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Co-utilisation of recycled ceramic waste and sawdust in refractory bricks: thermal–mechanical trade-offs and resource recovery potential

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ABSTRACT

The growing demand for low-cost and eco-friendly refractory materials has generated interest in locally available waste materials as alternatives to conventional refractories. This study investigates recycled ceramic waste and sawdust in refractory bricks, assessing their trade-off between mechanical strength and thermal insulation. Five formulations were prepared by maintaining clay at 35 wt% and varying the ceramic waste-to-sawdust ratio before firing at 1100 °C. The bricks were evaluated for water absorption, compressive strength, thermal conductivity and dimensional stability at 1100 °C. Water absorption increased from 7.8% to 22.4% as sawdust increased from 0 to 20 wt%, while compressive strength and thermal conductivity decreased from 18.6 to 6.7 MPa and 0.92 to 0.38 W/m·K, respectively. These trends are consistent with the proposed pore-forming effect of sawdust during firing. The formulation containing 55% ceramic waste, 35% clay and 10% sawdust provided the most balanced performance, with 12.8 MPa compressive strength, 0.63 W/m·K thermal conductivity, 13.9% water absorption and no visible deformation or cracking at 1100 °C. The findings demonstrate a thermal–mechanical performance envelope from redistributing a fixed 65% waste-derived fraction between ceramic waste and sawdust, indicating resource-recovery potential while recognising the need for further environmental and service-level assessment.

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KEYWORDS
Refractory bricks; ceramic waste recycling; sawdust; waste valorisation

1. Introduction

Refractory bricks are important engineering materials for protective linings in high temperature systems such as furnaces, kilns, incinerators and boilers. Their successful application relies on finding an adequate balance between mechanical integrity and thermal insulation: sufficient strength to withstand handling, thermal stresses and service loads, and low thermal conductivity to reduce heat losses during operation (Popescu, Abagiu, and Comănescu 2021; Seifert, Dittrich, and Bach 2021). Traditional refractories are usually made from high-grade fireclay, alumina and other mineral resources which are often expensive, energy-intensive to process, or not locally available in many developing economies (Djamaluddin et al. 2021). Consequently, industries such as small-scale foundries, bakeries, and agro-processing facilities often face higher costs associated with imported refractory materials.

The increasing interest in sustainable materials engineering has promoted the recovery of industrial and biomass wastes as alternative resources for value-added applications. Refractory materials derived from waste provide an attractive route to decrease dependence on virgin raw materials, while addressing growing waste-management challenges. Ceramic waste is a major by-product of construction, demolition, and ceramic manufacturing activities. In many developing countries including Uganda, the amount of ceramic waste generated is significant but underutilized. Waste from discarded sanitary ware together with timber-processing residues such as sawdust is often landfilled or indiscriminately dumped despite its potential for value-added applications in ceramic-based materials (Castellani et al. 2025; Debrah, Teye, and Dinis 2022; Mugambe et al. 2022). Several studies have shown the possibility of valorising ceramic waste in

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construction materials, including recycled aggregate in concrete, highlighting the potential of ceramic waste beyond traditional disposal options (Alshahwany, Abdulkareem, and Shlla 2024).

Sawdust, for instance, is an underutilized biomass residue in many developing regions that often leads to environmental concerns due to poor management practices, although it has potential for value-added applications (Udokpoh and Nnaji 2023).

Recycled ceramic waste has demonstrated great potential as a refractory raw material due to its silica-alumina composition, thermal stability and compatibility with the fired ceramic systems. Recent studies have shown that ceramic residues from industrial and construction sources can be transformed into refractory products with acceptable mechanical strength and phase stability (Khater et al. 2024a, 2024b; Seifert, Dittrich, and Bach 2021; Zoqi and Doosti 2024). The performance of the ceramic-waste-derived refractories, however, is strongly dependent on waste composition, particle characteristics and firing conditions, indicating that optimisation of processing and formulation is still required for different waste sources.

In contrast, biomass-derived wastes such as sawdust primarily influence ceramic products through their pore-forming behaviour. The internal pore networks formed by the combustion of organic matter during firing can reduce thermal conductivity and improve insulating performance.

