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# DEVELOPMENT AND PERFORMANCE EVALUATION OF COMPACT GREEN SAND BRICKS INCORPORATING FLY ASH: A SUSTAINABLE ALTERNATIVE TO CONVENTIONAL CLAY BRICKS

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**Abstract**

The construction industry's heavy reliance on conventional burnt clay bricks has caused serious environmental degradation, including topsoil depletion, high energy consumption, and substantial greenhouse gas emissions. This paper provides a comprehensive review and analysis of compact green sand bricks that incorporate fly ash—an industrial by product of coal fired thermal power plants—as a sustainable alternative. The study synthesises findings from recent experimental investigations into fly ash–cement–sand composite bricks, examining their mechanical properties, durability characteristics, and environmental performance. Results from multiple studies indicate that optimised fly ash–sand brick mixes can achieve compressive strengths ranging from 9.13 MPa to 28 MPa, with water absorption values below 20 % and negligible efflorescence [1, 7]. Life cycle assessment studies demonstrate that fly ash bricks can reduce carbon dioxide equivalent emissions by over 80 % compared with conventional sand block manufacturing [4]. The pozzolanic reactivity of fly ash, combined with appropriate curing regimes—particularly steam curing—enhances early age strength development and microstructural densification [1, 12]. This paper concludes that compact green sand bricks with fly ash represent a technically viable, economically attractive, and environmentally superior alternative to traditional clay bricks, thereby contributing to circular economy principles in the construction sector.

**Keywords:** Fly ash; green bricks; sustainable construction; compressive strength; water absorption; life-cycle assessment; industrial waste utilisation

## 1. Introduction

Bricks are among the oldest and most fundamental building materials, with a history dating back to the third millennium BC in Mesopotamia. Despite their ancient origins, they remain

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indispensable in modern construction because of their excellent thermal properties, workability, and structural reliability. However, the conventional production of burnt clay2-bricks imposes a heavy environmental burden. Traditional brick manufacturing involves extracting fertile topsoil, high temperature firing in kilns, and considerable energy consumption, all of which result in significant greenhouse gas emissions and depletion of natural resources [5, 11].The global generation of coal fly ash—a fine particulate residue from pulverised coalcombustion in thermal power plants—presents both an environmental challenge and an opportunity. India alone produces more than 110 million tonnes of fly ash annually; worldwide, less than 20 % of fly ash is used in concrete related applications, while the remainder is disposed of in landfills, causing soil and groundwater contamination [13]. Incorporating fly ash into brick manufacturing has emerged as a promising strategy to address both the waste disposal crisis and the environmental impacts of conventional brick production [5].

This paper reviews and analyses the development of compact green sand bricks containing fly ash, synthesising experimental findings on mix design optimisation, mechanical properties, durability characteristics, and environmental performance. The objective is to establish the technical viability and sustainability credentials of fly ash–sand bricks as a replacement for conventional burnt clay bricks.

## 2. Literature Review

### 2.1 Fly Ash: Composition and Pozzolanic Properties

Fly ash is a finely divided residue produced during the combustion of pulverised coal in thermal power plants. Its chemical composition is predominantly siliceous and aluminous, and it exhibits significant pozzolanic properties—that is, the ability to react with calcium hydroxide in the presence of water to form cementations compounds [13]. This pozzolanic reaction contributes to the development of compressive strength in fly-ash-based bricks over time, making fly ash a valuable supplementary cementations material [12].

The use of fly ash in brick manufacturing has been extensively investigated in various contexts. Researchers have evaluated the effects of particle size, curing duration, water-to-cement ratio, and firing temperature on brick properties [10]. The pozzolanic reactivity of fly ash can be activated under hydrothermal conditions, further enhancing the mechanical performance of fly-ash-based bricks [12].

**2.2 Environmental Imperatives for Sustainable Bricks**

The environmental footprint of conventional brick-making is substantial: the process consumes significant energy, emits greenhouse gases, and depletes fertile topsoil. The transition to sustainable brick production is therefore imperative. Fly-ash-based bricks offer a pathway to reduce these environmental impacts by utilising an industrial waste stream that would otherwise require disposal [11].

