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Research Article

Performance and Environmental Assessment of Waste-Derived Construction Composites from Agricultural and Industrial Residues

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ABSTRACT

This study addresses the growing need for sustainable construction materials by investigating the use of secondary raw materials to reduce environmental impact. The aim of the study is to evaluate and justify the use of industrial and agricultural waste in the production of construction composites with tailored physical and mechanical properties. A combination of experimental and computational methods was applied, including mechanical testing, thermophysical measurements, porometric analysis, and hydration monitoring. The results show that ash-based materials exhibit lower density and higher porosity, whereas slag-based composites demonstrate higher strength and improved frost resistance. Both material types showed improved environmental performance, including reduced CO_2 emissions, lower landfill burden, and increased waste utilisation. Additionally, waste-based materials achieved design strength in a shorter time compared to conventional construction materials. These findings confirm the potential of waste-derived materials for sustainable and efficient construction, contributing to resource conservation and reduced environmental impact in the building sector.

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1. INTRODUCTION

The relevance of the study is determined by the sustained growth in the volume of agricultural and industrial waste generated under conditions of production intensification and urbanisation, alongside the high resource intensity of the contemporary construction sector. A substantial proportion of waste continues to be directed to landfill disposal, causing land degradation, increased greenhouse gas emissions, and greater anthropogenic pressure on the environment (Mikhno et al., 2023; Chernets et al., 2008). The construction sector simultaneously remains one of the largest consumers of primary mineral resources. The use of waste in construction materials represents an effective strategy to reduce environmental impact and improve resource efficiency. The problem addressed in this study is the lack of coordinated approaches for the simultaneous assessment of physicomechanical, thermophysical, and environmental characteristics of construction materials derived from agricultural and industrial waste. A key challenge lies in the fragmented and inconsistent data on the influence of mineral composition and morphology of secondary components on composite structure and durability, which complicates cross-study comparability. Another gap is the insufficient standardisation of quantitative environmental indicators, such as landfill reduction and carbon emissions over the material life cycle.

In the context of environmental impact and resource efficiency, several studies have demonstrated the benefits of integrating secondary waste into construction materials. Vito et al. (2024) showed that urban and agro-industrial waste can reduce environmental pressure by lowering landfill volumes and increasing resource efficiency, while Xhexhi (2023) highlighted that the application of secondary construction materials supports sustainable urban development and energy-efficient architectural environments. Hysa et al. (2021) emphasised that materials with reduced resource intensity enhance sectoral sustainability, and Peng et al. (2023) indicated that agricultural, municipal, and industrial waste can reduce carbon footprints and material costs. Sangmesh et al. (2023) confirmed that agricultural-residue-based materials meet required performance standards while reducing environmental impact, and Duque-Acevedo et al. (2022) demonstrated that processing agricultural waste provides functionally comparable alternatives to conventional materials while conserving primary mineral resources. Kumar et al. (2025) noted that such materials contribute to environmentally oriented construction technologies, and Gupta et al. (2022) highlighted the potential of biomass conversion in reducing environmental risks associated with waste accumulation.

Regarding material properties and applications, studies have shown practical and functional advantages. Saeed and Hassan (2025) demonstrated that incorporating industrial and agricultural waste into concrete composites reduces carbon load and complies with sustainable construction standards. Anitha and Senthilselvan (2022) confirmed that agricultural waste enables the production of various construction materials while reducing resource intensity. AlBiajawi et al. (2022) found that treated agricultural and industrial waste exhibits improved pozzolanic activity, allowing partial substitution of conventional mineral components. Schmidt et al. (2021) showed that processing agricultural residues produces materials suitable for urban development while reducing resource losses.

Despite these advances, the influence of waste type on physicomechanical, thermal insulation, and performance characteristics of composites remains insufficiently investigated. To provide explicit benchmarks for the investigation, target performance indicators were defined in accordance with standard technical specifications and functional criteria for construction materials. The ash-based composites were designed to attain a compressive strength of approximately 6-7 MPa, a flexural strength of 2-2.5 MPa, a density of 1100-1200 kg/m³, and a thermal conductivity below 0.25 W/(m·K). The target values for slag-based composites were established at a compressive strength of 9-10 MPa, a flexural strength of 3-3.5 MPa, a density of 1400-1500 kg/m³, and a thermal conductivity below 0.3 W/(m·K). These metrics serve as benchmarks for assessing the effectiveness of waste integration and material performance.

The purpose of the study is to assess the feasibility of using agricultural and industrial waste for the production of construction materials with specified performance characteristics and reduced environmental impact. The objectives of the study include determining the influence of waste type on the properties of construction composites, evaluating their thermal insulation and environmental characteristics, and comparing the developed materials with conventional construction products.