However, the resulting increase in porosity generally reduces mechanical strength by decreasing the effective load-bearing area and introducing stress concentration sites. Previous investigations using agricultural and wood-derived additives have consistently reported this inverse relationship between insulation and strength (Arslan et al. 2021; Djamaluddin et al. 2021; Moujoud et al. 2023; Pitak et al. 2022; Zharmenov et al. 2022). Arslan et al. (2021) observed significant reductions in thermal conductivity when waste micro-cellulose fibres were incorporated into fired clay bricks, while Zharmenov et al. (2022) demonstrated the potential of renewable silica-containing wastes for producing insulating refractory materials. Pitak et al. (2022) further highlighted that firing temperature influences pore development and, consequently, the thermal and mechanical response of waste-modified ceramic materials.

Although individual waste materials have been extensively investigated, hybrid waste systems have also been reported in fired-clay and other ceramic products (Atan, Sutcu, and Cam 2021; Lachheb, Youssef, and Younsi 2023; Salleh et al. 2021). The remaining opportunity addressed here is therefore not the simple combination of two wastes, but the deliberate use of two constituents with contrasting engineering functions within a controlled compositional series. A material intended for high-temperature applications must satisfy multiple requirements simultaneously; therefore, evaluating strength or thermal conductivity independently may provide limited guidance for material selection. A formulation that maximises insulation may become unsuitable because of inadequate structural integrity, whereas a denser formulation may provide greater strength at the expense of thermal insulation.

The present study consequently treats the ceramic waste–sawdust ratio as a compositional design variable within a fixed 35% clay and 65% total waste framework. Ceramic waste serves primarily as the mineral, load-bearing fraction, whereas sawdust is introduced as a sacrificial pore-forming constituent. The resulting series does not permit independent estimation of the main effects or statistical interaction between ceramic waste and sawdust because their proportions change reciprocally. Rather, it enables the experimentally observed performance envelope along this specific substitution path to be established. This distinction is important when interpreting the contribution of the study and avoids attributing interaction effects that were not isolated experimentally.

This knowledge gap is therefore framed around composition–performance mapping rather than formal statistical optimisation. Understanding how the balance between functionally diverse waste constituents shifts mechanical strength, water absorption and thermal conductivity provides a practical basis for selecting a composition for a stated engineering priority. Such an approach is particularly relevant where locally available waste streams are abundant but conventional high-temperature materials are costly or difficult to procure.

The present work investigates the simultaneous use of recycled ceramic waste and sawdust in refractory bricks. Rather than claiming that hybrid waste incorporation itself is novel, the study examines how a fixed total waste fraction can be redistributed between a relatively dense mineral waste and a pore-forming biomass residue to establish an experimentally observed thermal–mechanical performance envelope. Five formulations were prepared with constant clay content and varying ceramic waste-to-sawdust ratios, and

the resulting bricks were evaluated for water absorption, compressive strength, thermal conductivity and dimensional stability at 1100 °C. The study therefore focuses on the composition–performance relationship along the investigated substitution path rather than on independent constituent effects or formal multi-objective optimisation.

By establishing this composition–performance relationship, the study provides a practical basis for selecting formulations according to competing structural and insulation requirements. The contribution is thus the experimentally defined performance envelope and the associated trade-off interpretation, rather than a claim of universal optimisation or statistical interaction between the two waste constituents.

2. Materials and methods

2.1. Materials

Clay, recycled ceramic waste, and sawdust used in the refractory brick formulations were sourced locally from Mbarara City, Uganda, while water was used as the mixing medium.

The materials were selected according to their complementary function in the refractory matrix. Recycled ceramic waste was incorporated as a thermally stable mineral component expected to contribute to structural integrity.

Sawdust was selected as a pore-forming additive to modify the thermal behaviour of the after firing. Clay was maintained as the binding phase to provide workability and cohesion during shaping. The proportions of recycled ceramic waste and sawdust were then varied reciprocally while keeping the total waste-derived fraction constant, allowing the resulting composition–performance trade-off to be examined. Because the two waste constituents were changed simultaneously in opposite directions, their individual effects and statistical interaction were not separately identifiable from this design.

Clay, obtained from a natural deposit, served as the primary binder, providing plasticity during moulding and cohesion throughout drying and firing. Recycled ceramic waste was obtained from discarded ceramic products.

Sawdust from the local sawmills was collected and incorporated as a potential pore-forming additive. Its high loss on ignition indicated that most of its mass was combustible. During firing, combustion of the organic fraction is expected to leave voids within the ceramic matrix; however, pore structure was not directly measured in the present study, so this mechanism is treated as a proposed interpretation supported by the measured property trends and previous literature.