Life-cycle assessment (LCA) studies have quantified the environmental benefits of fly-ash bricks. For example, Bakshi et al. demonstrated that fly-ash blocks achieve a reduction of more than 80 % in kg $CO_2$-equivalent compared with sand-block manufacturing using aerated autoclaved technology [4]. The five main environmental impact categories identified were climate change, terrestrial ecotoxicity, non-carcinogenic human toxicity, land use, and energy resources. Similarly, a comparative LCA of fly-ash and burnt-clay bricks estimated carbon dioxide emissions of 43.28 g $CO_2$ and 290 g $CO_2$ per brick, respectively [8].

**2.3 Previous Research on Fly-Ash–Sand Bricks**

Substantial research has been conducted on the development of fly-ash–sand bricks. Banu et al. investigated the production of light-weight structural bricks using fly ash from the Barapukuria Thermal Power Plant in Bangladesh. Their study identified an optimum mix of 55 % fly ash, 30 % sand, and 15 % hydrated lime with 14 % gypsum, demonstrating that good-quality, non-fired structural bricks could be produced from coal fly ash [2].

Abbass et al. conducted a comparative analysis of enriched fly-ash-based cement–sand compressed bricks under various curing regimes. Their research showed that steam curing enhances early strength, with an optimised mix achieving a compressive strength of 15.57 MPa, flexural strength of 0.67 MPa, and a water absorption rate of 20.08 %, with no efflorescence. Notably, a mix containing 9 % ordinary Portland cement and 50 % fly ash showed improved early strength of 4.95 MPa at 28 days [1].

Zhang et al. examined fly-ash–aeolian-sand-based green bricks under carbonation curing and found that compressive strength could be enhanced by 1.8 to 4.2 times relative to ambient-cured specimens, with maximum values reaching 9.8 MPa. This improved mechanical performance was attributed to the formation and distribution of calcium carbonate within brick pores, where it plays filling, supporting, and bridging roles [3].

## 3. Materials and Methods

### 3.1 Raw Materials

The primary raw materials for compact green sand bricks with fly ash typically include:

- **Fly ash**: Class F or Class C fly ash obtained from coal-fired thermal power plants, characterised by its pozzolanic properties and fine particle-size distribution [13].
- **Sand**: Natural river sand or manufactured sand (M-sand) as fine aggregate [10].
- **Cement**: Ordinary Portland Cement (OPC) as a binding agent [1].
- **Lime**: Hydrated lime as an additional binder and activator for pozzolanic reactions [2].
- **Gypsum**: Added to control setting time and enhance strength development [2].

### 3.2 Mix Design

Various mix proportions have been investigated in the literature. Table 1 summarises representative mix designs from experimental studies.

**Table 1: Representative Mix Designs for Fly-Ash–Sand Bricks**

| Study | Fly Ash (%) | Sand (%) | Cement (%) | Lime (%) | Gypsum (%) | Compressive Strength (MPa) |
|---|---|---|---|---|---|---|
| Banu et al. (2013) | 55 | 30 | – | 15 | 14 | Not specified |
| Abbass et al. (2024) | 50 | Variable | 9 | – | – | 15.57 |
| Zhang et al. (2026) | 46.15 | 54.8 | – | Auxiliary | – | 9.8 |

| **Study** | **Fly Ash (%)** | **Sand (%)** | **Cement (%)** | **Lime (%)** | **Gypsum (%)** | **Compressive Strength (MPa)** |
|---|---|---|---|---|---|---|
| Singh et al. (2022) | 25 | 53 | – | 20 | 2 | 10.25 |

*(Sources: compiled from Banu et al., 2013; Abbass et al., 2024; Zhang et al., 2026; Singh et al., 2022)*

### 3.3 Manufacturing Process

The manufacturing process for compact green sand bricks with fly ash typically involves the following steps [1, 2]:

1. **Material preparation**: Raw materials are weighed according to the specified mix proportions.
2. **Dry mixing**: Fly ash, sand, and other dry ingredients are thoroughly blended.
3. **Wet mixing**: Water is added to achieve the desired consistency and workability.
4. **Compaction**: The mixture is compacted in moulds under pressure to achieve the required density and shape.
5. **Curing**: Bricks are cured under controlled conditions—ambient, steam, or carbonation curing.

Compaction pressure and curing regime significantly influence the final properties of the bricks. Research indicates that a combination of 70/30 fly ash to common sand with 15 % liquid sodium silicate and 5 % lime produces the best-performing brick in terms of strength, mould-ability, and water absorption [11].

