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Sustainable Building Materials in Traditional Indian Construction: Performance, Challenges and Contemporary Applications

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Abstract: About one-third of global energy consumption (36%) and more than one-third of energy-related CO2 emissions originate from the construction sector, making its shift to sustainable construction imperative. Historically, conventional construction in India has used the local, low-energy construction materials, namely bamboo, lime mortar, rammed earth, laterite stone and natural fibres, providing many eco-friendly advantages over mainstream construction practices. This paper gives a systematic review of ten traditional Indian construction materials in terms of their performance characteristics, sustainability credentials and contemporary uses. The review is based on literature review and literature search carried on Scopus, Web of Science, ScienceDirect and SpringerLink databases with scientific publications being explored from 2005 to 2024. The analysis addresses mechanical properties, thermal efficiency, durability, embodied carbon and cost-effectiveness of the studied materials. Changes in the performance of mud blocks, rammed earth and compressed earth blocks have been shown to offer a good sustainability index with adequate structural efficiency. The study shows the various gaps in research including the lack of long-term performance data, standardization issues and absence of the digital construction model.

Keywords: Sustainable construction, Traditional building materials, Rammed earth, Bamboo, Embodied carbon, Green buildings, Indian architecture, Life cycle assessment

1. Introduction

The industry of construction globally consumes about 36% of the energy consumed. It is estimated that this sector produces about 39% of carbon emissions [1]. Similarly, in India, construction uses more than 30% of the total electricity produced and is expected to continue to grow due to urbanization and population growth [2]. Traditional building materials such as clay bricks, steel etc. are responsible for a significant amount of energy consumption and emissions [3]. Thus, scientists and practitioners have started exploring other environmentally friendly techniques and practices that can reduce consumption of energy while meeting the necessary building standards [4].

Traditional Indian architecture, which has a history spanning several millennia, has typically been built with local materials, which include town mud, bamboo, lime, laterite stones, timber and natural fiber. These materials are used through low-energy processes and are acquired from the construction site [5]. The use of indigenous materials in construction conforms to the meaning of sustainability as proposed in modern times [6]. Examples of constructions made with old building systems include the Chettinad houses in Tamil Nadu, the earthen forts in Rajasthan and bamboo houses in the northeastern states.

In addition to this, recent research has revived interest in these old construction materials because of the increasing concerns regarding embodied energy, carbon footprint reduction and the emergence of climate-responsive technologies [7]. Tens of researchers have focused on stabilized mud blocks, compressed earth blocks, rammed earth walls and lime mortar regarding their mechanical and thermal properties as well as their impact on the environment. However, some problems still prevent such technologies from being widely used. As a result, this review aims to summarize the existing information regarding sustainable traditional Indian building materials as well as their comparative performance and study the existing gaps in the research on the topic.

2. Objectives

The key targets of this assessment are (i) to systematically study the prior research concerning traditional Indian sustainable building materials like bamboo, rammed earth, stabilized mud blocks, lime mortar, fly ash bricks, compressed earth blocks, laterite stone, wood, natural fibers and stone masonry [8], (ii) compare the mechanical properties, thermal efficiency, durability, carbon footprint and cost effectiveness through the use of already published experimental and theoretical data, (iii) discover the limits and practical limitations of using the materials mentioned, (iv) assess the adequateness of using traditional materials for modern constructions with the use of stabilization and hybridization as well as digital construction technologies and (v) map the gaps and provide suggestions for future work in the area of sustainable construction.

3. Scope and Methodology

This review is being performed with the help of a systematic literature review method focused on the peer-reviewed articles, papers and official documents regarding sustainable traditional building materials in India. The literature survey has been conducted in five academic databases, including Scopus, Web of Science, IEEE Xplore, Science Direct and SpringerLink [9]. The keywords for inclusion purposes included combinations of "sustainable building materials", "rammed earth", "traditional Indian construction", "bamboo construction", "stabilized mud blocks", "lime mortar", "embodied energy" and "life cycle assessment". Studies that fulfilled the inclusion criteria included original experimental studies, comparative studies, or case studies published in English between the years of 2005 to March 2024. The exclusion criteria included studies that looked only at non-Indian issues or that were not published in indexed journals. In total, 187 publications were screened to find that 98 fulfilled the inclusion criteria and might be used in the paper.

