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Experimental Assessment and Machine Learning-Based Optimization of Groundnut Shell Bio-Bricks

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Abstract

This study investigates the development of sustainable bio-bricks incorporating groundnut shell (GNS) waste as a partial fine aggregate replacement with cement, fly ash, and hydrated lime to produce eco-friendly masonry materials. Bio-bricks containing 20–60% GNS were evaluated for mechanical, physical, thermal, and durability properties. The optimum mix satisfied Indian Standard requirements for first-class bricks, exhibiting adequate compressive strength, low water absorption, reduced density, negligible efflorescence, and superior thermal insulation. Hydrated lime mortar enhanced masonry performance, increasing compressive and shear strength. Response Surface Methodology and Artificial Neural Network models accurately predicted material properties, with ANN achieving $R^2 > 0.99$. The proposed masonry system improved energy efficiency, reduced life-cycle costs, and offers a sustainable, low-carbon alternative for energy-efficient building construction.

Keywords: Sustainable, Strength, Mortar, concrete, ML

1. Introduction

The rapid growth of the construction industry has significantly increased the demand for conventional building materials such as fired clay bricks and cement-based masonry units. However, the production of these materials requires substantial energy consumption and contributes considerably to greenhouse gas emissions, depletion of natural resources, and environmental degradation. The manufacture of fired clay bricks consumes fertile topsoil and large quantities of fossil fuels, resulting in high carbon dioxide (CO_2) emissions and loss of agricultural land. Consequently, the development of sustainable and environmentally friendly building materials has become a major research priority worldwide (UNEP, 2023; IEA, 2024).

The utilization of agricultural waste in construction materials has emerged as an effective strategy to promote sustainable development and support the principles of the circular economy. Agricultural residues are generated in enormous quantities every year, and improper disposal through open burning or landfilling creates serious environmental concerns. Converting these wastes into value-added construction products not only reduces environmental pollution but also conserves natural resources and lowers production costs. Various agricultural wastes, including rice husk ash, sugarcane bagasse ash, coconut shell, palm oil fuel ash, wheat straw ash, and groundnut shell, have been investigated as sustainable alternatives in cementitious materials and masonry units (Siddique, 2018; Thomas, 2018).

Groundnut (peanut) shell is one of the major agricultural by-products generated during peanut processing. India is among the leading producers of groundnuts, generating substantial quantities of shell waste annually. Most of this biomass is either discarded or burned, causing environmental pollution. Groundnut shells possess low density, porous structure, and good thermal insulating characteristics, making them a promising material for lightweight and energy-efficient masonry products. Previous investigations have demonstrated that the incorporation of groundnut shell in construction materials can reduce unit weight, improve thermal insulation, and contribute to sustainable waste management (Madurwar et al., 2013; Algin and Turgut, 2008).

Recent advances in sustainable masonry have also emphasized the use of supplementary cementitious materials such as fly ash and hydrated lime. Fly ash improves workability, long-term strength, and durability through pozzolanic reactions while simultaneously reducing cement consumption and carbon emissions. Hydrated lime enhances mortar plasticity, water retention, bond strength, and long-term durability by promoting continued carbonation and reducing shrinkage cracking. The combined use of fly ash and hydrated lime has therefore gained considerable attention in eco-friendly masonry construction (Neville, 2011; Mehta and Monteiro, 2014).

In addition to mechanical performance, thermal efficiency has become a critical requirement for modern building materials. Buildings account for nearly one-third of global energy consumption, and improving the thermal performance of masonry materials can substantially reduce cooling and heating loads. Lightweight bio-based bricks containing agricultural waste exhibit lower thermal conductivity than conventional fired clay bricks, thereby improving indoor thermal comfort and reducing building energy consumption. Consequently, sustainable masonry systems contribute not only to environmental conservation but also to energy-efficient building design (IEA, 2024; UNEP, 2023).

Recently, artificial intelligence (AI) and machine learning techniques have been increasingly adopted in civil engineering to optimize material proportions and accurately predict engineering properties. Response Surface Methodology (RSM) provides an efficient statistical approach for optimization with fewer experimental trials, whereas Artificial Neural Networks (ANN) effectively model nonlinear relationships between material composition and performance. These techniques have demonstrated excellent predictive capability for compressive strength, density, durability, and thermal properties of cementitious composites, significantly reducing experimental effort and development costs (Ahmad et al., 2021; Mohammed et al., 2023).