Prior to mixing, clay was air-dried, crushed, milled, and sieved to pass a 2 mm sieve; ceramic waste was cleaned, jaw-crushed, milled, and similarly sieved to pass a 2 mm sieve; and sawdust was air-dried and sieved to remove coarse fragments retained on a 2 mm sieve.

Water was added only during mixing, in quantities controlled by the moisture content of the raw materials, to achieve a workable plastic consistency while minimising excessive drying shrinkage.

2.2. Raw material characterisation

Each raw material was tested before brick production to assess its suitability and to help interpret the performance results of the bricks produced.

The particle size distribution of the clay and recycled ceramic waste was determined by sieving according to ASTM D422, and the uniformity (C_u) and curvature (C_c) coefficients were calculated to evaluate the gradation. The moisture content of the sawdust and recycled ceramic waste was determined by oven-drying to constant mass at 105 ± 5 °C as per ASTM D2216. The ash content of the sawdust was determined by controlled combustion in a muffle furnace according to ASTM D1102 and the loss on ignition (LOI) was measured by ASTM D7348 to quantify the part of combustible organic material that can form pores during firing. The plasticity of the clay was assessed through the Atterberg limits (liquid limit, plastic limit, and plasticity index) following ASTM D4318, using the Casagrande method, to evaluate its workability and binding suitability. The elemental oxide composition of the clay and recycled ceramic waste was determined by X-ray fluorescence (XRF) spectrometry following ASTM E1621, to establish their silica, alumina, and flux-oxide content and its implications for refractory performance.

2.3. Mix design and batching

Five formulations (M1–M5) were developed, maintaining the clay content at 35% by dry mass and the combined waste-derived content at 65%, while varying the proportions of recycled ceramic waste and sawdust. This compositional series was designed to map the experimentally observed transition from ceramic-waste-dominated to sawdust-enriched formulations and the associated thermal–mechanical trade-off. Because the two waste fractions were varied reciprocally, the design was not intended to estimate their independent main effects or interaction effects.

The proportions of recycled ceramic waste and sawdust were varied inversely in 5% increments of sawdust content (0, 5, 10, 15 and 20%) which corresponded to a decrease in ceramic waste content from 65 to 45% (Table 1).

Maintaining a constant clay fraction ensured that observed variations in brick performance were primarily associated with changes in the ceramic waste–sawdust ratio rather than differences in binder content. Batch quantities were calculated using a fixed 10 kg dry basis per mix according to:
Formula 1:

$$\textit{Material weight}\ (kg) \;=\; (\textit{Material proportion}\ (\%)\ /\ 100) \;\times\; \textit{Total batch weight}\ (kg)$$

2.4. Specimen fabrication

For each mix the dry ingredients were mixed until a uniform consistency was achieved and water was added slowly and kneaded to a cohesive, workable paste. Bricks of size 225 × 102 × 64 mm were cast in oiled steel moulds, compacted in layers to reduce entrapped air, struck off level and demoulded after initial set. The green bricks were air-dried at room temperature for 24–48 hours followed by oven-drying at 105 °C to constant mass to remove residual free moisture before firing.

Firing was performed in a high-temperature furnace at a controlled heating rate of 5 °C/min up to the sintering temperature of 1100 °C, held at peak temperature for 2–4 hours to promote sintering and densification, in line with firing regimes commonly adopted for waste-modified fired-clay products (Lachheb, Youssef, and Younsi 2023; Pitak et al. 2022). The same single sintering temperature was used for M1–M5, so that variations in properties could be attributed to mix composition rather than differences in firing. Fired refractory bricks were cooled slowly in the furnace to prevent thermal shock, then visually inspected, labelled, and dimensionally verified before testing.

2.5. Brick performance testing

Water absorption was determined by immersion of oven-dried specimens followed by mass comparison, following ASTM C20, to assess water uptake associated with the fired matrix. Compressive strength was determined using a compression testing machine at a controlled loading rate to failure, following ASTM C133, to evaluate load-bearing capacity. Thermal conductivity was measured using the guarded hot-plate method, following ASTM C177, to quantify steady-state heat transfer through each brick composition. Dimensional stability at 1100 °C was assessed by visual evaluation of deformation, cracking and surface changes after the firing treatment; this was used as a comparative observation rather than as a standardised refractoriness classification. Three replicate specimens were tested per mix for each property, and the reported values are the arithmetic mean of the three replicates. Given the limited replication and the compositional nature of the design, the analysis was intentionally descriptive and no inferential statistical model was fitted.

