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Development and Structural Characterization of Sustainable Unfired Bricks Utilizing Industrial Byproducts

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Abstract: The construction industry worldwide is under increasing pressure to transition towards sustainable practices and reduce its reliance on conventional clay-fired masonry units. The production of traditional burnt clay bricks contributes heavily to topsoil erosion, deforestation, and atmospheric pollution due to high-temperature kiln firing. This research presents a thorough experimental investigation into the development, optimization, and structural evaluation of unfired eco-friendly bricks produced from industrial byproducts, specifically fly ash, lime, black sand, fine gravel, and minimal cement binder. By evaluating physical characteristics including specific gravity, particle size distribution, matrix compaction, water absorption, density, and multi-stage compressive strength development up to 56 days, this study establishes an optimized mix design. The baseline composition consisting of 50% Black Sand, 20% Gravel, 10% Lime, 10% Cement, and 10% Fly Ash compressed at high forming pressures achieves superior 28-day compressive strengths exceeding 110 kg/cm² and long-term strength exceeding 16 MPa, while satisfying IS code standards for structural masonry.

Keywords: Fly ash, Black sand, Unfired eco-bricks, Compressive strength, Water absorption, Pozzolanic reactivity, Waste utilization, Sustainable infrastructure.

I. Introduction

1.1 Background and Global Context

Rapid urban growth and global infrastructure expansion have dramatically escalated the demand for essential building components, primarily structural bricks and concrete blocks. Traditionally, structural wall systems depend on fired clay bricks, which necessitate the extraction of millions of tons of fertile topsoil annually. The standard manufacturing procedure for clay bricks involves high-temperature thermal processing in kilns operating between 900°C and 1100°C. This energy-intensive process yields substantial emissions of carbon dioxide (CO₂), sulfur dioxide (SO₂), nitrogen oxides (NO_x), and particulate matter, significantly contributing to regional air pollution and global climate change.

Concurrently, thermal power plants, mineral processing plants, and mining sectors generate immense volumes of solid waste and industrial byproducts. Fly ash—a residual byproduct of coal combustion in thermal power stations—presents significant disposal challenges globally. When left unmanaged in ash ponds or open dumps, fly ash poses severe environmental risks, including groundwater contamination through heavy metal leaching and air pollution via airborne dust particles. Similarly, heavy mineral mining and coastal dredge processing yield heavy black sand residue, fine tailings, and gravel fractions that remain underutilized.

1.2 Sustainable Materials and Technical Rationale

To address the dual challenges of raw material depletion and industrial waste accumulation, researchers and civil engineers are focusing on sustainable building materials. Unfired masonry units (also known as non-burnt or cold-cured bricks) offer an effective solution. By eliminating the thermal firing phase, unfired brick technology reduces embedded energy consumption by up to 70–80% and substantially lowers carbon emissions per unit volume produced.

The engineering rationale for combining fly ash, lime, black sand, gravel, and hydraulic cement relies on synergistic pozzolanic and mechanical interlock mechanisms: Fly ash is rich in reactive silica (SiO₂) and alumina (Al₂O₃), which undergo pozzolanic reactions with calcium hydroxide provided by hydrated lime and cement hydration products. Black sand provides a heavy, dense, wear-resistant mineral filler framework, while fine gravel forms a robust internal aggregate skeleton. Portland cement functions as an early-strength catalyst and hydraulic binder, accelerating early handling strength while long-term hydration and pozzolanic reactions mature.

1.3 Scope and Objectives of the Research

This study presents a systematic experimental framework aimed at engineering high-performance unfired bricks from local industrial byproducts. The core research objectives are defined as follows:

- **Waste Utilization & Resource Recovery:** Maximize the volumetric replacement of natural topsoil and quarry sands using coal combustion fly ash and industrial mineral black sand.
- **Mix Proportioning Optimization:** Systematically evaluate multiple mix proportions of fly ash, black sand, gravel, lime, and cement to identify the optimal matrix for maximum packing density.
- **Mechanical Performance Characterization:** Measure multi-age compressive strength development at 3, 7, 14, 28, and 56 days under standard moist-curing conditions.
- **Durability Assessment:** Analyze physical density, water absorption rates, and matrix porosity under variable compaction pressure regimes.
- **Standards Compliance:** Verify that engineered unfired bricks satisfy Indian Standard (IS) specifications (IS 12854, IS 3495, IS 1077) for structural

load-bearing masonry units.

II. Materials And Experimental Methodology

2.1 Raw Material Characterization

All raw components were thoroughly sampled and characterized prior to mixture proportioning to establish their physical, chemical, and index properties. The constituent materials comprised Class F fly ash obtained from a thermal power station, hydraulic hydrated lime, Ordinary Portland Cement (OPC 53 grade), processed heavy black sand, and micro-gravel (size < 4.75 mm).

