



Performance of Solid Masonry Blocks Incorporating Rice Husk Ash Produced Under Open and Controlled Burning Conditions

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Abstract: The construction sector is responsible for a significant share of global CO₂ emissions, primarily from Portland cement production. Rice husk ash (RHA), an agro-industrial by-product rich in amorphous silica, offers a promising pozzolanic substitute for cement. This study evaluates the mechanical and durability performance of solid masonry blocks (215 mm × 105 mm × 65 mm) incorporating 10% RHA as a partial cement replacement, with RHA produced by open-air burning and controlled furnace calcination at 350°C, 650°C, and 800°C. All ash was ground and sieved to below 75 µm. Blocks were cured by the sprinkler method for 7 and 28 days, then tested for compressive strength (ASTM C129), water absorption (ASTM C642), and density. The 650°C-calcined RHA blocks achieved the highest 28-day compressive strength of 12.62 MPa, surpassing the plain cement control (11.24 MPa), while still meeting acceptable water absorption limits (13.35% vs. the 20% threshold). Open-burned RHA blocks performed worst due to incomplete combustion and elevated residual carbon. These results confirm that 650°C is the optimal calcination temperature for RHA intended for masonry block production, supporting its use as an eco-friendly, cost-effective partial cement replacement.

Index Terms: Calcination temperature, Compressive strength, Pozzolanic activity, Rice husk ash, Solid masonry blocks, Sustainable construction, Water absorption

1 INTRODUCTION

Portland cement production accounts for roughly 7% of global greenhouse gas emissions [1]. At the same time, the disposal of agricultural residues such as rice husk a by-product of rice milling creates significant environmental problems, as the material is commonly dumped or openly burned, releasing smoke and particulate matter [2]. Harnessing rice husk ash (RHA) as a supplementary cementitious material addresses both issues simultaneously: it reduces the cement demand and valorizes an otherwise wasted resource.

RHA derives its value from its high silica (SiO₂) content, which typically ranges from 82% to 94% depending on the combustion method and temperature [3]–[8]. When properly calcined, the silica remains in an amorphous phase that is highly reactive with calcium hydroxide (Ca(OH)₂) released during cement hydration a phenomenon known as the pozzolanic reaction. This secondary reaction produces additional calcium silicate hydrate (C-S-H) gel, the primary binder phase in cement systems, thereby densifying the microstructure and enhancing both strength and durability.

A growing body of literature has confirmed the effectiveness of RHA in concrete and mortar [3]–[10]; however, far fewer studies have examined its behavior in solid masonry blocks, where the mix proportions, compaction method, and curing regime differ meaningfully from cast concrete. Furthermore, the effect of varying calcination temperature on block performance has not been thoroughly compared within a single

experimental programme. The present study addresses this gap by producing RHA under four distinct conditions open-air burning, 350°C, 650°C, and 800°C furnace calcination and evaluating the resulting blocks against a plain cement control.

The specific objectives are to (i) compare the compressive strength of RHA-incorporated blocks at 7 and 28 days; (ii) assess water absorption relative to the ASTM C642 limit; (iii) measure bulk density; and (iv) identify the calcination temperature that yields the best overall performance for sustainable masonry construction.

2 LITERATURE REVIEW

The chemical composition of RHA is highly sensitive to combustion temperature. Studies consistently report SiO₂ content between 82% and 94%, with alumina (Al₂O₃) and iron oxide (Fe₂O₃) each below 2% (Table 1) [3]–[8]. The pozzolanic reactivity of RHA is maximized when silica is retained in an amorphous (non-crystalline) state. Below approximately 500°C, incomplete combustion leaves excessive residual carbon that dilutes the silica and impedes hydration. Above 700°C, the amorphous silica progressively crystallizes into quartz or cristobalite, which is essentially non-reactive with Ca(OH)₂ [4], [6].

Table 1. Optimal RHA Calcination Temperature and Silica Content from Key Literature Sources: [3]–[8]

Study	Optimal Burn Temp.	Silica Content (%)	Best RHA Replacement (%)
Arivalagan [3]	500–700°C	85–92	10–15
Kaleli et al. [4]	600–650°C	89–93	10–15
Mayooran et al. [5]	550–650°C	82–88	15
Xu et al. [6]	550–600°C	90–94	10–15
Alieu et al. [7]	550–650°C	88–93	15–20
Khan et al. [8]	600–650°C	90–92	10–15
This Study	650°C (optimal)	—	10

As summarised in Table 1, the optimal calcination temperature reported across key studies consistently falls within the 550–700°C range, with silica content peaking between 88% and 94%, further validating the temperature range selected in the present study.

