demolition can contribute to landfill issues if not properly managed. These environmental concerns highlight the urgent need for greener alternatives in the construction industry to reduce its ecological footprint.

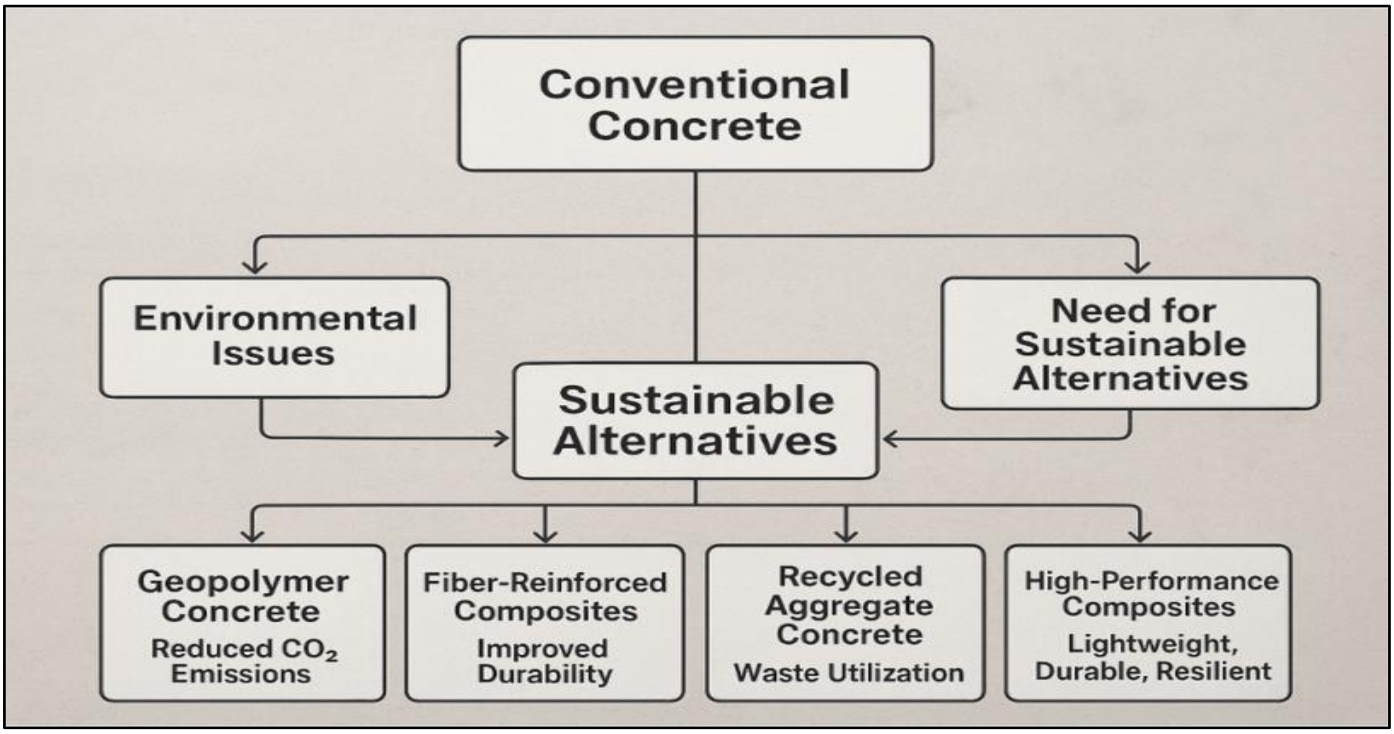

Fig 3 Sustainable Alternatives to Conventional Concrete

➤ *Need for Sustainable Alternatives*

Due to the environmental issues posed by conventional concrete, there is a pressing need to develop sustainable alternatives that minimize ecological damage. These alternatives aim to reduce carbon emissions, conserve natural resources, and promote recycling of waste materials. Sustainable concrete options not only help mitigate climate change but also improve the longevity and resilience of infrastructure. Governments, industries, and researchers are increasingly prioritizing sustainability in construction to meet global climate goals. This demand drives innovation toward eco-friendly materials and technologies.

➤ *Sustainable Alternatives*

Sustainable alternatives to conventional concrete focus on using eco-friendly materials and advanced composites that reduce environmental impact. These alternatives often incorporate recycled materials, industrial by-products, or innovative binders to decrease carbon emissions and waste. They are designed to maintain or improve mechanical properties such as strength and durability, ensuring they meet performance requirements. By adopting these options, the construction sector can significantly reduce its carbon footprint while maintaining structural integrity. These sustainable alternatives represent the future of green building practices.

➤ *Geopolymer Concrete (Reduced CO_2 Emissions)*

Geopolymer concrete is an eco-friendly alternative that uses industrial by-products like fly ash or slag instead of traditional cement. This type of concrete drastically reduces CO_2 emissions since it doesn't rely on Portland cement, which is a major source of carbon emissions.

Geopolymer concrete also exhibits excellent heat and chemical resistance, making it suitable for specialized applications. Its production contributes to waste recycling and reduces dependence on natural resources. This innovative material offers a promising solution for sustainable construction practices.