4. Literature Review

Bamboo is increasingly being used as a building material because of its fast growth rates, the high strength of bamboo and low energy requirements for processing it. According to Sharma et al. (2015), bamboo has the tensile strength depending on the type of bamboo and its age and being between 100 and 400 MPa, which makes it equal in strength with mild steel by weight [10]. Nevertheless, bamboo is prone to biological degradation, moisture absorption and dimensional instability, which makes it necessary to process it chemically or thermally to improve its endurance. It has been reported that borax and boric acid help to increase the process lifetime of bamboo in the tropics.

The use of rammed earth and stabilized mud block construction is one of the most researched traditional engineering technologies in the Indian subcontinent. According to Walker and Stace (1997), cement-stabilized blocks composed of 5-10 % of Portland cement have enough compressive strength of 3-7 MPa, which is adequate for low-rise buildings [11]. Venkatarama Reddy and Jagadish (2003) established the thermal conductivity of optimized compressed stabilized blocks to be in range of 0.55-0.85 W/mK, which is significantly lower than that of ordinary bricks [12]. Rammed earth construction allows reaching compressive strength of 1.5-4.0 MPa for unstabilized construction and up to 8.0 MPa for stabilized construction while the embodied energy of this technology is about 300-500 MJ/m^3, whereas for traditional bricks it reaches 2000-3000 MJ/m^3 [13]. Moreover, rammed earth construction allows for great thermal mass and passive temperature regulation in hot-arid and composite countries of India.

Throughout India, lime mortar has been a standard building material for centuries. The hydraulic lime mortars have a compressive strength of between 2-10 MPa depending on lime-aggregate ratios and curing conditions and they have benefits such as flexibility, moisture permeability and self-healing capabilities. Hence the need for the application of lime mortar as a building material in conservation activities, especially in seismic regions [14]. Fly ash bricks made with 50 to 60% Class F fly ash with lime and gypsum can give compressive strengths of between 7-15 MPa, which is better than clay bricks and at the same time the production has a lower embodied energy by around 60 to 70% [15].

Compressed earth blocks (CEB) are made to be very compact as compared to SMBs, as they are subjected to compaction pressures of 2 to 10 MPa, thus producing deeper blocks with uniform compressive strength of 4-12 MPa, depending on factors like soil grading, moisture content and the amount of compaction. Laterite rock in India is an iron-rich sedimentary rock found abundantly in the western and southern regions of the country and is generally used in the making of monuments. This rock exhibits compressive strength between 3 and 20 MPa along with thermal conductivity ranging from 0.7-1.0 W/mK. Wood is subjected to compressive forces ranging between 30 and 60 MPa according to the direction of the grain and it exhibits great seismic performance because of its capacity of absorbing energy. Natural fiber has been used in many types of earth-based composites among which jute, coir and sisal have shown around 20-40% of increase in flexural strength. Stone masonry using locally quarried granite, sandstone, or basalt is quite common in rural regions of the country because its compressive strength is more than 50 MPa, which makes it very durable.

Table 1: Summary of Key Studies on Traditional Indian Sustainable Building Materials