Table 1. Mix proportions and batch composition (10 kg dry batch basis).

Mix	Ceramic waste (%)	Clay (%)	Sawdust (%)	Waste-derived content (%)
M1	65	35	0	65
M2	60	35	5	65
M3	55	35	10	65
M4	50	35	15	65
M5	45	35	20	65

2.6. Data analysis

Descriptive statistics were computed from the three replicate specimens per mix. Standard deviations were calculated from the existing triplicate observations and are reported alongside the means in Table 4. Coefficients of variation across the reported properties and mixes ranged from 1.1% to 5.3%, indicating relatively low variability among replicates. Given the limited replication and the reciprocal compositional design, the analysis remains descriptive and no inferential statistical model was fitted.

3. Results

3.1. Raw material characterisation

The physical and chemical properties of the constituent raw materials are summarised in Tables 2 and 3. The recycled ceramic waste exhibited a moisture content of 0.39%, compared with 12.54% for the sawdust. The sawdust also recorded an ash content of 3.31% and a loss on ignition of 96.76%, indicating a high proportion of combustible organic matter. The clay exhibited a liquid limit of 30.30%, a plastic limit of 25.75%, and a plasticity index of 4.55%, indicating adequate plasticity for moulding. Particle size analysis yielded coefficients of uniformity (C_u) and curvature (C_c) of 3.94 and 1.00 for the recycled ceramic waste, and 6.20 and 0.69 for the clay, respectively. XRF analysis (Table 3) showed that the recycled ceramic waste contained higher SiO_2 (67.80%) and lower Al_2O_3 (18.70%) and Fe_2O_3 (1.10%) than the clay (56.10%, 24.90%, and 5.80%, respectively). Both materials exhibited combined SiO_2 and Al_2O_3 contents exceeding 75%.

3.2. Effect of mix composition on brick performance

The performance of the refractory bricks is summarised in Table 4. Water absorption increased progressively with increasing sawdust content, from 7.8% for M1 (0% sawdust) to 22.4% for M5 (20% sawdust)

Table 2. Raw material characterisation summary.

Property	Sawdust	Recycled ceramic waste	Clay
Moisture content (%)	12.54	0.39	–
Ash content (%)	3.31	–	–
Loss on ignition (%)	96.76	0.50	3.39
Plasticity index (%)	–	–	4.55 (LL 30.30, PL 25.75)
Cu/Cc (PSD)	–	3.94/1.00	6.2/0.69

Table 3. Chemical composition of clay and recycled ceramic waste (XRF, wt.%).

Oxide	Clay (%)	Recycled ceramic waste (%)
SiO2	56.10	67.80
Al2O3	24.90	18.70
Fe2O3	5.80	1.10
CaO	2.60	4.10
MgO	1.70	1.00
K2O	3.10	3.20
Na2O	1.10	2.80
TiO2	1.00	0.60
MnO	0.12	0.06
P2O5	0.18	0.14
Loss on Ignition (LOI)	3.39	0.50

Table 4. Thermal–mechanical performance of fired bricks by mix ($n = 3$, averaged; sintered at 1100 °C).

Mix	Water absorption (%)	Compressive Strength (MPa)	Thermal conductivity (W/m·K)	Dimensional stability at 1100 °C
M1	7.8 ± 0.2	18.6 ± 0.2	0.92 ± 0.02	No deformation/cracking
M2	10.6 ± 0.2	15.9 ± 0.2	0.78 ± 0.02	No deformation/cracking; slight surface texture change
M3	13.9 ± 0.2	12.8 ± 0.2	0.63 ± 0.02	No structural damage; minor surface roughening
M4	17.8 ± 0.3	9.6 ± 0.2	0.49 ± 0.02	Surface cracks; slight edge distortion
M5	22.4 ± 0.3	6.7 ± 0.2	0.38 ± 0.02	Significant cracking; moderate deformation

(Figure 1). Conversely, compressive strength decreased from 18.6 to 6.7 MPa, while thermal conductivity declined from 0.92 to 0.38 W/m·K (Figure 2). The corresponding variation in compressive strength and thermal conductivity across the five formulations is presented in Figure 3. Variability among the three replicates was low, with coefficients of variation of 1.1–5.3% across the reported properties, supporting the consistency of the observed trends.