Specific gravity tests were performed in accordance with IS 1727-1967 (for pozzolanic materials and cementitious binders) and IS 1122-1974 (for natural aggregates and mineral fillers). Specific gravity was determined using standard Pycnometer and Le Chatelier flask methods under controlled laboratory temperatures ($27 \pm 2^\circ\text{C}$).

Table 1: Physical and Index Properties of Raw Constituents

Material Component	Specific Gravity	Primary Physical State / Origin	Engineering Role in Matrix
Black Sand	3.00	Heavy mineral residue (Fine aggregate)	Heavy mineral filler, high bulk density
Ordinary Portland Cement	3.15	Dry hydraulic powder (OPC 53)	Hydraulic catalyst & early-strength binder
Fine Micro-Gravel	2.75	Screened aggregate (<4.75 mm)	Coarse aggregate framework & mechanical interlock
Hydrated Lime	2.48	Dry fine powder (Ca(OH) ₂ rich)	Pozzolanic activator, calcium donor
Class F Fly Ash	2.18	Pulverized coal combustion byproduct	Pozzolanic reactive filler, micro-void packing

2.2 Mix Design and Proportioning Strategy

The proportioning strategy focused on optimizing particle packing density while maintaining sufficient moisture for complete binder hydration and workability during high-pressure compaction. A baseline benchmark formulation (Base

Mix, BM) was formulated based on preliminary packing trial mixtures and standard fly ash brick guideline recommendations. Subsequent trial blends were proportioned by systematically varying binder contents (lime and cement) and fine aggregate ratios to evaluate sensitivity.

Table 2: Experimental Mix Proportions (% by Dry Mass Weight)

Mix ID / Designation	Black Sand (%)	Gravel (%)	Lime (%)	Cement (%)	Fly Ash (%)	Water Content (%)
Base Mix (BM)	50.0	20.0	10.0	10.0	10.0	14.0
Mix Series 2 (S21-S24)	50.0	20.0	5.0	10.0	15.0	14.0
Mix Series 3 (S31-S34)	50.0	26.0	6.0	8.0	10.0	14.0
Mix Series 4 (S41-S42)	70.0 (50+20)	0.0	10.0	10.0	10.0	14.0

2.3 Specimen Preparation, Molding, and Curing Protocol

Manufacturing of test specimens followed a standardized mechanical press protocol. Raw materials were dry-mixed in a

pan mixer for 3 minutes to achieve homogeneous constituent dispersion. Potable mixing water (fixed at 14% by dry mass weight) was sprayed uniformly across the dry mixture and wet-

The homogeneous moist mixture was transferred into precision steel mold cavities measuring 50 mm × 50 mm × 50 mm (cubical test blocks) and standard full-scale brick molds (230 mm × 110 mm × 75 mm). Specimens were compacted using a heavy-duty hydraulic compression system operating under controlled forming pressures ranging from 10 MPa to 25 MPa (1000 psi to 3000 psi equivalent). Uniaxial compression was applied at a constant strain rate of 0.9 kN/s.

Following compaction, demolding was carried out after 3 to 4 hours of initial setting in clean ambient room conditions. Demolded specimens were transferred to a dedicated curing bay and subjected to moist-curing by wrapping in saturated gunny sacks at a controlled ambient temperature of $27 \pm 2^\circ\text{C}$. Specimens were maintained under continuous wet-curing conditions until designated testing ages of 3, 7, 14, 28, and 56 days.

III. Experimental Results and Discussion

3.1 Density and Compaction Pressure Interdependence

The physical density of unfired eco-bricks depends heavily on applied compaction pressure during molding. High forming pressure forces fine fly ash particles and lime into micro-voids between black sand grains and gravel aggregate, significantly reducing inter-particle porosity. Experimental measurements indicated that increasing forming pressure from 10 MPa (1450 psi) to 20 MPa (2900 psi) yielded a dry density increase from 1.98 g/cm³ to 2.24 g/cm³. This high matrix density directly contributes to reduced moisture permeation and improved mechanical load

resistance.

3.2 Water Absorption and Durability Behavior

Water absorption is a critical indicator of brick durability, weathering resistance, and susceptibility to freeze-thaw degradation or efflorescence. Water absorption testing was conducted per IS 3495 (Part 2)-1992 by oven-drying specimens at 110°C for 24 hours, recording dry mass (Wd), and subsequently immersing specimens in cold water for 24 hours to measure saturated mass (Ws).

$$\text{Water Absorption (\%)} = [(W_s - W_d) / W_d] \times 100$$

Test results demonstrated a direct inverse relationship between compaction pressure and water absorption. Bricks molded under 1000 psi (6.9 MPa) exhibited an average water absorption of 14.63%. Increasing forming pressure to 3000 psi (20.7 MPa) reduced water absorption to 11.58%. All tested mix compositions fell well within the maximum allowable limit of 20% specified by IS 1077 for common building bricks, confirming high weather resistance.

