

Development and Performance Evaluation of Sustainable Composite Wall Cladding Integrating Recycled PET, Waste Tire Steel Fibers, and Rice Husk Ash (RHA)

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ABSTRACT

The accumulation of polyethylene terephthalate (PET) waste, vehicle tires, and rice husk ash (RHA) presents a critical environmental challenge in developing countries. This study explores a sustainable composite wall cladding that integrates recycled PET as a polymeric binder, river sand, waste tire steel fibers (SFs), and RHA fillers. Material characterization (XRF, thermal analysis) confirmed a high silica content in RHA (91%) and sand (82%), with a PET melting threshold of 240-255°C. The composites were fabricated through a hot-mixing process at 250°C, while maintaining constant PET and SFs content, systematically varying the RHA-to-sand substitution ratio from 0% to 20% by weight. The experimental results demonstrated that enhancing RHA concentration typically reduced density (from 2.469g/cm³ to 1.495 g/cm³) due to low specific gravity of the ash. While water absorption slightly enhanced (1.8% to 3.12%), values maintained the "Vitreous" range of ASTM C373. Compressive strength exhibited an optimal peak of 24.1 MPa at a 12.5% RHA concentration, supported by impact energy absorption (3.29 Joules) without visible damage. The study reveals an optimal mix design of 12.2% RHA and 36.6% sand, demonstrating that RHA serves as an effective secondary reinforcement up to a critical threshold before binder starvation occurs. This research establishes a technical framework for circular economy practices in Tanzania, contributing to a high-performance, low-cost alternative to traditional cladding materials.

Keywords: Repurposed PET, Rice husk ash, Recycled steel fibers, Sustainability, Circular economy.

INTRODUCTION

Polyethylene Terephthalate (PET) plastic has emerged as a cornerstone of modern packaging and beverage industries due to its cost-effectiveness, high strength-to-weight ratio, and exceptional durability (Soong et al., 2022). This relatively inexpensive, lightweight, and durable material has the potential to be recycled into various products with a broad range of applications (Hossain et al., 2024). The packaging industry utilizes the highest quantity of PET plastics produced globally and is one of the main contributors of waste plastics in the environment (Wan et al., 2024). The widespread application of plastics has contributed to a high volume of plastic waste, leading to harmful environmental impacts. Inadequate management of these plastic streams causes landfill congestion and environmental pollution (Sharma et al., 2024). Therefore, there is an urgent need for sustainable management strategies for plastic waste, particularly landfill and recycling in urban areas.

In the accelerating urbanizing regions like Mbeya, Tanzania, the social burden of waste management is inextricably connected to public health and economic stability. The accumulation of PET plastic and agricultural waste is not merely an environmental issue but a social-economic one, often drains municipal

resources and hindering community prosperity. Transitioning from a 'linear' to a 'circular economy' enables the transformation of these local waste streams into high-value construction materials. This transition mitigates the housing deficit in developing nations by providing cost-effective, sustainable alternatives to conventional cement-based materials while catalyzes local industrial innovation and employment creation. Consequently, an empirical assessment of these composites provides a technical foundation for social policies that merge sustainable infrastructure with environmental equity.

Recycling PET plastic for construction applications is a promising way to support sustainability and environmental conservation. Recycling serves as a valuable technique for mitigating the growing accumulation of PET plastic waste bottles in landfills and the environment. Recent studies into innovative applications of recycled PET plastic wastes in construction pose a significant opportunity to reduce environmental impact, promote the development of sustainable alternative materials, and lower construction costs. PET Plastic wastes can serve as a binder, modifier, or cement replacement in composite materials (Jawaid et al., 2023; Muringayil Joseph et al., 2024).