Visual assessment after firing at 1100 °C revealed no structural deformation or cracking in M1–M3. Minor surface cracking accompanied by slight edge distortion appeared in M4, whereas M5 exhibited pronounced cracking and moderate deformation.

3.3. Most balanced formulation

Among the five formulations, M3 (55% ceramic waste, 35% clay, and 10% sawdust) provided the most balanced combination of the measured properties among the mixtures investigated. It exhibited a

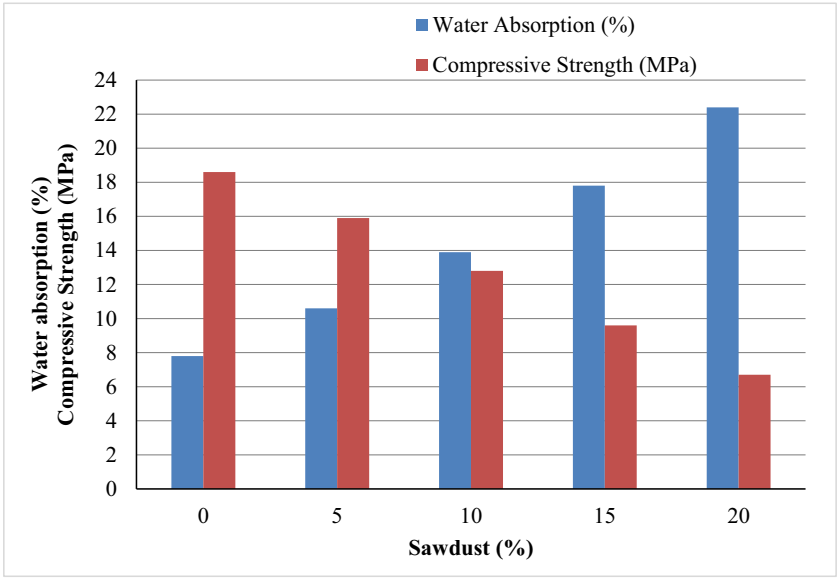


Figure 1. Water absorption and compressive strength of refractory bricks with varying sawdust content (M1–M5).

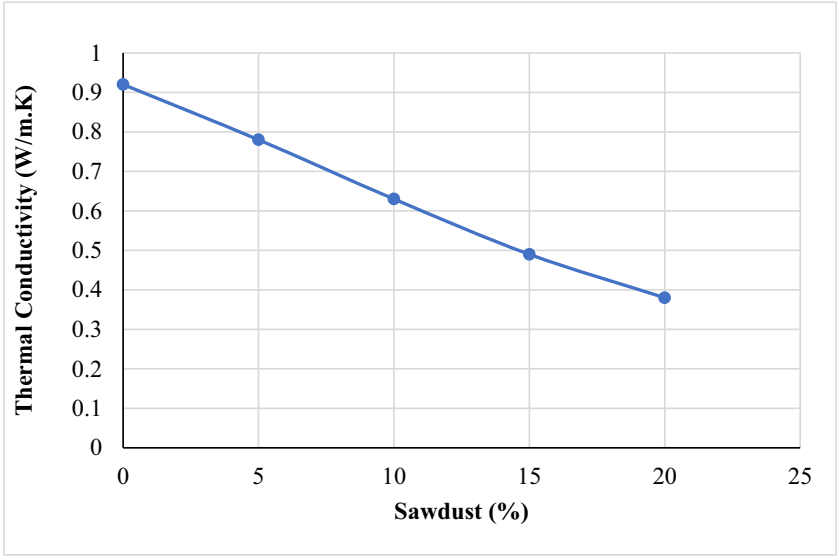


Figure 2. Thermal conductivity of refractory bricks with varying sawdust content (M1–M5).