➤ *Fiber-Reinforced Composites (Improved Durability)*

Fiber-reinforced composites incorporate fibres such as glass, carbon, or synthetic materials into concrete to enhance

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its structural performance. These fibers improve the material's durability, tensile strength, and resistance to cracking. By increasing toughness and extending lifespan, Fiber-reinforced composites help reduce maintenance and repair needs. This improvement in durability translates to more sustainable infrastructure with fewer resources consumed over time. Such composites are increasingly used in both conventional and sustainable concrete mixes to optimize performance.

➢ *Recycled Aggregate Concrete (Waste Utilization)*

Recycled aggregate concrete replaces natural aggregates with recycled materials sourced from construction and demolition waste. This approach helps divert significant amounts of debris from landfills and reduces the demand for virgin aggregates. Using recycled aggregates supports resource conservation and decreases the environmental footprint of concrete production. Though sometimes requiring adjustments in mix design, recycled aggregate concrete can achieve comparable performance to conventional concrete. It represents a key strategy in promoting circular economy principles within construction.

➢ *High-Performance Composites (Lightweight, Durable, Resilient)*

High-performance composites are advanced concrete materials engineered for superior strength, durability, and resilience while often being lightweight. These composites integrate special additives or reinforcements that enhance mechanical properties and resistance to environmental factors. Their lightweight nature reduces transportation and structural load, contributing to overall sustainability. These materials are ideal for demanding applications such as infrastructure exposed to harsh conditions or requiring extended service life. High-performance composites exemplify the evolution of concrete towards smarter, more efficient building solutions.

III. RESEARCH GAPS

While some of the sustainable materials such as bamboo fibber geopolymers, polymer concrete, and recycled composites exhibit great mechanical properties in the laboratory setting, fewer data exist about their long-term durability, weathering, and structural performance in real field applications. Lack of Proper Standardization and Codes All the green materials lack complete building codes, standards, or guidelines, and it is challenging for engineers and architects to integrate them confidently in the conventional building process. Environmental Impact Assessments Although life cycle assessments

(FCAs) are progressively carried out, there is a requirement for systematic, comparative quantifications of the entire environmental effects of sustainable versus traditional materials under various climatic and geographical conditions. Cost-Effectiveness and Scalability There is generally little consideration given to the economic viability and scalability of sustainable substitutes in research. Excessive initial expenditure, restricted availability, and manufacturing difficulties may hinder their implementation in large-scale applications. Integration with Future Technologies Although technologies like nanotechnology, biotechnology, and additive manufacturing provide means to improve material performance, there is a lack of research on how these innovations can be systematically integrated with green composites. Performance under Harsh Conditions Few studies examine how green materials behave under harsh conditions like seismic activity, excessive rain, freeze-thaw conditions, and high industrial exposure.

IV. SUMMARY AND DISCUSSION

This paper highlights a major shift in engineering practices from reactive problem-solving to predictive and proactive strategies. Traditionally, engineers addressed structural failures and material inefficiencies only after they became apparent, often relying on extensive laboratory testing or post-failure analysis to make improvements. This reactive model, while useful in the past, was time-consuming, costly, and inefficient, often leading to delays and increased resource consumption.

In contrast, modern engineering increasingly embraces predictive approaches that allow potential challenges to be identified and addressed before they escalate. By incorporating tools such as simulation modelling, performance forecasting, and real-time monitoring, engineers can now optimize materials and systems early in the design process. This shift not only reduces the likelihood of failure but also ensures that projects proceed more smoothly, with fewer interruptions and more accurate timelines.

A critical component of this evolution is the integration of sustainability into engineering decisions. Predictive strategies support sustainable design by minimizing waste, improving energy efficiency, and reducing environmental impacts across the lifecycle of a project. Engineers are now expected to consider long-term ecological consequences alongside technical and economic factors, resulting in infrastructure that is not only functional but also environmentally responsible. This transition marks a significant step forward in the engineering profession. It reflects a broader awareness of the interconnectedness between technology, society, and the environment. For the wider community, it means the development of infrastructure that is safer, more resilient, and better equipped to adapt to future challenges. Ultimately, predictive and sustainable engineering practices represent a smarter, more forward-looking approach to building and maintaining the systems that support modern life.

V. CONCLUSION

Though the construction industry has contributed and continues to contribute to the societal good, it is associated with high levels of energy use, resource depletion, and large-scale environmental impacts. This paper advocates for the use of sustainable construction materials to build green and resilient built environments. Reviewed sustainable materials include bamboo, engineered wood, polymer concrete, cement-stabilized rammed earth, bamboo Fiber geopolymer,

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25nov955

recycled composites, and optimized concrete mixtures and steel slag. These sustainable materials indicate that sustainable construction can provide structural performance and environmental sensibility.

Comparatively, bamboo Fiber geopolymer and polymer concrete provide optimum structural performance; rammed earth, bamboo, and recycled composites have favourable ecological performance such as low embodied energy and low carbon footprint. Applications of these materials can be in a structural frame, pavement, wall, panel, and high-performance concrete mixes which demonstrates the possibilities of low- or high-rise construction.

Research gaps remain to be filled in the areas of long-term performance, standardization, cost competitiveness, scale, connection to advanced technology, and testing in severe conditions. While research gaps are still present, there is a need to begin filling the gaps to advance the sustainable use of materials.

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