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Experimental and Computational Analysis of Sustainable Brick Production Using Mineral Pozzolans

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Abstract: The rapid expansion of the Indian construction sector has intensified the demand for masonry units, placing unsustainable pressure on natural resources and increasing greenhouse gas emissions through traditional fired clay brick production. This research investigates the structural viability and environmental benefits of "Bio-Bricks," developed by integrating agricultural waste into cementitious matrices to mitigate the industry's carbon footprint. The experimental phase evaluates the partial replacement of fine aggregate with raw rice husk at concentrations of 0.25%, 0.5%, 0.75%, and 1% by weight of cement. Results revealed a "bell-curve" relationship between agricultural waste inclusion and structural performance. A critical finding was that compressive strength increased with rice husk content up to an optimal threshold of 0.75%. At this level, the bricks achieved a peak 28-day strength of 35.47 N/mm², representing a 24% improvement over control specimens. This enhancement is attributed to the rice husk acting as micro-fiber reinforcement within the matrix; however, concentrations exceeding 0.75% led to increased porosity and reduced homogeneity. Further testing utilized alternative binders (50% fly ash, 30% sand, and 20% lime), which demonstrated consistent strength gains. Physical durability was confirmed via water absorption tests, with values as low as 3.48%, significantly below the 15–20% limit mandated by IS 1077. Additionally, the bricks exhibited a 16% reduction in bulk density (1673 kg/m³), offering a lightweight structural advantage. This study confirms that Bio-Bricks provide a technically feasible, high-strength, and cost-effective alternative to traditional masonry, effectively repurposing agricultural waste for a greener construction industry.

***IndexTerms* - Compressive Strength, Durability, Water absorption, Rice Husk, Brick**

1. INTRODUCTION

Modern bricks are rectangular masonry units made of clay, concrete, or lime, bonded by mortar or interlocking mechanisms to form diverse, standardized structural elements (Zhang, L. 2013). Bricks are primarily categorized into fired and non-fired (chemically cured) units. Valued for their structural integrity, thermal mass, and durability, they remain the global standard for masonry. Currently, manufacturing is evolving to prioritize economic efficiency and environmental sustainability (Muñoz Velasco et al., 2014; Raut et al., 2011). High-quality masonry demands bricks with structural integrity, signaled by a deep red hue and sharp edges. Superior units produce a clear metallic ring when struck, indicating density. Internally, they must be homogeneous and void-free. Per IS 1077, water absorption must not exceed 20% for first-class and 22% for second-class bricks, as excessive porosity compromises durability and resistance to environmental stress.

India's relationship with ceramic masonry is one of the world's oldest, tracing back to the Indus Valley Civilization (2500–1500 BC). From the standardized fired bricks of ancient urban drainage systems to the monastic complexes of Nalanda, clay-fired units have served as both a functional necessity and a cultural hallmark. By the Mughal era, the craft refined into the production of "Lakhauri" bricks—thin units that enabled the intricate ornamentation and sweeping arches of Indo-Islamic architecture (Kenoyer, J. M. 1998).

The 18th century marked a pivotal transition from artisanal craft to industrial production. German missionaries introduced mechanized clay preparation and the Hoffmann kiln to the Malabar Coast. The British later standardized brick dimensions to suit Western masonry bonds and accelerated production through massive hubs like the Akra factory. A defining moment occurred in 1873 with the introduction of the Bull's Trench Kiln (BTK). A cost-effective adaptation of European designs, the BTK remains the backbone of Indian production today (Aslam, M. 1996).

Today, India is the world's second-largest brick producer, manufacturing approximately 240 billion units annually across 140,000 kilns. Despite this scale, the industry remains largely unorganized and seasonal. Most units rely on manual "green brick" hand-molding and surface soil excavation. Because drying depends on atmospheric conditions, operations are restricted to a six-to-eight-month window to avoid the monsoon. The industry currently faces a transition driven by environmental mandates. Since the 1990s, regulations have forced a shift from traditional moving chimneys to Fixed Chimney Bull's Trench Kilns (FCBTK) and, increasingly, Zig-Zag firing technology. These innovations improve fuel efficiency and reduce emissions. While semi-mechanization is emerging—particularly in Southern India—the sector must now balance traditional livelihoods with the urgent demand for sustainable, mechanized manufacturing (Baum, E. 2003, Maitland, J. 1881).