2. METHODOLOGY

The study was conducted in 2024 under laboratory and semi-industrial conditions at the Laboratory of Construction Materials in Tirana (Republic of Albania). Experiments were performed under controlled conditions at 20±2°C and 60±5% relative humidity. Specimen moulding and curing were carried out under standardised laboratory conditions. Rice husk ash, sourced from a local agro-industrial region, was used as the agricultural waste-based material due to its high availability, mineral activity, and significant generation volume as a by-product of rice processing. The ash met the following inclusion criteria: absence of visible organic impurities, stable mineral composition, preliminary drying to constant mass, and grinding to a residue not exceeding 5% on a 90 μm sieve. Exclusion criteria included elevated levels of unburnt carbon, unstable granulometric composition, and the presence of foreign inclusions.

Granulated blast-furnace slag, supplied by a metallurgical enterprise in the Balkan region, was used as the industrial waste-based material due to its high hydraulic activity, stable chemical composition, and established use in construction materials production. The slag was granulated, dried, and ground to achieve homogeneous dispersion. Materials exhibiting secondary carbonation, heterogeneity, or excessive moisture content were excluded. Waste-based materials (rice husk ash and blast-furnace slag) and conventional construction materials (heavy concrete and ceramic brick) were included for comparative analysis. Identical specimen geometries and curing regimes were applied across all samples. The study was conducted in accordance with the European Code of Conduct for Research Integrity (2023).

Mechanical testing included compressive strength (n=5, uncertainty ±2%), flexural strength (three-point bending), shrinkage during curing, and dimensional stability. Thermal testing included thermal conductivity, thermal resistance, thermal diffusivity, specific heat capacity, and thermal cycling resistance. Measurements were performed using calibrated equipment, including NETZSCH DSC 214 Polyma, LFA 467 HyperFlash, and STA 449 F3 Jupiter (Germany), while specimen dimensions were measured using Mitutoyo digital calipers (Japan). Structural characterization included density, total and open porosity, pore size distribution, structural densification coefficient, capillary water absorption, water saturation coefficient, hydration degree (thermogravimetric analysis), sound absorption coefficient, filler-matrix adhesion, and specific surface area. Environmental assessment included recycled content, carbon footprint, energy consumption, natural resource savings, recyclability potential, cumulative environmental damage, and landfill reduction.

Life cycle assessment was performed using SimaPro 9.5 software (Netherlands) with the Ecoinvent v3.9 database (Switzerland). System boundaries were defined as cradle-to-gate, and the functional unit was 1 m³ of material. The average density was calculated as the ratio of mass to volume. Compressive strength was determined under axial loading to failure, while flexural strength was measured using a three-point bending configuration. Water absorption was evaluated after saturation to constant mass. Standardised testing procedures were applied for all mechanical and physical characterisations.

Total porosity was determined by the water saturation method, while open porosity was calculated using hydrostatic weighing according to formula (1):

$$P_{\text{open}} = \frac{m_{\text{saturated}} - m_{\text{hydro}}}{\rho_w \cdot V} \times 100, \tag{1}$$

where variables represent standardised definitions. The average pore size was determined using mercury porosimetry. The structural densification coefficient was calculated using formula (2) as it provides an indicative measure of particle packing efficiency and composite compactness, which is particularly relevant for waste-based materials where particle morphology varies significantly.

$$K_{\text{dens}} = \frac{\rho_{\text{actual}}}{\rho_{\text{theor}}}, \tag{2}$$

where variables are defined in a standard manner. The specific surface area of particles was measured because it strongly affects water adsorption, binder interaction, and early-stage structure formation in composites with irregularly shaped waste-derived particles. Capillary water absorption and the water saturation coefficient were calculated using formula (3):

$$K_{\text{ws}} = \frac{V_{\text{absorbed}}}{V_{\text{pore}}}, \tag{3}$$

where K_{ws}: water saturation coefficient, dimensionless; V_{absorbed}: volume of water absorbed by the specimen, cm^3; V_{pore}: total pore volume of the material, cm^3. The degree of hydration of the binder phase was determined using thermogravimetric analysis as it directly indicates the effectiveness of binder activation, which varies depending on the type of agricultural or industrial waste used.

The degree of hydration was determined via thermogravimetric analysis (105–900°C, NETZSCH STA 449 F3 Jupiter). Thermal properties were measured using laser flash analysis (LFA 467 HyperFlash) and differential scanning calorimetry (DSC 214 Polyma). Thermal resistance was calculated from conductivity and specimen thickness measured with Mitutoyo calipers. Sound absorption at 500 Hz was determined using a Brüel & Kjær impedance tube system (Denmark).

Frost and thermal cycling resistance were evaluated in a Binder MK 115 climatic chamber (Germany). Residual strength was determined by comparing pre- and post-exposure mechanical performance. Dimensional stability was assessed using a Mitutoyo dial indicator.