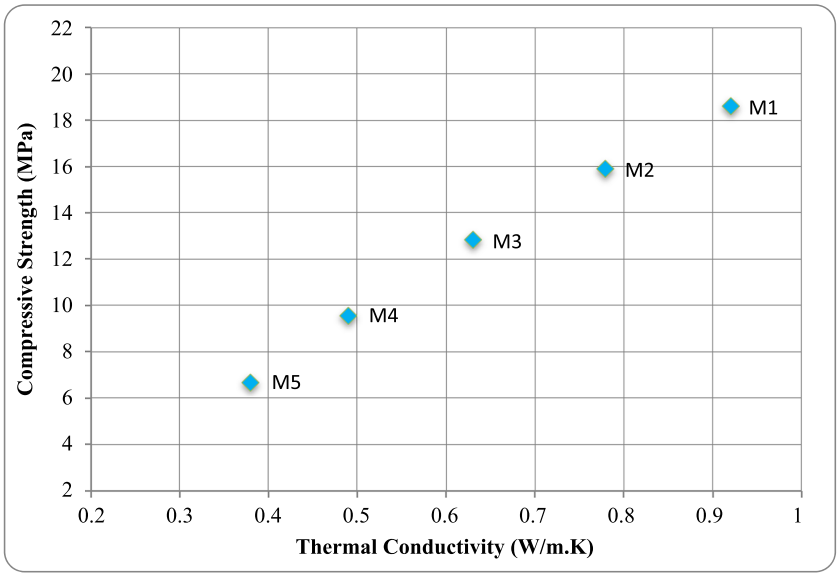


Figure 3. Compressive strength versus thermal conductivity for mix designs M1–M5.

compressive strength of 12.8 MPa, a thermal conductivity of 0.63 W/m·K and a water absorption of 13.9%, with no visible deformation or cracking following firing at 1100 °C. M3 was therefore selected for focused discussion as the most balanced formulation within the tested composition range. This designation is comparative and does not imply a formal global optimum or multi-objective statistical optimum.

4. Discussion

4.1. Raw material characterisation

The chemical composition of the raw materials provides a basis for interpreting the observed behaviour of the refractory bricks. Both the clay and the recycled ceramic waste exhibited combined SiO_2 and Al_2O_3 contents exceeding 75%, an oxide combination associated with silica–alumina ceramic systems. This is consistent with the high-temperature stability reported for ceramic-waste-derived materials by Khater et al. (2024a, 2024b). However, XRF characterises elemental oxide composition rather than the crystalline phases formed during firing; therefore, the present results cannot establish specific post-firing mineral phases.

The recycled ceramic waste also contained considerably less Fe_2O_3 than the clay. The lower Fe_2O_3 content may have contributed to the dimensional stability observed in the ceramic-waste-rich formulations, although this interpretation cannot be confirmed from XRF alone because phase evolution and liquid-phase formation were not characterised. In contrast, the high loss on ignition (96.76%) recorded for the sawdust confirms that it consisted predominantly of combustible organic matter, supporting its intended role as a sacrificial pore-forming constituent.

The physical characteristics of the raw materials also influenced their suitability for processing and may have contributed to the observed behaviour of the brick mixtures. The low moisture content of the recycled ceramic waste (0.39%) indicates that it contributed little inherent moisture during batching, whereas the higher moisture content of the sawdust (12.54%) was considered when controlling the mixing water. The clay exhibited a relatively low plasticity index of 4.55%, but was sufficiently workable for moulding when combined with the other constituents. The particle-size characteristics of the ceramic waste and clay also provided the basis for particle packing within the mixtures, although their direct contribution to the measured brick properties was not isolated in the present experimental design. The sawdust ash content of 3.31% further indicates that only a small fraction of the residue remained as inorganic ash after combustion, consistent with its primary role as a sacrificial pore-forming constituent.

4.2. Effect of mix composition on brick performance

The reductions in compressive strength and thermal conductivity observed with increasing sawdust content are directly demonstrated by the measured results. A plausible explanation is that combustion of the organic fraction of sawdust during firing leaves additional voids within the ceramic matrix, which can increase water uptake while reducing heat transfer and effective load-bearing area. However, because pore volume, pore connectivity and microstructure were not directly measured, pore formation should be regarded as the proposed mechanism rather than a directly verified observation (Figure 4). This interpretation is consistent with previous work; Alabduljabbar et al. (2021) reported that sawdust incorporation altered porosity, absorption and compressive strength in fired clay bricks and showed that firing conditions also affected the resulting properties.