A consistent finding across studies is that a 10–15% cement replacement with well-processed RHA is optimal for masonry blocks and sandcrete [9], [10]. Gunawardhana and Gamage [11] showed that RHA particles finer than 75 µm produced the best pozzolanic response in sand-cement blocks, with strength gains over the control at the 10% replacement level. Beyond 15–20%, dilution of the binder phase progressively reduces strength [9]–[11]. The present study adopts a 10% replacement level, consistent with this evidence base.

3 MATERIALS AND METHODS

This section describes the raw materials used, the procedures adopted for RHA preparation under open and controlled calcination conditions, the mix proportions and fabrication method for solid masonry blocks, and the standardised testing protocols applied to evaluate their mechanical and durability performance.

3.1 Materials

Ordinary Portland Cement (OPC) grade 43 conforming to standard requirements was used throughout. Fine aggregate was clean river sand with a maximum particle size of 2.5 mm. Rice husks were

sourced from a local rice mill in Sri Lanka and cleaned to remove stones, broken grains, and organic debris before combustion.

3.2 RHA Preparation

Four RHA batches were produced. In the open-burn method, dry rice husks were burned outdoors under uncontrolled atmospheric conditions until fully converted to ash, yielding a dark grey to black product. For the controlled batches, the open-burned ash was re-heated in a muffle furnace at three target temperatures 350°C (25 min), 650°C (47 min), and 800°C (58 min) held in pozzolana crucibles, then cooled inside the furnace. All four ash types were subsequently milled for 40 minutes in a laboratory fast-mill (500 g capacity) and sieved through a 75 µm vibrating sieve, retaining only the sub-75 µm fraction for use in the mix. This particle-size cut-off is consistent with the fineness requirement identified by Gunawardhana and Gamage [11].

3.3 Block Fabrication and Mix Proportions

A cement-to-sand mass ratio of 1:6 with a water-to-cementitious-material ratio of 0.50 was adopted, consistent with ASTM C305 guidance and with the higher water demand of fine RHA particles. Ten percent of the cement mass was replaced by RHA in the experimental batches; the control batch contained no RHA. Calculated batch quantities per block were: cement 271.67 g, RHA 30.19 g (experimental) or cement 301.86 g (control), sand 2,012.4 g, and water 151.2 g. Cement and RHA were first dry-mixed, then sand was added and blended, after which water was introduced gradually to produce a consistent, workable mortar.

The mortar was cast into wooden moulds measuring 215 mm × 105 mm × 65 mm (volume 0.001467 m³), filled in three layers each tamped 25 times with a rod to remove entrapped air. Demoulding was performed after 24 hours at room temperature. A total of ten blocks per mix type were produced five for 7-day testing and five for 28-day testing.

3.4 Curing

Blocks were cured by the sprinkler method clean water applied twice daily for either 7 or 28 days, consistent with ASTM C192. This approach replicates common site practice in tropical climates and was adopted from the reference study by Mayooraan et al. [5].

3.5 Testing

Compressive strength was measured using a servo-controlled compression-testing machine after 7 and 28 days of curing (ASTM C129). Strength was computed as the failure load divided by the nominal plan area of the block (215 mm × 105 mm = 22,575 mm²). Water absorption was determined per ASTM C642: specimens were oven-dried at 100–105°C for 24 h, weighed (dry weight W_1), fully immersed in water at $27 \pm 2^\circ\text{C}$ for 24 h, and reweighed (wet weight W_2). Water absorption (%) = $[(W_2 - W_1) / W_1] \times 100$. Density was computed from the dry mass and measured block dimensions.

4 RESULTS AND DISCUSSION

This section presents and interprets the compressive strength, water absorption, and density results obtained from solid masonry blocks incorporating 10% RHA produced under four distinct calcination conditions, evaluated at 7 and 28 days of curing.

4.1 Compressive Strength at 7 Days

As presented in Table 2, Table 2 presents the 7-day compressive strength results. The control blocks achieved an average of 8.86 MPa, which serves as the baseline. All blocks with RHA calcined at or above 350°C exceeded this baseline, whereas the open-burned RHA blocks were below it at 8.29 MPa.

Table 2. 7-Day Compressive Strength Results

Sample Type	Sample No.	Weight (g)	Max. Load (kN)	Avg. Compressive Strength (MPa)
Control (no RHA)	CS1, CS2	2.656 – 2.668	199.8 – 200.1	8.86
Open-Burned RHA	OB1, OB2	2.662 – 2.697	185.5 – 188.7	8.29
350°C RHA	350-1, 350-2	2.655 – 2.686	191.9 – 194.2	8.55
650°C RHA	650-1, 650-2	2.708 – 2.715	220.8 – 223.7	9.85
800°C RHA	800-1, 800-2	2.715 – 2.731	215.6 – 216.2	9.57