## 4. Results and Discussion

### 4.1 Compressive Strength

Compressive strength is the most critical mechanical property for structural applications. The compressive strength of fly-ash–sand bricks varies significantly with mix composition, compaction pressure, and curing conditions.

Abbass et al. demonstrated that steam curing significantly enhances early-age strength development. Their optimised mix (MD: 5S) achieved a compressive strength of 15.57 MPa; however, excessive fly-ash replacement (70 %) with lower cement content negatively affected physico-mechanical properties [1].

Studies on the co-utilisation of fly ash and pickling sludge as partial substitutes for river sand showed that gradually increasing pickling sludge (2.5–10 %) and reducing fly ash (47.5–40 %) was incremental to compressive strength, with values reaching up to 28 MPa. This finding suggests that the inclusion of supplementary materials can further enhance the mechanical performance of fly-ash–sand bricks [7].

Under carbonation curing, the compressive strength of fly-ash–aeolian-sand bricks was enhanced by 1.8 to 4.2 times relative to ambient-cured specimens, with maximum values reaching 9.8 MPa at 0.6 MPa pressure and 14 days of curing. The carbonation process involves the formation of calcium carbonate within brick pores, which plays filling, supporting, and bridging roles [3].

The Taguchi method for process-parameter optimisation identified that water-to-binder ratio and stone-dust content play significant roles in compressive-strength development. Estimated optimum values include a water-to-binder ratio of 0.4, fly-ash content of 39 %, coarse sand of 24 %, and stone dust of 30 % [9].

### 4.2 Water Absorption

Water absorption is a crucial durability parameter because excessive absorption can lead to freeze–thaw damage and reduced structural integrity. According to the Bureau of Indian Standards (BIS), good bricks should have water absorption not exceeding 20 % of their weight.

The water absorption of fly-ash–sand bricks typically falls within acceptable limits. Abbass et al. reported a water absorption rate of 20.08 % for their optimised fly-ash–cement–sand composite bricks [1]. Comparative analysis of fly-ash bricks with conventional clay bricks showed that fly-ash bricks have lower water absorption (by 0.8 %) and exhibit nil efflorescence [8].

Microstructural analysis using scanning electron microscopy (SEM) revealed that compositions with fly-ash inclusion had dense microstructures, validating the sorptivity results. This densification contributes to reduced water absorption and enhanced durability [1].

**4.3 Density and Thermal Properties**

Fly-ash–sand bricks typically exhibit lower density than conventional clay bricks, contributing to reduced structural dead loads and improved thermal insulation. Densities in the range of 1600–1700 kg/m³ have been reported for fly-ash bricks [11]. The lower density is attributed to the porous nature of fly-ash particles and the reduced need for high-temperature firing.

Thermal conductivity of fly-ash bricks has been reported at approximately 0.95 W/mK, contributing to energy savings in buildings by maintaining cooler indoor temperatures and reducing air-conditioning requirements [5]. This low thermal conductivity makes fly-ash bricks suitable for green-building applications where thermal comfort and energy efficiency are prioritized.

**4.4 Durability and Efflorescence**

Durability is a key consideration for construction materials. Fly-ash–sand bricks have demonstrated favorable durability characteristics, including resistance to efflorescence. The optimized fly-ash–cement–sand composite bricks were reported to be devoid of efflorescence [1].

Freeze–thaw resistance is another important durability parameter, particularly in cold climates. Research indicates that fly-ash bricks can pass the 50 freeze–thaw cycles required by ASTM standards. When compressed at 28 MPa and cured for 24 hours in a 66 °C steam bath with air-entrainment agents, fly-ash bricks can last for more than 100 freeze–thaw cycles [14].

Drying shrinkage of fly-ash bricks is typically low, with values ranging from 0.035 % to 0.14 %, which is well within acceptable limits for structural applications. This low shrinkage contributes to dimensional stability and reduced cracking risk [14].

**4.5 Environmental Performance**

The environmental benefits of fly-ash–sand bricks are substantial. Life-cycle assessment studies consistently demonstrate significant reductions in carbon emissions compared with conventional alternatives. Fly-ash blocks achieve a reduction of over 80 % in kg $CO_2$-equivalent compared with sand-block manufacture [4]. The primary environmental impact categories include climate change, terrestrial ecotoxicity, non-carcinogenic human toxicity, land use, and energy resources.

The utilization of fly ash in brick production addresses multiple sustainability challenges: it diverts industrial waste from landfills, reduces the consumption of natural resources (topsoil and sand), and eliminates the need for high-temperature firing in kilns, thereby reducing energy consumption and greenhouse gas emissions [5, 11].