The present results show a coupled reduction in thermal conductivity and compressive strength as sawdust content increased from 0 to 20 wt%, with thermal conductivity decreasing from 0.92 to 0.38 W/m·K and compressive strength from 18.6 to 6.7 MPa. Arslan et al. (2021) similarly reported reduced thermal conductivity and strength with increasing pore-forming waste, while Cultrone et al. (2020) demonstrated that both additive content and firing temperature influence pore structure and the physical properties of fired clay bricks. Pitak et al. (2022) likewise showed that firing temperature can modify pore development and associated thermal and mechanical behaviour. These studies support the interpretation that both composition and firing conditions can influence the observed trade-off, although the present study deliberately held firing temperature constant at 1100 °C so that composition was the principal experimental variable.

The present study extends earlier hybrid-waste investigations by using a fixed total waste fraction and systematically moving along a ceramic-waste-to-sawdust substitution path. This establishes an experimentally observed thermal–mechanical performance envelope, but it should not be interpreted as demonstrating independent constituent effects or a statistical interaction. Formal multi-objective optimisation approaches, such as the response-surface and desirability-based framework used by Raut et al. (2025), can identify mathematical optima when sufficient experimental designs and response models are available. The present five-mixture design was not constructed for that purpose; consequently, M3 is reported as the most balanced formulation among the tested mixtures rather than as a formal mathematical optimum.

The dimensional-stability observations in Section 3.2 (no visible deformation or cracking in M1–M3 and progressively greater cracking/deformation in M4–M5) indicate a composition-dependent change in resistance to the 1100 °C firing treatment. They should not be interpreted as a standardised refractoriness measurement. The lower thermal conductivity observed in the higher-sawdust mixes indicates potential for lower steady-state heat transfer at the material level. However, room-temperature thermal conductivity alone does not establish heat-loss performance of a refractory lining during actual service. As demonstrated in other thermally oriented composite studies, service-level thermal behaviour may require heat-transfer analysis or exposure testing; such assessments were outside the scope of the present work (Adamu et al. 2025).

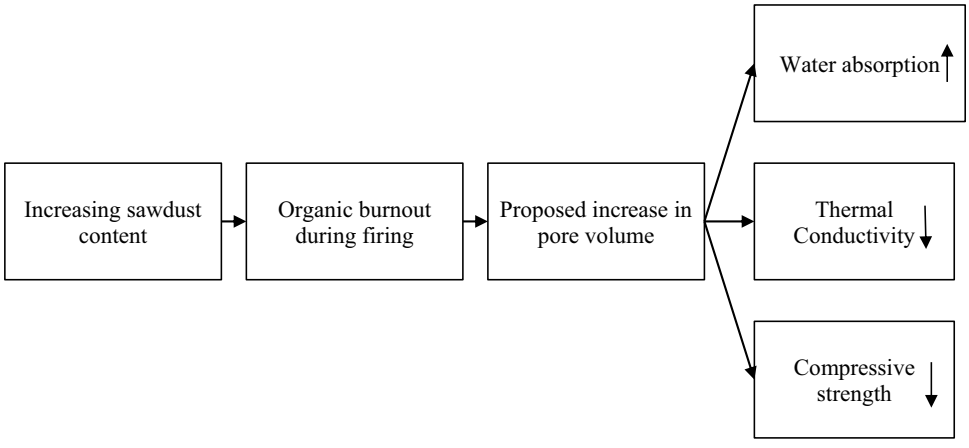


Figure 4. Conceptual relationship between increasing sawdust content, proposed pore formation and measured performance trends.

4.3. Most balanced formulation

M3 was selected as the most balanced formulation because it avoided the extreme performance observed at either end of the composition range. M1 and M2 provided higher compressive strength but also higher thermal conductivity, whereas M4 and M5 provided lower thermal conductivity but progressively lower strength and, for M4–M5, visible cracking or deformation after firing. M3 maintained 12.8 MPa compressive strength and 0.63 W/m·K thermal conductivity, together with 13.9% water absorption and no visible deformation or cracking at 1100 °C. The selection is therefore a comparative engineering judgement within the five tested formulations, not a formal optimisation result.

Because clay was fixed at 35% across all five mixes, the combined ceramic waste and sawdust fraction remained constant at 65% of dry mass (Table 1); only the internal split between the two waste streams changed. Thus, every formulation incorporated approximately two-thirds waste-derived constituents. This demonstrates a substantial resource-recovery component in the material design, consistent with previous studies on the valorisation of waste-derived pore-forming materials (Salleh et al. 2021) and the use of waste materials in fired ceramic products. However, it does not by itself establish an overall environmental advantage. The refractory bricks were fired at 1100 °C and held at peak temperature for 2–4 hours, so the energy requirement of processing must be considered when assessing environmental performance. A quantified environmental, carbon or economic assessment was beyond the scope of the present study.