The open-burned sample's inferior performance is attributed to high residual carbon content resulting from uncontrolled, incomplete combustion. Excess carbon dilutes the reactive silica phase and can physically disrupt the paste matrix [4], [5]. Blocks with 350°C RHA marginally improved to 8.55 MPa as partial thermal activation began to reduce the carbon fraction without yet crystallizing the silica. The most pronounced improvement appeared at 650°C (9.85 MPa), consistent with the broad literature consensus that the 550–650°C range maximises amorphous silica content and pozzolanic activity [3]–[8]. The 800°C blocks (9.57 MPa) were slightly weaker than the 650°C group, consistent with the onset of silica crystallization that reduces reactivity beyond this temperature [4], [6]. All samples exceeded the 7 MPa minimum for non-load-bearing masonry units specified in ASTM C129.

4.2 Compressive Strength at 28 Days

The 28-day results presented in Table 3 reinforce and amplify the 7-day trends.. The 650°C RHA blocks reached an average of 12.62 MPa 12.3% higher than the control (11.24 MPa) confirming that continued pozzolanic reaction between the amorphous silica and $\text{Ca}(\text{OH})_2$ contributes additional C-S-H binding over the curing period. This outcome aligns with findings by Alieu et al. [7] and Khan et al. [8], who reported 10–15% strength gains at 28–90 days for properly calcined RHA. Open-burned RHA blocks remained the weakest at 8.68 MPa, falling below the control. The 800°C group (11.77 MPa) remained competitive with the control but could not match the 650°C group, suggesting that crystalline silica formed at higher temperatures limits long-term pozzolanic contribution. The strength gain from 7 to 28 days was most pronounced for the 650°C blocks (28.2% increase), further evidence of an active, ongoing pozzolanic reaction.

Table 3. 28-Day Compressive Strength Results

Sample Type	Sample No.	Weight (g)	Max. Load (kN)	Avg. Compressive Strength (MPa)
Control (no RHA)	CS1, CS2	2.688 – 2.726	251.6 – 256.0	11.24
Open-Burned RHA	OB1, OB2	2.677 – 2.689	194.8 – 196.9	8.68
350°C RHA	350-1, 350-2	2.672 – 2.693	204.4 – 218.3	9.34
650°C RHA	650-1, 650-2	2.736 – 2.758	276.9 – 292.9	12.62
800°C RHA	800-1, 800-2	2.623 – 2.775	262.9 – 268.4	11.77

As shown in Fig. 1, the 650°C-calcined RHA blocks achieved the highest 28-day compressive strength (12.62 MPa), exceeding the control by approximately 12.3%, consistent with the pozzolanic activity range reported by Alieu et al. [7] and Khan et al. [8].

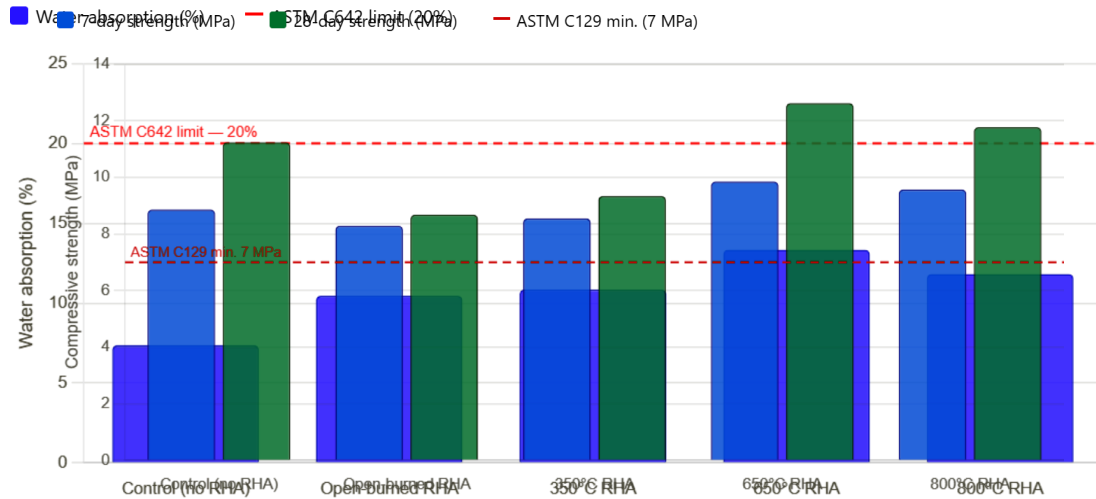


Fig. 1. Compressive strength of solid masonry blocks incorporating 10% RHA produced under open-burning and controlled calcination conditions (350°C, 650°C, and 800°C) at 7 days and 28 days of curing. The dashed line indicates the ASTM C129 minimum compressive strength of 7 MPa for non-load-bearing masonry units.