Carbon footprint per unit volume was calculated using formula (4):

$$\mathrm{CF_v} = \frac{\sum \mathrm{CO_{2eq}}}{\mathrm{V}}, \tag{4}$$

where $\mathrm{CF_v}$: carbon footprint per unit volume, kg CO_2-eq./m^3; $\sum\mathrm{CO_{2eq}}$: total greenhouse gas emissions converted to CO_2 equivalent over the material's life cycle, kg CO_2-eq.; V: volume of produced material, m^3.

Specimen volume was calculated from geometric dimensions measured using a digital caliper Mitutoyo CD-15CX (Japan). Energy consumption during production was estimated as the sum of electrical and thermal energy consumed at all technological stages using the formula (5):

$$\mathrm{E_{tot}} = \mathrm{E_{el}} + \mathrm{E_{th}}, \tag{5}$$

where $\mathrm{E_{tot}}$: total energy consumption for material production, MJ/t; $\mathrm{E_{el}}$: electrical energy consumption across all stages, MJ/t; $\mathrm{E_{th}}$: thermal energy consumption across all stages, MJ/t.

Energy consumption was recorded using a Fluke 435 Series II power quality analyser (USA). Reduction in consumption of natural mineral resources was determined by comparing primary raw material use in conventional formulations with that in the developed composites. Calculations were based on material balances using the formula (6):

$$\Delta\mathrm{R} = \frac{\mathrm{R_{trad}} - \mathrm{R_{dev}}}{\mathrm{R_{trad}}} \times 100, \tag{6}$$

where $\Delta\mathrm{R}$: reduction in natural mineral resource consumption, %; $\mathrm{R_{trad}}$: primary mineral raw material consumption in the conventional formulation, kg/t of product; $\mathrm{R_{dev}}$: primary mineral raw material consumption in the developed composite, kg/t of product.

The potential for reprocessing the material was determined experimentally through repeated crushing and assessment of the suitability of secondary aggregate. Particle size distribution after crushing was determined using a Retsch AS 200 laboratory vibrating sieve (Germany). The ecological index of raw material substitution was calculated as an integral dimensionless indicator. Reduction of landfill load was determined by the volume of waste diverted from disposal, based on mass and bulk density. Waste volume was calculated from mass and bulk density determined by the gravimetric method. The mass of a structure with equal load-bearing capacity was determined by calculation based on experimentally measured compressive strength and average material density using the formula (7):

$$\mathrm{M_k} = \frac{\mathrm{N_{req}}}{\sigma_{\mathrm{comp}}}, \tag{7}$$

where $\mathrm{M_k}$: mass of the structure with equal load-bearing capacity, kg/m^2, $\mathrm{N_{req}}$: required design load, Н/$м^2$, σ_{comp}: compressive strength of the material, Pa. Specific material consumption was defined as an indicator characterising the material expenditure per unit of ensured strength.

Specimen mass and strength measurements were performed using standard laboratory equipment. The thermal inertia coefficient was calculated from experimentally measured thermophysical properties using the formula (8):

$$\mathrm{I} = \sqrt{\lambda \cdot \rho \cdot \mathrm{c}}, \tag{8}$$

where I: thermal inertia coefficient, relative units; λ: thermal conductivity coefficient, $\rho$is material density, kg/m^3; $\mathrm{c}$is specific heat capacity, J/(kg·K). The time required to achieve design strength was recorded experimentally based on the moment when the normative strength level was achieved within standard curing periods. Tests were conducted at ages of 1, 7, 14, and 28 days of curing under controlled laboratory conditions.

The specific consumption of binder was determined from the mixture composition and confirmed by weighing components using Ohaus Pioneer PX224 analytical scales (USA). The level of secondary raw materials in the material composition was defined as the mass share of waste in the total mass of the composite. Component masses were recorded during mixture preparation. The equivalent load on the foundation was calculated from the mass of structural elements using the formula (9):

$$\mathrm{F} = \mathrm{M} \cdot \mathrm{g}, \tag{9}$$

where F: equivalent load on the foundation, N; M: mass of the structural element, kg; g: acceleration due to gravity.

Cumulative environmental damage was expressed through an integral LCA index. Including these environmental assessments provides a rationale for the ecological relevance of each methodological step, showing how the chosen tests inform both material performance and sustainability outcomes. Calculations were performed using SimaPro 9.5 software (Netherlands) with the Ecoinvent v3.9 database (Switzerland) following standard life cycle scenarios for construction materials.