4.4. Limitations and future work

4.4.1. Limitations affecting interpretation

The present study establishes the composition–performance relationship for the investigated ceramic-waste–sawdust series at laboratory scale, but several limitations constrain interpretation. The experimental design used reciprocal substitution of ceramic waste and sawdust at a constant total waste fraction; consequently, independent constituent effects and statistical interaction effects cannot be separated. The study also used a single firing temperature (1100 °C), so the reported trends should not be generalised to other firing schedules without further evidence. Replication was limited to three specimens per mix per property, supporting descriptive comparison rather than strong inferential statistical conclusions.

The study did not include direct porosity measurements, SEM or XRD characterisation. Consequently, pore formation and phase development are proposed mechanisms rather than directly verified microstructural observations.

4.4.2. Future validation and scale-up needs

Repeated thermal cycling, slag or chemical attack, thermal gradients and long-term service durability were not investigated. These factors may affect the residual strength, dimensional stability and thermal behaviour of the bricks under practical high-temperature service, as illustrated by studies of other waste-based high-temperature materials (Janga et al. 2024). These service-related factors are particularly relevant to the higher-sawdust formulations, for which the measured insulation benefit was accompanied by greater cracking and deformation at 1100 °C. Increased pore volume may provide pathways for chemical ingress, while repeated heating and cooling could amplify existing cracking; these effects require direct durability testing before service suitability can be established.

The study also did not quantify embodied energy, carbon emissions, life-cycle impacts or economic performance. The present sustainability contribution is therefore limited to demonstrated waste incorporation and resource-recovery potential. Future work should evaluate firing-energy demand, environmental impacts and service durability before industrial-scale application is considered.

5. Conclusion

This study demonstrated the feasibility of producing refractory bricks incorporating recycled ceramic waste and sawdust while systematically varying their ratio at a constant clay content and total waste fraction. Increasing sawdust content was associated with progressively lower thermal conductivity and compressive strength and higher water absorption. Among the investigated formulations, M3 (55%

recycled ceramic waste, 35% clay and 10% sawdust) provided the most balanced combination of compressive strength (12.8 MPa), thermal conductivity (0.63 W/m·K), water absorption (13.9%) and dimensional stability at 1100 °C.

The principal contribution is the experimentally observed thermal–mechanical performance envelope obtained by redistributing a fixed 65% waste-derived fraction between relatively dense ceramic waste and a pore-forming biomass residue. The results provide a basis for comparing formulations according to competing strength and insulation requirements, while recognising that the reciprocal substitution design does not permit independent constituent effects, interaction estimation or formal multi-objective optimisation.

The findings demonstrate resource-recovery and waste-valorisation potential, but an overall environmental advantage cannot be established from waste content alone because production required firing at 1100 °C for 2–4 hours. Further work involving phase and pore characterisation, repeated thermal exposure, service-level heat-transfer assessment, and environmental and economic evaluation is required before practical application is considered.

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Author contributions

CRediT: **Pathias Ndyabijuka:** Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing; **Ernest Atwijukire:** Data curation, Formal analysis, Investigation, Methodology; **Hosea Eridadi Mutanda:** Investigation, Methodology, Resources, Writing – review & editing; **Josephine Najjobyo:** Formal analysis, Methodology, Supervision, Writing – review & editing; **Joyce Kayanja Gumoshabe:** Data curation, Methodology, Resources; **James Mbabazi:** Methodology, Supervision, Writing – review & editing.

Disclosure statement

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Data availability statement

The datasets supporting the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.21884020 under a Creative Commons Attribution 4.0 International (CC-BY 4.0) licence. The repository includes the mix design proportions, raw material characterisation data (Atterberg limits, particle size distribution, XRF composition), and individual specimen-level replicate readings underlying all averaged values, tables, and figures reported in this article.

Open scholarship



This article has earned the Centre for Open Science badge for Open Data. The data and materials are openly accessible at https://doi.org/10.5281/zenodo.21884020. To obtain the author's disclosure form, please contact the Editor.

Declaration of generative AI use

In the course of preparing this manuscript, the authors used AI-assisted technologies such as Claude Anthropic and Grammarly to improve the style, support the structuring of the text, improve clarity, readability, and presentation. After using these tools/services, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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