Author [Ref.]	**Dataset**	**Methods**	**Contribution**	**Limitations**
Venkatarama Reddy & Jagadish (2003) [12]	Laboratory Tests	Experimental	Optimal cement for stabilized earth blocks, thermal conductivity values for SMBs	Limited to specific Bangalore soils, no long-term durability data
Sharma et al. (2015) [10]	Laboratory Tests	Experimental, Comparative	Comprehensive bamboo mechanical properties across multiple species	No long-term creep or moisture degradation assessment
Kumar (2003) [15]	Lab Tests, Field Survey	Experimental, LCA	Fly ash brick strength exceeding burnt clay with 60-70% lower embodied energy	Limited geographical coverage, no high-rainfall zone assessment
Walker & Stace (1997) [11]	Laboratory Tests	Experimental	Properties of cement-stabilized compressed earth blocks and mortars	Validated only for specific soil gradations, no seismic evaluation
Arandigoyen & Alvarez (2007) [14]	Laboratory Tests	Mechanical Testing	Compressive strength and carbonation kinetics of hydraulic lime mortars	Short-term curing only, no long-term weathering resistance evaluation
Pacheco-Torgal & Jalali (2012)	Literature Database	Review	Lessons from earth construction for future eco-efficient	Broad scope with limited quantitative comparative

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[4]			building	analysis
Hammond & Jones (2008) [3]	Literature Database	LCA, Comparative	Embodied energy and carbon data for construction materials inventory	UK-focused data, limited applicability to Indian material variants

5. Result and Discussion

A comparative study of conventional Indian sustainable construction materials shows differences in mechanical, thermal, environmental and economic characteristics. Regarding compressive strength, both laterite stone and fly ash bricks show the highest compressive strengths in the range of 7-20 MPa and 7-15 MPa respectively, which conforms to the requirements for multi-storey low-rise buildings [12, 15]. Rammed earth and compressed earth blocks should be placed in the centre of the aforementioned two materials in terms of compressive strength, as their range is from 1.5 to 12 MPa that depends on the method of stabilization used, while bamboo and timber provide excellent tensile and flexural strengths that would work well with masonry systems in hybrid designs [10, 11].

Thermal properties investigation shows that rammed earth, stabilized mud blocks and compressed earth blocks act well concerning thermal mass properties, having the thermal conductivity values from 0.55 to 1.0 W/mK and showing 40-65% better performance than conventional burnt bricks [12, 13]. Bamboo and timber own lower thermal conductivity of 0.12 - 0.30 W/mK and are considered to be better performers in thermal insulation because of their smaller thickness. All these features have high significance in hot-dry and composite climate zones of India, where the use of thermal mass and insulation can result in a decrease in energy consumption for the building operation by 25-40% comparing to regular masonry buildings [3, 5].

From an environmental standpoint, it can be seen that stabilized mud blocks, rammed earth and compressed earth blocks are the materials with the lowest values of embodied carbon with values between 15 and 60 $kgCO_2/m^3$ as opposed to 200-350 $kgCO_2/m^3$ shown in the case of burnt clay bricks [13,15]. The cost analysis revealed that earth-based materials, such as rammed earth, SMBs and CEBs, are 20-50% cheaper than traditional alternatives taking into account labor and availability of the soil [11]. The use of these traditional materials in modern construction requires major changes, as it is necessary to develop quality control measures, standardized testing and building codes that take into account the influence of the variability of natural materials on the performance characteristics of the structure [8].

Table 2: Comparative Performance Assessment of Traditional Indian Sustainable Building Materials

Material	**Strength (MPa)**	**Thermal Perf.**	**Durability**	**Sustainability**	**Cost**	**Modern Applications**
Bamboo	100-400 (T)	Good	Moderate	Very High	Low-Med	Scaffolding, roofing, partitions
Lime Mortar	2-10	Moderate	High	High	Medium	Heritage conservation, plastering
Rammed	1.5-8.0	Excellent	High	Very High	Low	Load-bearing

Earth						walls
Fly Ash Brick	7-15	Moderate	High	High	Low-Med	Masonry walls, partitions
Stabilized Mud Block	3-7	Very Good	Moderate	Very High	Very Low	Affordable housing
Laterite Stone	3-20	Good	Very High	High	Low	Walls, foundations
Timber	30-60 (C)	Good	Moderate	Moderate	Med-High	Frames, trusses, flooring
Comp. Earth Block	4-12	Very Good	Good	Very High	Low	Masonry, affordable housing