3. RESULTS AND DISCUSSION

3.1. Mechanical Properties and Density Characteristics of the Developed Materials

The most pronounced differences were recorded in the average density values. For the material based on granulated blast-furnace slag, the density was 1450 kg/m³, whereas for the composite with rice husk ash, this value reached 1150 kg/m³. The observed difference of 300 kg/m³ indicates variations in matrix compaction and pore volume. The higher density of the slag-based material indicates a smaller proportion of open pores, whereas the ash-based material was characterised by a more developed porous structure. This distinction is mechanistically linked to the different contributions of silica and hydraulic phases: the reactive calcium silicates in slag accelerate C-S-H gel formation, leading to a denser matrix, whereas the amorphous silica in rice husk ash participates in pozzolanic reactions, forming secondary C-S-H phases that partially densify the matrix while maintaining higher porosity.

Substantial differences were also identified in compressive strength. The maximum value of this parameter was recorded for the material based on granulated blast-furnace slag and amounted to 9.5 MPa, whereas for the material with rice husk ash, compressive strength reached 6.8 MPa. The higher compressive strength of slag-based composites is explained by rapid C-S-H formation and the presence of hydraulically active phases, whereas rice husk ash composites gain strength more gradually through pozzolanic reactions with calcium hydroxide. The combination of these reactions significantly enhances early-age strength development, allowing the materials to reach design strength within 14 days compared to 28 days for conventional binders (Neville, 2011; Scrivener et al., 2018). Overall, the data demonstrate a clear microstructure-strength relationship: increased matrix densification and reduced porosity correlate with higher compressive resistance. The lowest values among the analysed indicators were recorded for the thermal conductivity coefficient of the rice husk ash-based material. Its value was 0.21 W/(m·K), whereas for the material containing granulated blast-furnace slag, this indicator reached 0.29 W/(m·K). This difference reflects the relationship between pore structure and thermal performance: higher porosity in ash-based composites reduces thermal diffusivity, improving insulation performance but reducing mechanical strength, whereas the denser slag matrix enhances heat transfer.

Frost resistance also differed significantly between the materials. The material based on granulated blast-furnace slag demonstrated resistance to 50 freeze-thaw cycles, whereas the material with rice husk ash withstood 35 cycles. The observed variation is associated with differences in water absorption and pore connectivity: higher frost resistance corresponds to a lower volume of pores filled with moisture, reducing the risk of damage during water phase transitions. The combined analysis of the selected indicators revealed stable relationships between density, compressive strength, thermal conductivity, and frost resistance. An increase in density was accompanied by an increase in compressive strength and frost resistance, as well as an increase in thermal conductivity coefficient (Marchuk & Nishchota, 2018; Ratov et al., 2023). In contrast, a decrease in density correlated with reduced thermal conductivity and lower compressive resistance. These relationships are governed by differences in mineral composition and particle morphology of the waste materials used (Table 1).

Table 1. Physical and mechanical characteristics of construction materials based on waste

Indicator	Material based on agricultural waste (rice husk ash)	Material based on industrial waste (granulated blast furnace slag)
Average density, kg/m^3	1150	1450
Compressive strength, MPa	6.8	9.5
Flexural strength, MPa	2.4	3.1
Water absorption, %	11.6	8.3
Thermal conductivity coefficient, W/(m·K)	0.21	0.29
Environmental safety class	E1	E1

*European Code of Conduct for Research Integrity (2023); Reinhard Oppl (2011).

The obtained values fall within the range characteristic of lightweight structural and thermal-insulation construction materials. The results highlight the engineering implications for design: rice husk ash composites offer reduced density and improved thermal insulation, making them suitable for energy-efficient structures, while slag-based composites provide higher strength and frost resistance, making them suitable for load-bearing applications. The CO_2 reduction associated with the use of these waste materials is significant and comparable to values reported for similar lightweight construction composites (Ortega et al., 2022), demonstrating a clear real-world environmental benefit. Hence, targeted selection of waste type allows control over mechanical, thermal, and environmental performance under comparable technological conditions, emphasizing the trade-offs between strength, insulation, and sustainability in material design.

3.2. Influence of the Nature of Waste on the Structural Density of Composites

The most pronounced differences between the investigated composites were observed in total porosity. For materials produced using rice husk ash, this parameter was 28.5%, whereas for composites based on granulated blast-furnace slag, total porosity reached 18.9%. This difference reflects distinct mechanisms of microstructure formation: slag-based composites develop a denser matrix due to rapid hydration of hydraulic phases (C-S-H formation), whereas the amorphous silica in rice husk ash contributes to higher porosity through slower pozzolanic reactions and particle agglomeration. The increased porosity of ash-based composites was attributed to the morphology of ash particles, their high dispersion, and the presence of a developed specific surface area, which contributed to the formation of both open and closed pores. Open porosity was determined using the hydrostatic weighing method, which allowed quantification of interconnected pores responsible for water saturation and mass transfer. Slag-based materials formed a more compact structure characterised by a lower pore volume. In summary, increased porosity in ash-based composites corresponds to lower structural compaction and compressive strength but enhanced thermal insulation performance.