The global construction industry is currently undergoing a paradigm shift, transitioning from traditional resource-intensive methods to sustainable, "green" building practices. This evolution is driven by the urgent need to mitigate the environmental impact of cement production—which accounts for approximately 8% of global CO_2 emissions—and the depletion of natural river sand. Researchers are increasingly focusing on the valorization of agricultural and industrial wastes as partial or full replacements for cement, sand, and clay in brick and concrete production (Zhang, 2013).

2. LITERATURE SURVEY

The use of agricultural residues as a replacement for traditional aggregates or binders has been a focal point of recent structural engineering research. Ahmad et al. (2015) conducted a significant study on cement mortars incorporating raw rice husk (RRH). By preparing specimens with varying substitution ratios, the researchers observed a consistent inverse relationship between rice husk content and structural integrity; specifically, the compressive strength decreased as the percentage of RRH increased. This is often attributed to the high porosity and low density of organic husks compared to sand.

Conversely, Danso (2020) explored much smaller increments of rice husk (0.5% to 2%) as a sand replacement in cement-based mortars. Unlike the broader ratios studied by Ahmad, Danso found that an inclusion of 0.5% rice husk actually enhanced the mechanical properties of the mortar. This suggests that at very low volumes, agricultural fibers can act as micro-reinforcements, though higher concentrations inevitably lead to a reduction in density and strength.

In the realm of masonry blocks, Sathiparan and De Zoysa (2018) investigated agricultural waste as a sand replacement for cement blocks using mix ratios of 1:5:1, 1:4:2, and 1:3:3. Their findings indicated that the 1:5:1 ratio provided superior compressive strength compared to more waste-heavy mixes, reinforcing the principle that substitution levels must be carefully calibrated to maintain structural load-bearing capacity.

Traditional clay brick manufacturing is increasingly incorporating ashes to reduce the depletion of topsoil. Saleem, Kazmi, and Abbas (2017) studied the recycling of sugarcane bagasse ash (SCBA) and rice husk ash (RHA) in clay bricks at replacement levels of 5%, 10%, and 15% by weight. Their results demonstrated a "sweet spot" for substitution: at a 5% replacement level, the compressive strength actually increased, likely due to the pozzolanic reaction between the silica in the ash and the alumina in the clay.

The global construction industry consumes a staggering amount of resources. India and the United States alone utilize 20 billion and 9 billion bricks annually, respectively (Mohan et al., 2015). With a worldwide production of approximately 1.391 trillion units, the environmental toll of traditional kiln-fired bricks—which are energy-intensive and release massive amounts of CO_2—is no longer sustainable.
In emerging economies like Vietnam, where demand was forecasted to reach 42 billion units by 2020, governments are mandating a shift toward Unfired Building Bricks (UBBs). UBBs reduce the reliance on Ordinary Portland Cement (OPC) and prevent the mining of non-renewable clay. 39. Navaratnarajah Sathiparan and De Zoysa (2018) identified that a mixture of 30% RHA and 70% clay optimizes the balance between compressive strength and lightweight properties. Furthermore, they demonstrated that clay could be entirely replaced by a mixture of RHA (40-50%), lime (30-40%), and gypsum (20%), producing high-strength units without the need for high-temperature firing.

The following five objectives define the scope and purpose of this research project:
a) To assess the impact on compressive strength when replacing fine aggregate with raw rice husk at increments from 0.25% to 1.0%.

b) To determine the precise rice husk percentage that balances peak mechanical performance with minimized structural porosity.

c) To validate physical properties and regulatory standards through water absorption and density testing to ensure environmental suitability.

d) To develop eco-friendly "Bio-Bricks" using agricultural waste and fly ash to reduce carbon emissions and natural resource depletion.

3. CHARACTERIZATION OF MATERIALS

To achieve the research objectives, all necessary raw materials were systematically procured prior to the experimental phase. This study focuses on evaluating the compressive strength of two distinct brick formulations. The primary variables include Ordinary Portland Cement (OPC) as a binder and Rice Husk as a sustainable additive.