2. Literature Review

The Jannat et al. (2021) reviewed the utilization of nut shell wastes, including groundnut, cashew, walnut, and pistachio shells, in bricks, mortar, and concrete. The review concluded that nut shell wastes can successfully replace conventional construction materials while satisfying relevant standards. However,

additional research on durability, thermal insulation, and long-term performance was recommended.

Gupta et al. (2020) presented a comprehensive review on sustainable unfired bricks manufactured using industrial and agricultural wastes. The study highlighted that the incorporation of waste materials significantly reduced embodied energy and carbon emissions while improving the environmental sustainability of masonry products. Further optimization of mix proportions was suggested for commercial applications.

Sathiparan et al. (2023) reviewed the application of groundnut shell and its derivatives in construction materials. The authors reported that groundnut shell ash and powder can effectively replace cement and fine aggregates in concrete, masonry blocks, and stabilized earth blocks. The review identified limited research on bio-bricks, thermal performance, and microstructural characterization, indicating the need for further investigation.

Junaid et al. (2022) reviewed lightweight concrete produced using agricultural and industrial waste materials. Their findings indicated that lightweight bio-based materials considerably reduce dead load while improving thermal insulation and sustainability. However, careful optimization is required to maintain adequate mechanical strength.

Khalil et al. (2021) investigated the use of sugarcane bagasse ash as a supplementary cementitious material. The study concluded that agricultural ashes improve compressive strength, durability, and resistance to aggressive environments through pozzolanic reactions while simultaneously reducing cement consumption and carbon emissions.

Nakkeeran et al. (2024) developed bio-bricks using groundnut shell, fly ash, cement, and hydrated lime. Machine learning techniques, namely Response Surface Methodology (RSM) and Artificial Neural Networks (ANN), were employed to optimize compressive strength, dry density, and water absorption. The ANN model achieved prediction accuracy with R^2 values exceeding 0.99, demonstrating the effectiveness of AI-based optimization for sustainable construction materials.

Nakkeeran et al. (2025) experimentally investigated the structural and thermal performance of masonry constructed with groundnut shell bio-bricks and hydrated lime mortar. The developed masonry exhibited approximately 7.9% higher compressive strength and 12.6% higher shear strength than conventional masonry while significantly improving thermal insulation and indoor comfort.

Ahmad et al. (2021) reviewed machine learning applications for predicting concrete properties. The authors concluded that Artificial Neural Networks, Support Vector Machines, and ensemble learning algorithms accurately estimate compressive strength and durability with minimal experimental effort, making AI an effective tool for sustainable material optimization.

Mohammed et al. (2023) reviewed artificial intelligence applications in sustainable construction materials. The study reported that machine learning techniques significantly improve prediction accuracy for strength, density, durability, and thermal performance while reducing laboratory testing time and development costs.

Scientific Reports (2024) demonstrated that combining agricultural waste, fly ash, hydrated lime, and machine learning provides an economical and environmentally friendly approach to manufacturing bio-bricks. The developed bricks satisfied first-class brick requirements according to Indian Standards while reducing construction costs and improving the building energy envelope. [21-25].

3. Materials and Method

The materials used in this study included Ordinary Portland Cement (OPC 53 Grade), Class F fly ash, hydrated lime, river sand, groundnut shell (GNS) waste, and potable water. Groundnut shells were collected from local agricultural processing units, cleaned to remove impurities, oven-dried, and ground into fine particles before use as a partial replacement for fine aggregate. The physical, chemical, and microstructural properties of all constituent materials were characterized through particle size analysis, specific gravity, X-ray fluorescence (XRF), and scanning electron microscopy (SEM).

Bio-bricks were manufactured by replacing fine aggregate with groundnut shell at 20%, 30%, 40%, 50%, and 60% by volume. The mixtures were thoroughly blended, compacted into standard brick moulds, demoulded after 24 hours, and water-cured for 28 days. The optimum mix was selected based on compressive strength. Subsequently, dry density, water absorption, efflorescence, and thermal conductivity tests were conducted in accordance with relevant Indian Standards. Hydrated lime mortar was prepared with different proportions to determine the optimum mix through compressive strength testing. Masonry prisms and wall panels were then constructed using the optimized bio-bricks and mortar to evaluate compressive strength, shear strength, and thermal performance. Furthermore, Response Surface Methodology (RSM) and Artificial Neural Networks (ANN) were employed to optimize the mix proportions and accurately predict the engineering properties of the developed sustainable masonry system.