The lowest values among the considered parameters were observed for the average pore size in slag-based composites. This indicator was 18 µm, whereas in materials with rice husk ash, the average pore size reached 45 µm. Smaller pores in slag composites result from more uniform particle packing and effective filler-binder interaction, while larger pores in ash composites arise from particle agglomeration and higher water demand. Substantial differences were also identified in the structural compaction coefficient. The maximum value of this parameter was recorded for the material based on granulated blast-furnace slag and amounted to 0.86 relative units, whereas for composites with rice husk ash, the compaction coefficient did not exceed 0.72 relative units. This confirms the microstructure-strength relationship: denser particle packing in slag composites leads to higher compressive resistance, whereas ash composites, with more developed microporosity, exhibit lower strength but improved thermal insulation properties.

The highest values of specific surface area were recorded for composites based on rice husk ash and amounted to 520 m²/kg. For materials containing granulated blast-furnace slag, this indicator reached 310 m²/kg. A higher specific surface area in ash composites increases particle–binder interaction, influencing early hydration processes, water redistribution, and microstructural development. The degree of hydration of the binder phase was higher in slag-based composites. In materials based on granulated blast-furnace slag, this indicator reached 78%, whereas in composites with rice husk ash, the degree of hydration was 61%. Higher hydration in slag composites indicates more complete participation of hydraulic phases, contributing to higher density and strength, whereas lower hydration in ash composites reflects slower pozzolanic reactions and a more porous structure. The combined analysis of the selected indicators allowed the identification of relationships between pore structure parameters and the properties governing density and strength of the composites. In particular, an increase in total porosity and average pore size correlates with a decrease in the structural compaction coefficient and compressive strength, while a decrease in porosity correlates with a higher degree of hydration and improved mechanical performance. The water saturation coefficient further confirms differences in pore connectivity and thermal performance between the materials (Table 2).

Table 2. Influence of waste type on the strength and density of the resulting composites

Indicator	Material based on agricultural waste (rice husk ash)	Material based on industrial waste (granulated blast furnace slag)
Total porosity, %	28.5	18.9
Open porosity, %	21.4	13.2
Average pore size, µm	45	18
Structure compaction coefficient, relative units	0.72	0.86
Adhesion of the filler to the matrix, MPa	1.9	2.7

The results demonstrate that the type of waste has a decisive influence on microstructure formation in composites. Rice husk ash-based materials are characterised by higher total porosity, larger average pore size, and greater specific surface area, leading to reduced density and compressive strength but improved thermal insulation performance. Materials containing granulated blast-furnace slag exhibit lower porosity, smaller pore size, higher structural compaction, and a higher degree of hydration, resulting in superior strength and frost resistance. These trends are consistent with the mechanistic influence of silica versus hydraulic phases, highlighting the possibility of tailoring material properties for specific engineering applications. Finally, the CO_2 reduction potential associated with these waste-based composites is significant, aligning with values reported for similar lightweight construction materials in the literature, demonstrating both environmental and practical engineering relevance.

3.3. Operational Behaviour of Materials under Thermal Exposure

The most pronounced differences between the studied materials were observed in thermal resistance. For the composite based on rice husk ash, the value of this parameter was 1.18 $m^2 \cdot K/W$, whereas for the material incorporating granulated blast-furnace slag, thermal resistance reached 0.86 $m^2 \cdot K/W$. This difference reflects variations in pore structure, where a higher proportion of air-filled pores in ash-based composites acts as an effective thermal barrier, while denser slag-based composites exhibit more continuous solid-phase pathways, facilitating heat conduction.

The lowest values among the considered indicators were observed for the thermal diffusivity of the rice husk ash-based material. Its value was 0.42 mm^2/s, whereas for the composite with granulated blast-furnace slag, this indicator reached 0.58 mm^2/s. Lower thermal diffusivity in ash-based composites corresponds to slower temperature propagation, which is associated with higher total porosity and a reduced number of heat-conducting contacts between solid particles. In contrast, the higher thermal diffusivity of slag-based composites reflects their denser structure and greater continuity of the solid phase, enabling faster heat transfer (Marchuk, 2021; Ibrahimova et al., 2024). The highest values of vapour permeability were recorded for the material containing rice husk ash. The value of this indicator was 0.32 mg/(m·h·Pa), whereas for the composite based on granulated blast-furnace slag, vapour permeability reached 0.21 mg/(m·h·Pa). This indicates that increased porosity and the presence of an interconnected capillary network in ash-based composites promote moisture transport, whereas the denser structure of slag-based composites limits vapour diffusion.