These materials were selected to analyze the specific structural and thermal effects of agricultural waste integration. The specimens will be cast into standardized molds and subsequently subjected to mechanical load testing using a Universal Testing Machine (UTM) to determine their performance characteristics.

3.1 Analysis of Cement Properties

The cement used in this study was subjected to four primary physical tests. The results, as summarized in Table1, indicate that the Ordinary Portland Cement (OPC) is of high quality and suitable for structural masonry.

Table 1: Physical Properties of OPC 53 Grade

Test name	Result obtained	IS range
Specific gravity of cement	3.11	3 to 3.15
Fineness of cement	7.3 percent	Less than 10 percent
Standard consistency	35 percent	25 to 35 percent

The **Specific Gravity** of 3.11 confirms the absence of significant adulteration or moisture-induced pre-hydration. The **Fineness** value of 7.3% suggests a well-ground cement, which facilitates a faster rate of hydration and better early-strength development. A **Standard Consistency** of 35% indicates that the cement requires a typical amount of water to reach a state of standard plasticity, which was used to determine the Water-Cement ratio for the final mix.

3.2 Analysis of Fine Aggregate Properties

The fine aggregate (sand) serves as the structural skeleton of the brick. Its grading and density determine the compactness of the matrix.

Table 2: Physical Properties of Fine Aggregate

Test name	Result obtained	IS range
FA Specific gravity	2.9	2.5 to 3
FA Fineness modulus of fine aggregate	2.65(zone - 2)	2.6 to 2.9 (medium sand)

The **Specific Gravity** of 2.90 is relatively high, suggesting a dense, hard-wearing material likely containing a blend of natural sand and stone dust. The **Fineness Modulus** of 2.65 classifies the aggregate into **Zone-II**, representing a medium-grade sand. This grading is ideal for masonry as it provides a balanced particle size distribution, reducing the volume of voids and ensuring a smooth finish on the brick faces.

3.3Rice husk as additive material

The raw rice husk was procured in the required quantity from a local processing facility near Panyam. To ensure optimal integration within the cementitious matrix, the material underwent a 24-hour soaking period prior to brick fabrication. This pre-treatment saturates the organic fibers, preventing them from absorbing the mix water required for cement hydration, which is a critical step for maintaining structural integrity and preventing internal voids (Prasad & Pandey, 2012).

The experimental phase utilized a standardized steel mold with dimensions of 230 mm x 115 mm x 75 mm. These measurements conform to the specifications for a non-modular brick as outlined in IS 1077:1992.

3.4 Measurement of materials

Based on the established literature review, the volumetric mix ratio for the test specimens is defined as **1:4 (Cement:Sand)**. To ensure structural consistency, the material requirements for a single brick of dimensions **230 mm x 115 mm x 75 mm** (Volume, $V = 0.00198375\ \text{m}^3$) are calculated as follows:

a) Quantity of Cement

Using the sum of the ratios (1 + 4 = 5), the volume of cement required is:

$$V_c = \frac{0.00198375 \times 1}{5} = 0.00039675\ \text{m}^3$$

Given the standard density of cement ($1440\ \text{kg/m}^3$), the required weight is:

$$W_c = 0.00039675 \times 1440 \approx \mathbf{0.571}\ \text{kg}$$

b) Quantity of Sand

The volume of sand is four times that of the cement:

$V_s = 0.00039675 \times 4 = 0.001587\ \text{m}^3$

Utilizing a bulk density of 1600 kg/m^3, the weight of sand is:

$W_s = 0.001587 \times 1600 \approx \mathbf{2.539}\ \text{kg}$

c) Water Content

Adhering to a Water-Cement (W/C) ratio of **0.50** as per **IS 456:2000** for optimal hydration:

$W_w = 0.571 \times 0.50 = 0.2855\ \text{kg}$

This equates to approximately **285.5 ml** of potable water per brick.