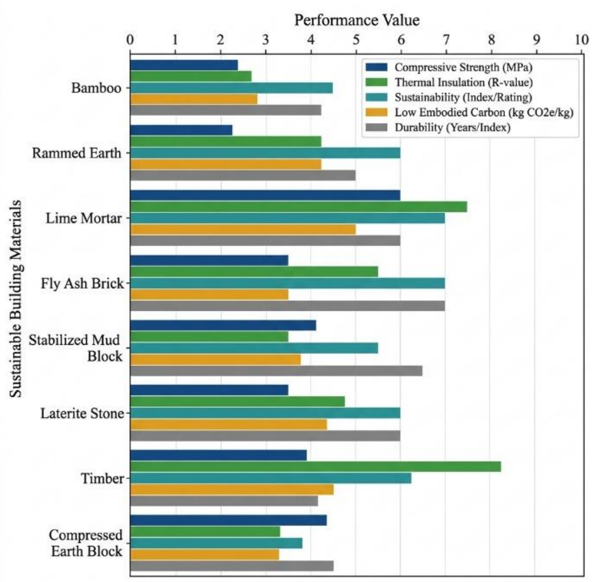

Fig. 1: Comparison Performance of Traditional Indian Sustainable Building Materials

6. Findings

The key findings of the systematic review are as follows:

1. Stabilized mud and compressed earth blocks provide the most suitable combination of structural efficiency, thermal functioning and sustainability when it comes to cheap housing in various areas of India [11, 12].
2. Bamboo produces the best sustainability index, as its embodied energy is less than 50 MJ/m³, but its vulnerability to biodegradation means treatments must use either chemicals or heat for it to last longer [10].
3. Rammed earth walls produce the best thermal mass that allows passive temperature regulation with energy

savings of 25-40% as compared to the common techniques used in construction in hot-dry climates [13].

4. Fly ash bricks provide compressive strength that is 40-70% more than regular burned clay bricks and reduce embodied energy by around 60-70% [15].
5. Laterite stone is characterized by an incredible durability due to low processing, but it can only be found in parts of western and southern India.
6. Information on life cycle assessment for traditional Indian building materials is scarce, as less than 15% of the studies mentioned have put an emphasis on cradle-to-grave evaluations [3].

7. Limitations and Research Gaps

Even if research on the use of sustainable traditional materials has increased, there are still various limitations and research gaps. First, most of published studies focus on only short-term laboratory testing of materials, so that less than 10% of all articles accessed in the review reflected durability tests with service life longer than five years [10, 13]. The lack of long-term durability studies performed under real-life conditions signifies the lack of confidence in predicting the lifetime of earth and bio-resources.

Second, the diversity of soil composition, species of bamboo and mineralogy of laterite defined in the different areas of the Indian subcontinent results in a high heterogeneity of performance that is not properly reflected in existing standards [8, 12]. Nowadays, the Bureau of Indian Standards does not have proper provisions under various groups of traditional materials, which creates difficulties in using them in engineered construction projects. Third, the understanding of the combination of traditional materials with modern digital technologies is still limited. Fourth, the existing policies and green building rating systems in India do not take into consideration the sustainability of traditional materials as much as it is required [5, 7].

Conclusion

The performance, issues and current uses of ten conventional Indian sustainable building materials have been thoroughly analyzed in this review. Earthy materials like stabilized mud blocks, compressed earth blocks and rammed earth provide useful properties that suit India's development aspirations such as structural safety, thermal efficiency, low embodied carbon and economic feasibility. Bamboo and composites reinforced with natural fibers are good lightweight solutions, while ensuring good durability requires additional treatment. Fly ash bricks offer effective solutions for waste management, while laterite stones and lime mortars provide good longevity shown through the performance of the centuries. Future studies should focus on monitoring and evaluating long-term performance of the materials and on formulating the requirements through Indian standards. In addition, building information modeling and new technology involvement, as well as machine learning methods in material properties studies should be implemented.

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