Residual strength after thermal exposure was higher in slag-based composites. For this composite, the indicator value reached 91%, whereas for the material containing rice husk ash, residual strength was 82%. The higher residual strength in slag-based composites is associated with reduced thermal deformation and a more stable binding phase, whereas in ash-based composites, the more porous structure and redistribution of internal stresses during heating lead to slightly greater structural changes. The combined analysis of the specified indicators enables the identification of stable interrelationships between the thermal insulation and operational properties of the studied composites. Higher thermal resistance is consistently associated with lower thermal diffusivity and increased vapour permeability, confirming that pore structure, pore size, and pore connectivity govern heat and moisture transport. Simultaneously, higher residual strength correlates with denser structures and lower porosity, illustrating the microstructure-performance relationship (Leshchenko & Semko, 2015; Salmanova & Akbarli, 2024) (Table 3).

Table 3. Thermal insulation and performance properties of the developed materials

Indicator	Material based on agricultural waste (rice husk ash)	Material based on industrial waste (granulated blast furnace slag)
Thermal resistance, $m^2 \cdot K/W$	1.18	0.86
Thermal diffusivity, mm^2/s	0.42	0.58
Residual strength after thermal exposure, %	82	91
Dimensional stability in service, %	0.41	0.29

The observed trends confirm that thermal and operational behaviour is directly governed by pore structure and material density. Materials with higher porosity and larger pore volume, such as those based on rice husk ash, demonstrate superior thermal insulation and moisture transport but slightly reduced residual mechanical strength. Denser slag-based composites, conversely, combine higher residual strength and better dimensional stability with lower thermal resistance and slower moisture transfer. These findings highlight the possibility of tailoring composites for specific thermal or mechanical applications through the selection of the appropriate waste type.

3.4. Reduction of Environmental Burden through the Processing of Secondary Raw Materials

The proportion of recycled waste was higher in materials based on granulated blast-furnace slag. The value of this indicator was 45%, whereas for composites based on rice husk ash, the proportion of recycled waste was 32%. This difference indicates that slag-based composites enable greater substitution of primary raw materials with secondary components, enhancing resource efficiency and reducing reliance on virgin materials. A significant reduction in waste disposal volume was recorded for granulated blast-furnace slag-based materials. For this material, the reduction reached 410 kg per tonne of finished product, whereas for rice husk ash-based composites, the value of this indicator was 280 kg/t. This reflects the higher incorporation of industrial residues in slag-based composites, which directly decreases the amount of material sent to landfills.

The lowest carbon footprint per unit volume was observed for rice husk ash-based composites. The value of this indicator was 145 kg CO_2-eq./m³, whereas for materials containing granulated blast-furnace slag, the carbon footprint reached 178 kg CO_2-eq./m³. The lower carbon footprint in ash-based composites reflects reduced energy intensity and lower emissions during raw material processing, despite lower substitution of primary resources. Greater reductions in life cycle CO_2 emissions were observed for slag-based materials. The reduction in emissions reached 260 kg CO_2-eq. per tonne of product, whereas for composites with rice husk ash the indicator was 190 kg CO_2-eq./t. This demonstrates that the incorporation of slag as a secondary material effectively mitigates greenhouse gas emissions through partial replacement of energy-intensive primary components (Zhikeyev et al., 2024; Paton et al., 2005). A more substantial decrease in natural mineral resource consumption was also observed for slag-based composites. For these materials, the reduction in consumption reached 52%, whereas for rice husk ash composites, the indicator was 38%. The higher resource savings confirm that slag can functionally replace conventional mineral fillers and binders more efficiently than ash.

The combined analysis of the specified indicators allowed the identification of interrelationships between the degree of waste utilisation, carbon balance parameters, and reduced burden on waste management systems. In particular, an increase in recycled waste proportion was accompanied by larger reductions in disposal volume and life cycle CO_2 emissions, while lower carbon footprint values per unit volume reflected reduced energy intensity in production stages. These relationships highlight the practical impact of waste selection on real-world environmental performance (Table 4).

Table 4. Environmental efficiency of waste recycling in the production of construction materials

Indicator	Material based on agricultural waste (rice husk ash)	Material based on industrial waste (granulated blast furnace slag)
Share of recycled waste in the composition, %	32	45
Reduction in life cycle CO_2 emissions, kg CO_2-eq./t	190	260
Carbon footprint of the material, kg CO_2-eq./m^3	145	178
Reduction in consumption of natural mineral resources, %	38	52

The obtained results reflect differences in the environmental profiles of materials derived from agricultural and industrial waste. Slag-based composites were characterised by higher recycled waste content, greater reduction in disposal volume, larger decreases in life cycle CO_2 emissions, and more pronounced savings in natural mineral resources. Rice husk ash-based composites, on the other hand, exhibited the lowest carbon footprint per unit volume, highlighting their efficiency in terms of energy demand and emission reduction. These differences confirm the influence of waste origin and functional role on the environmental performance of construction materials.