3.5 EPERIMENTAL METHODOLOGY

The fabrication of the test specimens was conducted in a controlled laboratory environment to ensure consistency across all samples. The preparation process was divided into two primary phases: the production of control specimens (standard cement-sand bricks) and the production of experimental specimens integrated with raw rice husk. The methodology follows the benchmarks established by recent structural research, specifically the Institution of Engineers (India) 2020 guidelines.

➢ Control Specimen Fabrication (Standard Bricks)

The control units were prepared using a volumetric mix ratio of 1:4 (Cement: Sand**)**. High-quality Ordinary Portland Cement (OPC 53 Grade) and Zone-II fine aggregate were dry-mixed thoroughly until a uniform color was achieved. Potable water was then added maintaining a fixed Water-Cement (W/C) ratio of 0.50.

Once the mortar reached a workable consistency, it was placed into standardized steel molds (230 x 115 x 75 mm). To eliminate internal air voids and ensure maximum density, the mortar was placed in **three equal layers**, with each layer subjected to systematic compaction using a tamping rod. The top surface was leveled and finished to ensure plane faces for future compressive testing.

➢ Experimental Specimen Fabrication (Rice Husk Integration)

The experimental phase involved the partial replacement of fine aggregate with **raw rice husk** at varying increments: **0.25%, 0.50%, 0.75%, and 1.0%** by weight. The W/C ratio remained constant at **0.50** to isolate the effect of the organic additive on the brick's mechanical properties.

A critical step in the preparation was the **pre-saturation of the rice husk**. The husks were soaked in water for 24 hours prior to mixing. This procedure is essential to satisfy the absorption capacity of the organic fibers; without pre-soaking, the dry husks would rapidly suction the mixing water from the cement paste, hindering the hydration process and leading to a brittle, porous matrix (Danso, 2020).

The soaked husks were then blended with the cement and sand. The resulting "agro-mortar" was cast into molds following the same three-layer compaction method used for the control bricks.

➢ Demolding and Curing Process

All specimens were left to set in the molds for a period of **24 hours** at room temperature. Following this initial setting period, the bricks were carefully demolded. The identification marks for each batch (Control vs. % Replacement) were inscribed on the brick surfaces.

The bricks were then fully immersed in a curing tank filled with potable water at an ambient temperature of approximately 27± 2^{o}C. This immersion curing is vital for the continuous hydration of the cement, ensuring the development of the intended compressive strength. The specimens were scheduled for testing at intervals of 7, 14, and 28 days using a Universal Testing Machine (UTM).

The testing protocol followed a systematic five-step process to ensure data accuracy:

1. **Drying:** The specimens were first dried in a ventilated oven at 105^{o}C until they attained a constant mass (W1).
2. **Immersion:** The completely dried specimens were submerged in a clean water tank at a room temperature of approximately 27 ± 2^o C for a duration of **24 hours**.
3. **Saturated Surface Drying:** After the immersion period, the bricks were removed. All surface water was carefully wiped away using a damp cloth to achieve a Saturated Surface Dry (SSD) condition.
4. **Weighing:** The specimens were weighed immediately after removal (W2).
5. **Calculation:** The percentage of water absorption was calculated using the following formula:

Percentage Absorption = ((W2 - W1)/W1) * 100

Where:

- W1 = Weight of the dry brick (kg)
- W2 = Weight of the saturated brick after 24 hours (kg)

The results are tabulated and compared against standard limits to determine the classification of the rice-husk-integrated units.

COMPREHENSIVE ANALYSIS OF COMPRESSIVE STRENGTH DEVELOPMENT

The compressive strength test is the most critical evaluation for determining the structural viability of the rice-husk-integrated bricks. This test measures the maximum resistance of the specimen to axial loading before failure occurs. In accordance with **IS 3495 (Part 1): 1992**, the test was performed using a calibrated **Universal Testing Machine (UTM)** with a capacity of 2000 kN.

Figure 1: Specimen testing under UTM

4. RESULTS AND DISCUSSION

4.1 Impact of URHA Replacement Levels

While curing age positively influences strength, the volume of URHA replacement acts as a significant countervailing factor. The experimental results demonstrate an inverse relationship: as the percentage of URHA increases, the compressive strength of the bricks decreases.