Furthermore, unfired bricks made with fly ash have gained attention in recent decades, contributing to overall environmental benefit through reduced carbon emissions. The high performance, reduced carbon emissions, and low material cost of fly-ash-based bricks position them as ideal replacements for conventional bricks [5].

## 5. Case Studies and Practical Applications

### 5.1 Fly-Ash Brick Production in India

India, as one of the world's largest producers of coal fly ash, has witnessed significant development in fly-ash brick manufacturing. The FaL-G (Fly ash-Lime-Gypsum) brick technology has been promoted as an eco-friendly alternative to conventional clay bricks. This technology avoids the use of fossil fuels in the production process, contributing to energy conservation and reduced greenhouse gas emissions [8].

The Kota Super Thermal Power Station in Rajasthan, India, generates approximately 1.64 to 2.03 million tonnes of fly ash annually, providing a substantial raw-material source for brick manufacturing. Case studies of fly-ash brick manufacturing units in this region have demonstrated the technical and economic viability of large-scale production [11].

### 5.2 Innovative Applications

Recent innovations have expanded the applications of fly-ash-based bricks. Start-ups like Co2ncrete in Gujarat, India, are building prefabricated homes using fly ash, silica sludge, and other factory by-products that would otherwise end up in landfills. These initiatives demonstrate the potential of fly-ash bricks to address both housing shortages and industrial-waste-management challenges [5].

Vedanta Aluminum has established a women-led fly-ash brick manufacturing facility in Jharsuguda, Odisha, that produces close to one crore bricks annually. Such initiatives contribute to economic development while promoting sustainable construction practices.

## 6. Challenges and Future Directions

Despite the demonstrated benefits of fly-ash–sand bricks, several challenges remain for widespread adoption [5, 11]:

1. **Quality variability**: The properties of fly ash vary depending on the source coal and combustion conditions, leading to inconsistent brick quality [13].
2. **Regulatory gaps**: Standardized production methods and quality-control procedures need to be established and enforced.
3. **Market acceptance**: Consumer and industry preferences for traditional clay bricks present barriers to adoption.
4. **Production challenges**: Specific technical challenges in manufacturing, including optimal compaction pressure and curing conditions, require further research [9].

Future research directions should focus on [5, 14]:

- Optimisation of mix designs for specific applications and climatic conditions.
- Development of predictive models for compressive strength using machine-learning algorithms.
- Investigation of the long-term durability of fly-ash–sand bricks under various environmental conditions.
- Integration of multiple waste streams to further enhance sustainability and circular-economy principles.
- Life-cycle cost analysis to demonstrate economic benefits over the full building lifecycle.

## 7. Conclusion

This paper has reviewed and analysed the development of compact green sand bricks incorporating fly ash as a sustainable alternative to conventional burnt clay bricks. The key findings are as follows:

1. **Technical viability**: Fly-ash–sand bricks can achieve compressive strengths ranging from 9.13 MPa to 28 MPa, depending on mix composition and curing conditions, meeting or exceeding the requirements of relevant standards [1, 7, 3].
2. **Durability**: These bricks exhibit favourable durability characteristics, including water absorption below 20 %, minimal efflorescence, low drying shrinkage (0.035–0.14 %), and resistance to freeze–thaw cycles [1, 8, 14].
3. **Environmental sustainability**: Life-cycle assessment studies demonstrate that fly-ash bricks achieve over 80 % reduction in carbon dioxide equivalent emissions compared with conventional alternatives, while also conserving natural resources and diverting industrial waste from landfills [4].
4. **Economic viability**: The use of fly ash—an industrial by-product available at low cost—combined with reduced energy requirements for manufacturing, makes fly-ash–sand bricks economically attractive [11].
5. **Practical applicability**: Successful case studies in India and elsewhere demonstrate the scalability and practical viability of fly-ash brick production, with applications ranging from individual housing to large-scale construction projects [5, 8].

The compact green sand brick with fly ash represents a technically viable, environmentally superior, and economically attractive alternative to conventional clay bricks. Its adoption can contribute significantly to sustainable construction practices, circular-economy principles, and the global transition towards low-carbon building materials. Continued research, supportive policy frameworks, and industry collaboration are essential to overcome remaining challenges and realise the full potential of this sustainable building material.

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