3.5. Comparison of the Operational and Environmental Parameters of Materials

Lower structural mass was observed for waste-based materials under equal load-bearing capacity. For the developed materials, this indicator was 185 kg/m², whereas for conventional construction materials it reached 240 kg/m². This difference demonstrates that the reduced density and optimized microstructural arrangement of waste-based composites result in lighter structural elements, which can positively influence foundation design and overall structural efficiency. Specific material consumption was also lower for waste-based materials. For these materials, this indicator was 165 kg/MPa·m³, whereas for conventional materials it reached 210 kg/MPa·m³. Lower specific consumption reflects the optimized distribution of components in the mix, achieving the required mechanical performance with reduced raw material input. The most pronounced difference between the compared materials was observed in the time required to reach design strength. For the developed materials, this period was 14 days, whereas for conventional construction materials it reached 28 days. This twofold acceleration is associated with the high reactivity of mineral components and rapid formation of the binding matrix, resulting in enhanced early-age strength development.

The integral environmental effect indicator was diminished for waste-derived materials (Blasi et al., 2023). The cumulative environmental damage value, as shown by the LCA index, was 0.64 relative units, while traditional construction materials registered a value of 1. This signifies a substantially lower ecological impact throughout the life cycle, due to reduced energy consumption, lower use of primary resources, and decreased emissions from transportation, consistent with the higher incorporation of locally sourced waste materials. The combined analysis of these indicators reveals relationships between structural characteristics and operational performance. A decrease in structural mass correlates with reduced specific material consumption, while shorter curing times enable faster commissioning, highlighting efficiency gains for both construction and environmental performance.

Comparison of the indicators also demonstrates differences in load distribution within building systems. Lower structural mass and reduced material consumption for waste-based materials correspond to decreased equivalent foundation loads, whereas conventional materials require more robust supporting structures due to higher mass and material use. Differences in thermophysical properties were also identified. The thermal inertia coefficient was lower for waste-based materials, reflecting their lightweight structure and enhanced thermal insulation, whereas higher values for conventional materials are associated with greater mass and higher thermal inertia, which slow temperature changes but increase energy demand for heating and cooling.

Environmental performance, expressed through the life cycle index, correlates with material consumption and hardening time. Lower LCA values for waste-based materials are associated with decreased primary raw material use, lower energy consumption across production and transport stages, and shorter technological processes, whereas higher values for conventional materials reflect the cumulative environmental burden from energy-intensive production, longer curing, and reliance on virgin resources (Table 5).

Table 5. Comparative analysis of developed materials and conventional construction materials

Indicator	**Waste-based materials (rice husk ash/granulated blast furnace slag)**	**Conventional construction materials (concrete, ceramic brick)**
Mass of the structure at equal load-bearing capacity, kg/m^2	185	240
Specific material consumption, kg/MPa·m^3	165	210
Share of secondary raw materials in the composition, %	32-45	≤5
Cumulative environmental damage (LCA index), relative units	0.64	1

The results of this study demonstrate that waste-based composites, incorporating rice husk ash or granulated blast furnace slag, exhibit a distinct combination of structural, operational, and environmental performance compared to conventional construction materials. Specifically, waste-based materials achieve lower structural mass, reduced material consumption, decreased cumulative environmental damage, and faster strength development (Azizov et al., 2019; Valujeva et al., 2024). These properties highlight their suitability for applications where lightweight, efficient, and environmentally conscious construction is required, such as building envelopes, self-supporting elements, and structures with limited foundation capacity. Analysis of thermal and mechanical performance revealed clear differences between slag-based and ash-based composites, as illustrated in Figure 1, which presents a comparative evaluation of porosity, density, thermal conductivity, and compressive strength.

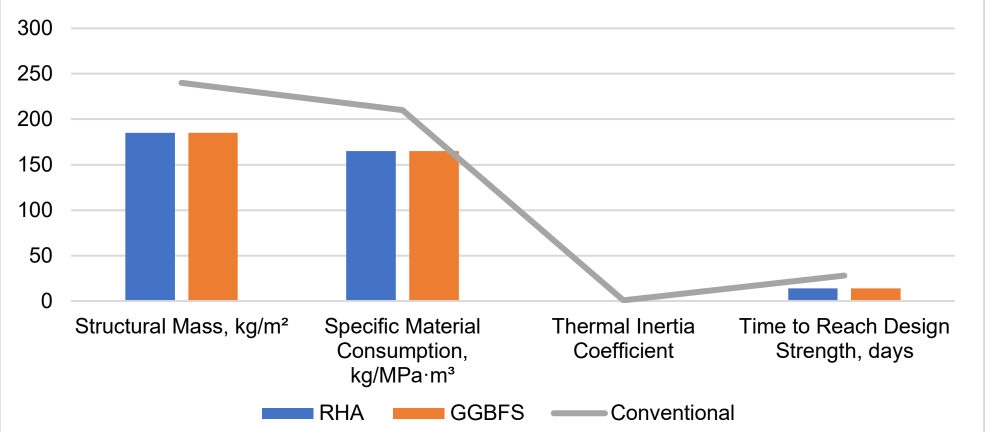

Figure 1. Comparative performance of waste-based and conventional construction materials