3.3 Compressive Strength Development Analysis

Compressive strength testing was conducted using a calibrated 5000 kN capacity digital Compression Testing Machine (CTM) in accordance with IS 3495 (Part 1)-1992. Uniaxial compressive load was applied continuously without shock at a rate of 0.6 kN/s (14 N/mm²/min) until structural failure occurred.

$$\text{Compressive Strength (fc)} = \text{Failure Load (N)} / \text{Bearing Area (mm}^2\text{)}$$

Table 3: Multi-Age Compressive Strength Development (kg/cm² and MPa)

Mix Designation	3-Day Strength	7-Day Strength	14-Day Strength	28-Day Strength	56-Day Strength
Base Mix (BM)	42 kg/cm ²	68 kg/cm ²	89 kg/cm ²	110 kg/cm ² (10.8 MPa)	16.4 MPa
Series 2 (S21-S24)	38 kg/cm ²	61 kg/cm ²	82 kg/cm ²	102-108 kg/cm ²	14.8 MPa
Series 3 (S31-S34)	40 kg/cm ²	63 kg/cm ²	84 kg/cm ²	103-107 kg/cm ²	15.1 MPa
Series 4 (S41-S42)	35 kg/cm ²	56 kg/cm ²	76 kg/cm ²	99-100 kg/cm ²	12.6 MPa

3.4 Microstructural Reaction Mechanisms

The ongoing strength gain observed up to 56 days is attributed to progressive C-S-H (Calcium Silicate Hydrate) and C-A-H (Calcium Aluminate Hydrate) gel formation. Initial strength (3 to 7 days) is driven by hydration of OPC cement. Secondary long-term strength gain (14 to 56 days) results from slow pozzolanic reactions between dissolved silica from fly ash particles and free calcium hydroxide derived from hydrated lime and cement.

The Base Mix formulation achieved an optimal balance: 10% cement provided sufficient early handling strength, while 10% lime and 10% fly ash provided sustained pozzolanic activity. Furthermore, the dense heavy mineral grain structure of 50% black sand combined with 20% fine gravel produced a well-

graded skeleton, preventing micro-cracking during curing.

IV. Economic And Environmental Sustainability Analysis

4.1 Carbon Footprint and Embedded Energy Reduction

A lifecycle assessment comparison reveals significant environmental benefits of the proposed unfired eco-brick compared to traditional fired clay bricks. Standard thermal clay brick firing consumes approximately 2.0 to 2.5 MJ of energy per brick, releasing roughly 200–250 g of CO₂. In contrast, cold-cured unfired fly ash-black sand bricks eliminate thermal energy input entirely. The carbon footprint is limited to cement manufacturing and transportation, resulting in a net carbon footprint reduction of 60% to 75% per thousand bricks produced.

4.2 Production Cost and Commercial Viability

Industrial byproducts such as fly ash and black sand tailings are available at minimal cost compared to topsoil or river sand. By incorporating 60% combined waste byproducts (50% black sand + 10% fly ash), raw material procurement costs are reduced by approximately 30–40%. Additionally, eliminating coal fuel consumption for kilns reduces operational overhead, making commercial manufacturing highly competitive for load-bearing and non-load-bearing structural applications.

V. Conclusion And Recommendations

This research confirms the technical feasibility, structural performance, and environmental sustainability of manufacturing unfired eco-friendly bricks using fly ash, lime, black sand, fine gravel, and minimal cement binder. Key conclusions derived from experimental results include:

- **Optimal Mix Design:** The Base Mix (BM)—composed of 50% Black Sand, 20% Gravel, 10% Lime, 10% Cement, and 10% Fly Ash at 14% water content—yields superior performance across all curing ages.
- **Structural Compressive Strength:** Base Mix specimens achieved an average 28-day compressive strength of 110 kg/cm² (10.8 MPa) and a 56-day strength of 16.4 MPa, exceeding Class 10 IS 1077 code requirements for structural masonry.
- **Low Water Absorption:** High forming compaction pressures (20 MPa / 3000 psi) reduced water absorption to 11.58%, ensuring high durability and moisture resistance.
- **Sustainability Impact:** Cold-cured manufacturing eliminates thermal emissions, conserves natural topsoil, and repurposes solid industrial wastes, supporting circular economy initiatives.

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