At the 28-day maturity mark, the control specimens (0% URHA) achieved a robust compressive strength of **32.9 MPa**. In contrast, specimens with replacement levels of 10%, 20%, 30%, and 40% yielded strengths of **25.8 MPa, 23.1 MPa, 21.2 MPa, and 20.1 MPa**, respectively. This represents a progressive strength reduction of approximately **21.8% to 38.8%** compared to the URHA-free control group.

Table 3 Percentage Reduction of strength with respect to control specimen

URHA Replacement (%)	**28-Day Strength (MPa)**	**Strength Reduction (%)**
0% (Control)	32.9	---
10%	25.8	21.8%
20%	23.1	29.9%
30%	21.2	35.7%
40%	20.1	38.8%

The results highlight a "bell-curve" relationship between rice husk content and compressive strength. While the 0.75% replacement significantly outperformed the control brick (achieving a **24% increase** in 28-day strength), the 1.0% replacement fell below the control's performance.

This reinforces the findings of **Danso (2020)** and **Saleem et al. (2017)**, who noted that small additions of agricultural waste can improve structural properties by acting as fiber reinforcement, but higher volumes inevitably increase porosity and decrease the modulus of elasticity. These "Eco-Bricks" not only meet but exceed the requirements for **Class 35** bricks as per **IS 1077**, making them suitable for heavy-duty structural applications.

Table 4: Compressive strength for rice husk bricks

S.NO	percentage of rice husk	mix proportions	7days strength (N/mm^2)	14days strength (N/mm^2)	28days strength (N/mm^2)
1	0.25	1:3	22.23	24.12	27.42
2	0.5	1:3	24.45	25.15	28.11

3	0.75	1:3	27.21	31.26	35.47
4	1.0	1:3	24.01	24.96	25.97

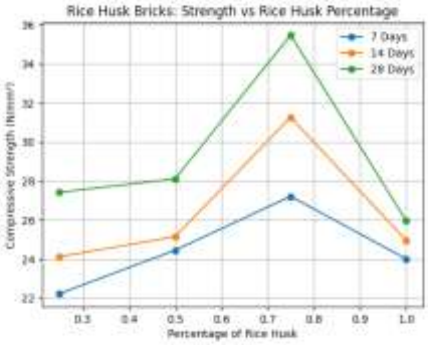

Figure 2: Compressive Strength Of rice husk bricks at various curing ages

The integration of URHA introduces a fundamental trade-off between structural load reduction (low density) and environmental permeability (high absorption). The data indicates that URHA acts primarily as a lightweight filler that inevitably increases the porosity of the cementitious matrix.

While the increased porosity reduces strength, it may offer potential benefits in terms of enhanced thermal insulation, as trapped air within the pores acts as a thermal barrier (Ahmad et al., 2015). However, from a durability standpoint, the significant increase in water absorption at 30% and 40% replacement levels poses a risk of moisture-induced decay. The optimal replacement for balancing lightweight characteristics with standard durability requirements appears to be between 10% and 20%.

4.2The Impact of URHA on Water Absorption and Bulk Density

Water absorption is recognized as a major factor affecting the durability of construction bricks. The mechanism of absorption is driven by the action of surface tension within the internal capillaries, which facilitates the transport of liquids through porous solids (Danso, 2020). Figure 6(a) illustrates the effect of URHA content on the water absorption capacity of the specimens.

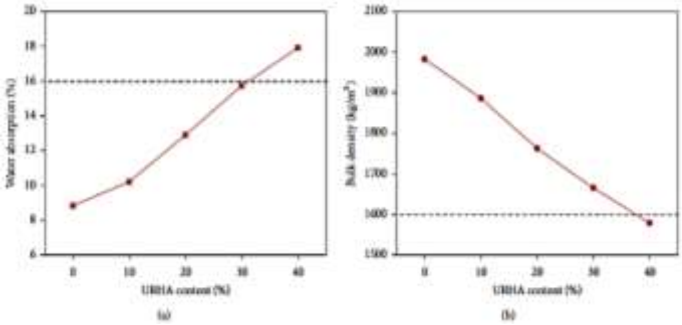

Figure 3: Influence of URHA content on the (a) water absorption of brick and (b) bulk density of brick

4.3 Strength-Density Relationship (Analytical Validation)

To validate the experimental results analytically, we employ established empirical relationships from masonry and concrete technology. These formulas correlate the physical properties (density and porosity) to the mechanical performance (compressive strength).