4. Result

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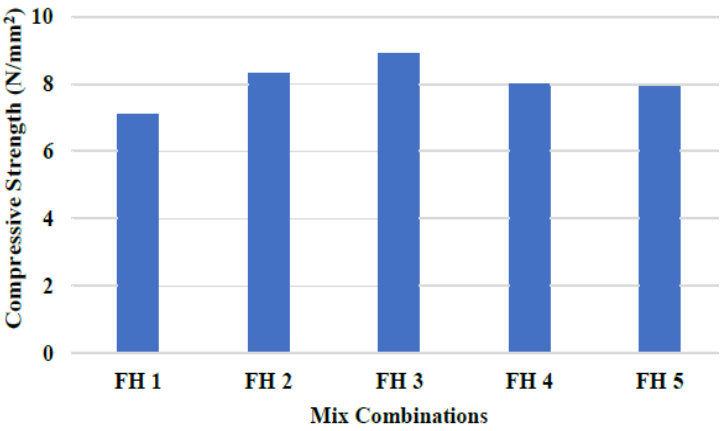


Fig. 1 Mix vs Compressive strength

The experimental results demonstrated that the incorporation of groundnut shell (GNS) significantly influenced the physical, mechanical, and thermal properties of the developed bio-bricks. Among the investigated mixtures, the optimum GNS replacement level achieved the highest compressive strength while satisfying the requirements for first-class bricks specified in the Indian Standard Code. The developed bio-bricks exhibited lower dry density than conventional fired clay bricks, indicating their lightweight nature, while maintaining acceptable water absorption and negligible efflorescence. The porous structure of groundnut shell enhanced thermal insulation, resulting in reduced heat transfer and improved indoor thermal comfort.

Hydrated lime mortar exhibited superior bonding characteristics and attained a maximum compressive strength of 49 N/mm^2, contributing to enhanced masonry performance. Masonry prisms constructed using the optimized bio-bricks and hydrated lime mortar showed a 7% increase in compressive strength and a 12% improvement in shear strength compared with conventional masonry. Response Surface Methodology (RSM) models achieved coefficients of determination (R^2) above 0.8, whereas Artificial Neural Network (ANN) models demonstrated excellent prediction accuracy with R^2 values exceeding 0.9. Building energy simulations indicated reductions of more than 10% in life-cycle energy costs and over 8% in Energy Use Intensity (EUI), confirming the suitability of the proposed bio-brick masonry system for sustainable and energy-efficient construction.

5. Conclusion

This study successfully developed sustainable bio-bricks using groundnut shell (GNS) waste as a partial replacement for fine aggregate in combination with cement, fly ash, and hydrated lime. The experimental investigation confirmed that the optimized bio-brick mix satisfied the Indian Standard requirements for first-class bricks with respect to compressive strength, dry density, water absorption, and efflorescence. The incorporation of groundnut shell reduced the unit weight of the bricks while significantly improving their thermal insulation properties. Hydrated lime mortar enhanced the bonding characteristics and mechanical performance of the masonry system, resulting in improved compressive and shear strength compared with conventional masonry. Machine learning techniques, including Response Surface Methodology (RSM) and Artificial Neural Networks (ANN), accurately predicted material properties and effectively optimized the mix design, with ANN demonstrating superior prediction accuracy ($R^2 > 0.99$). Furthermore, building energy analysis revealed reduced energy consumption, lower life-cycle costs, and improved thermal comfort. Overall, the developed bio-brick masonry system offers an environmentally friendly, structurally reliable, and energy-efficient alternative to conventional building materials. The findings support the practical implementation of agricultural waste-based masonry products for sustainable, low-carbon, and resource-efficient construction.

The optimized bio-brick mix consisted of cementitious materials comprising 10% Ordinary Portland Cement, 40% - 50% fly ash, and hydrated lime, while the fine aggregate fraction contained 27%- 73% groundnut shell and natural sand.

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and publication of this article.

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