Slag-based materials showed higher density, lower porosity, and improved resistance to cyclic thermal loading, resulting in greater strength and durability, whereas ash-based composites exhibited increased porosity and lower thermal conductivity, providing enhanced insulation but reduced mechanical performance (Rudovsky et al., 2019; Sevdimaliyev et al., 2023). These findings confirm that the type of waste directly influences the balance between structural strength and thermal performance, highlighting the functional role of pore structure in material behaviour. The study further demonstrates the quantitative relationship between microstructural features and performance, with rice husk ash increasing total porosity and reducing thermal conductivity, while slag promotes denser structures with higher strength (Kalair et al., 2021; Thomas et al., 2021). From a technological perspective, variability in waste composition may affect material properties (Ngayakamo & Onwualu, 2022; Gil, 2022). However, the controlled experimental approach used in this study enables the identification of consistent relationships between structural parameters and performance, supporting reproducibility and practical application.

Regarding environmental efficiency, waste-based composites demonstrate comparable or superior performance relative to biopolymer- and alternative-binder-based materials while simultaneously meeting strength, density, and frost resistance requirements (Losini et al., 2021; Zhang et al., 2022; Livne et al., 2022; Bouargane et al., 2023). This indicates a viable pathway for sustainable construction using mineral waste streams without the complexity of bio-based systems. Finally, comparisons with studies on synthetic and organic waste valorisation (Sharma et al., 2021; Lizundia et al., 2022; Abd Elkodous et al., 2022; Jayanthi et al., 2023) suggest that mineral waste-based composites provide predictable and well-balanced combinations of strength, thermal insulation, and early-age performance without requiring complex additives. Accelerated hydration kinetics and rapid C-S-H gel formation explain the improved early-age strength, confirming the practical advantages of waste-based composites over conventional materials.

4. CONCLUSION

This study provided a comprehensive evaluation of construction materials produced using rice husk ash and granulated blast furnace slag, analysing their physical, mechanical, structural, thermal, performance, and environmental characteristics and comparing them with conventional construction materials. Rice husk ash-based materials exhibited lower density, higher porosity, and enhanced thermal insulation, whereas slag-based materials showed higher strength, lower porosity, and greater resistance to mechanical and thermal loading conditions.

Thermal and operational performance indicated that ash-based composites had higher thermal resistance and lower thermal diffusivity, making them suitable for insulation-oriented applications. Slag-based materials demonstrated superior residual strength after thermal exposure, greater dimensional stability, and higher frost resistance, making them appropriate for load-bearing structural applications. Reduced structural mass and faster strength development in waste-based materials enable accelerated construction processes and their application in projects with limited foundation capacity. Environmental efficiency metrics confirmed the benefits of waste incorporation. The recycled waste share reached 32-45%, landfill reduction ranged from 280-410 kg per tonne of product, CO_2 emissions decreased by 190-260 kg CO_2-eq./t, and the overall environmental impact was reduced compared to conventional materials. These results highlight the potential of waste-based composites as sustainable and environmentally friendly alternatives to traditional construction materials.

The study was limited by the use of a restricted set of waste materials under controlled laboratory conditions. Future research should focus on evaluating durability and long-term performance under real operational conditions, optimising mix designs for different applications, assessing industrial-scale production feasibility, and conducting more comprehensive life cycle assessments (LCA) with expanded system boundaries and impact categories to better quantify environmental benefits. Overall, the findings demonstrate that waste-based composites offer a promising combination of structural performance, thermal efficiency, and environmental sustainability, providing a strong foundation for further development and industrial application. Taken together, the results indicate that waste-based composites represent a viable and scalable alternative to conventional construction materials, supporting more sustainable and resource-efficient construction practices.

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CONFLICT OF INTEREST
The authors declare no conflicts of interest.

AUTHOR CONTRIBUTION

Alfred Lako: Conceptualization, Methodology, Project administration, Data collection, Writing original draft. Mikael Lako: Formal analysis, Investigation, Supervision, Validation, Writing, Reviewing and Editing.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author.

DECLARATION OF GENERATIVE AI

Not applicable.

ETHICS

Not applicable.

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