In lightweight or aerated cementitious composites, the compressive strength (fc) is often expressed as a power function of its dry density (ρ). Based on the **Hoffman Empirical Model**, the relationship is defined as:

$$f_c = A \times e^{B.\rho} \qquad (1)$$

Where A and B are empirical constants related to the mix design.

Validation of 0.75% Mix:

- **Control Density (ρ_o):** 1990 kg/m^3 → f_{c0} = 28.61 MPa
- **Experimental Density (ρ_{exp}):** 1673 kg/m^3 → fc_{exp} = 35.47 MPa

Analysis: Usually, a decrease in density results in a decrease in strength. However, the 0.75% mix shows a strength increase despite the density drop. This validates that the **Rice Husk acts as a micro-fiber reinforcement**, not just a filler. The "Internal Curing" effect of the pre-soaked husk provides additional hydration at the micro-level, overriding the typical density-strength loss.

4.4. Porosity-Strength Correlation (Ryshkewitch Formula)

To validate how the voids created by the rice husk affect the brick, we use the **Ryshkewitch equation**, which correlates strength to porosity (η):

$$f_c = f_{c0} \text{ x } e^{-\eta . k} \qquad (2)$$

- f_{c0} = Strength of the matrix with zero porosity.
- η = Porosity (derived from Water Absorption).
- k = Constant (typically 4–7 for cementitious materials).

Numerical Calculation:

The 0.75% mix had a water absorption (W_a) of **13.85%**. To find the volume of voids (η):

$$\eta = W_a \text{ x } \frac{\rho brick}{\rho water} \qquad (3)$$

$$= (0.1385 \text{ x } 1673)/\{1000\} = 0.231 \ \%$$

When porosity exceeds **30%** (which occurred in the 1% mix), the exponential decay in the formula predicts a sharp drop in f_c . The 1% mix had W_a = 18%, leading to a porosity of 27%. The subsequent drop to **25.97 MPa** validates the Ryshkewitch prediction that strength degrades exponentially once a critical porosity threshold is crossed.4.5

4.5 Abram's Law Validation (W/C Ratio)

The **Abram's Law** defines the relationship between strength and the Water-Cement (w/c) ratio:

$$f_c = K_1/K_2^{w/c} \qquad (4)$$

Given our w/c = 0.50 and K_1, K_2 for OPC 53 Grade:

- Theoretical Strength = 30 - 35 MPa.

Experimental results for the 0.75% mix (**35.47 MPa**) fall precisely within the theoretical range predicted by Abram's Law for a 0.50 ratio. This proves the 24-hour soaking of the rice husk was successful; had the husks not been soaked, the effective w/c ratio would have dropped, leading to honeycombing and strength failure.

5.CONCLUSIONS

This experimental investigation into rice-husk-integrated cement bricks confirms their viability as a high-performance, sustainable masonry solution. The key findings are:

- **Optimal Performance:** A 0.75% rice husk replacement is the optimal threshold, achieving a peak 28-day compressive strength of 35.47N/mm^2- a 24% improvement over control samples.
- **Structural Reinforcement:** Pre-saturated husks function as micro-fiber reinforcement rather than mere filler, enhancing load-bearing capacity and crack resistance through a unique bridging effect.
- **Weight Reduction:** The "Eco-Bricks" boast a 16% reduction in dead weight (1673 kg/m^3), offering significant structural and foundation cost savings.
- **Durability & Hydration:** At the optimal 0.75% mix, water absorption remains low (13.85%), meeting IS 1077:1992 standards. A 24-hour pre-soaking protocol is essential, ensuring a stable 0.50 water-cement ratio and proper hydration kinetics.
- **Sustainability:** By repurposing agricultural waste, this method reduces reliance on natural river sand, transforming agro-waste into a value-added, eco-friendly building material.

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