4.3 Water Absorption

Table 4 reports the water absorption and density results for all mix types. The control blocks showed the lowest absorption at 7.37%, reflecting a dense, low-porosity matrix formed by normal cement hydration alone. All RHA-containing blocks absorbed more water, a pattern attributed to the characteristically high specific surface area of finely ground RHA particles, which creates additional capillary pore pathways [11]. Absorption increased progressively from open-burned (10.46%) through 350°C (10.85%) to 650°C (13.35%), after which it declined to 11.83% for the 800°C group. The higher absorption of the 650°C blocks is a consequence of the very fine, porous ash particles providing more surface area and pore volume; however, this must be balanced against the superior strength achieved. Critically, all five mix types remained well below the 20% ASTM C642 limit, confirming acceptable durability for construction use.

Table 4. Water Absorption and Density Results

Sample Type	Dry Wt. W_1 (g)	Wet Wt. W_2 (g)	Water Absorption (%)	ASTM C642 Limit (%)	Density (g/cm^3)
Control	2.686	2.884	7.37	< 20	0.00183
Open-Burned RHA	2.608	2.881	10.46	< 20	0.00177
350°C RHA	2.653	2.941	10.85	< 20	0.00180
650°C RHA	2.613	2.962	13.35	< 20	0.00178
800°C RHA	2.487	2.821	11.83	< 20	0.00169

As illustrated in Fig. 2, water absorption increased with calcination temperature up to 650°C (13.35%), attributed to the higher specific surface area of amorphous RHA particles [11]; however, all block types remained well below the ASTM C642 threshold of 20%, confirming acceptable durability for masonry construction applications.

Fig. 2. Water absorption (%) of solid masonry blocks incorporating 10% RHA produced under different calcination conditions,

measured in accordance with ASTM C642. The dashed line indicates the 20% maximum permissible water absorption limit. All mix types remained within the acceptable durability threshold.

4.4 Density

The 650°C RHA blocks exhibited the highest average 28-day density (1.872 g/cm³), slightly above the control (1.844 g/cm³), indicating that the pozzolanic reaction products densified the block matrix. The open-burned and 350°C groups were comparable to the control, while the 800°C group showed slightly lower and more variable density, suggesting microstructural irregularities possibly introduced by partial silica crystallization and localized cracking. These density trends are broadly consistent with the compressive strength rankings, reinforcing the view that 650°C calcination produces the most structurally coherent RHA-block composite.

4.5 Mechanism and Synthesis

The superior performance of 650°C RHA can be explained by the interplay of three factors. First, calcination at this temperature eliminates virtually all residual carbon (loss on ignition typically < 5%) [4], [6], maximizing the reactive silica fraction. Second, the amorphous silica structure is preserved unlike the crystalline forms that appear above 700°C allowing efficient reaction with Ca(OH)₂ to form secondary C-S-H. Third, the milling and 75 µm sieving step ensures fine, high-surface-area particles that accelerate the pozzolanic reaction. Open-burning fails to deliver any of these conditions consistently: temperature fluctuations leave unburned carbon and partially crystallized domains, resulting in low and variable pozzolanic activity.

The trade-off between strength and water absorption is an important practical consideration. Although 650°C RHA blocks absorb more water than the control, their compressive strength is higher, and their water absorption remains within accepted limits. Future mix optimization for example, incorporating a small dosage of superplasticizer to reduce the water-to-cementitious ratio could further reduce porosity without sacrificing workability.

5 CONCLUSIONS

This study demonstrated that replacing 10% of Portland cement with RHA calcined at 650°C produces solid masonry blocks with a 28-day compressive strength of 12.62 MPa approximately 12% above the plain cement control while maintaining water absorption within the ASTM C642 limit. Key conclusions are:

- 1) Calcination temperature is the decisive variable: 650°C maximises amorphous silica content and pozzolanic reactivity, outperforming both lower-temperature (350°C) and higher-temperature (800°C) treatments.
- 2) Open-air burning is inadequate for masonry applications: uncontrolled temperatures leave residual carbon that suppresses pozzolanic activity and reduces block strength below the control level.
- 3) All RHA blocks regardless of calcination method satisfy the ASTM C129 minimum 7-day strength of 7 MPa and the ASTM C642 water absorption limit of 20%, confirming structural suitability.
- 4) The approach reduces Portland cement consumption by 10%, lowering associated CO₂ emissions and simultaneously diverting rice-milling waste from open burning or landfill.
- 5) Future work should explore additional curing periods (56 and 90 days), a range of RHA replacement levels (5–20%), and real-world environmental exposure to fully characterize long-term durability.

These findings support the adoption of 650°C-calcined RHA as a technically viable and

environmentally beneficial cement supplementary material, particularly in South and Southeast Asian countries where rice agriculture and construction activity intersect.

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