Various studies have explored the significant application of PET plastics as binders in plastic-based composites. For instance, Ahmat et al. (2021) utilized PET plastics as a binder and cocoa hull powder to produce composite materials for bathroom walls. Composites manufactured by incorporating 40% to 50% recycled PET plastic as a binder exhibited enhanced mechanical strength (Karedla et al., 2024; Mache et al., 2023). In a study by Peter Laurian et al. (2024) on hot-blended PET plastic and sand found that incorporating 50% recycled PET plastic binder with 50% sand was sufficient for developing wall cladding composite materials with improved mechanical properties. This matrix ratio yields a high compressive strength (17 MPa) and low water absorption (0.84%) at a controlled temperature of 250°C. Notably, the utilized PET waste plastic exhibited a 355°C flash point and a 360°C fire point, and sand was mainly composed of 84.8% SiO₂ content. Ahmat et al. (2021); and Rojas-Valencia et al. (2022) found that recycled PET plastic can be utilized in the manufacture of partition blocks and bathroom wall tiles, and has also been revealed to be suitable for structural composite applications. Furthermore, the inclusion of recycled PET plastic in asphalt binders has been proven to enhance adhesion, viscosity, compressive strength, and durability (Awolusi et al., 2023; Mashaan et al., 2021).

While study on plastic waste inclusion as composite materials has potentially gained attention in construction due to their excellent properties, their specific inclusion for wall cladding remains relatively insufficient (Da Silva et al., 2021; Naderi Kalali et al., 2023). Critically, current research typically does not adequately highlight the unique performance demands of wall cladding or overall investigate the significance of incorporated PET plastic, sand, recycled steel fiber, and RHA for this specific use (Kumar & Bedi, 2025). Therefore, this research presents a novel investigation into the strategic inclusion of recycled steel fibers and RHA to PET-based composites to enhance their mechanical and durability characteristics, especially for wall cladding applications.

Recycled steel fibers, particularly those repurposed from vehicle tires, can enhance the mechanical strength and fire performance of composite materials (Ahmed et al., 2022). The inclusion of fiber reinforcements in composites can often decrease crack width under load, hence improving mechanical and durability characteristics in composites (Farhan et al., 2021; Wen et al., 2022). A study by Zeybek et al. (2022) revealed that 2% tire-recycled steel fibers was optimum in the performance evaluation of fiber-reinforced composites after incorporating 1%, 2%, and 3% fiber content in the observation of compression, splitting tensile, and flexure tests. Furthermore, Aisheh et al., (2022) revealed that the inclusion of 2.25% steel fiber content exhibited the optimal mechanical strength, and the mechanical properties of ultra-high-performance geopolymer concrete improved as the volume of steel fibers increased. However, higher fiber inclusion and adverse orientation can create voids that allow water to enter the composite (Dalvand & Ahmadi, 2021; Farhan et al., 2021).

Beyond tire-waste fibers, rice husk ash (RHA) offers significant potential as a sustainable component in construction materials. RHA, a byproduct of burning rice husks, is mainly composed of silica, transformed from waste into valuable composites, paving the way towards a circular economy. Incinerating rice husk at 600°C for three (3) hours results in ash with approximately 80% silica content, exhibiting pozzolanic activity

considered suitable for construction projects (Amran et al., 2021). The study by Tayeh et al. (2021) found that utilizing rice husk ash (RHA) as a filler component and a partial replacement for cement enhances the strength and durability characteristics of various composites, including concrete, tiles, and bricks. Similarly, Nurhayati & Susanto. (2020) demonstrated that replacing 10% or more of cement with RHA can adjust the optimum moisture content and reduce the maximum dry density in concrete. Furthermore, Yatawara & Athukorala. (2021) identified that a 7.5% RHA content was optimal when replacing clay soil with RHA (5%, 7.5%, 10%, 15%, and 20% by weight) in earth blocks for structural and non-structural internal walls. Soni et al. (2022) determined an optimal mixture for plastic composite materials consisting of 15% RHA, 70% plastic, and 15% sand. Jittin et al. (2020) reported that integrating 10-20% of RHA improves the engineering performance of construction materials. Despite its promising applications, the extensive use of RHA in construction is somewhat limited by the lack of well-defined inclusion procedures for its utilization as a supplementary cementitious material (Faried et al., 2021). Therefore, a well-detailed technical review on integrating RHA into alternative materials is the key to facilitating cleaner production pathways (Jittin et al., 2020).

This study explored the suitability of integrating rice husk ash (RHA), recycled PET plastic, and recycled steel fibers into composite wall cladding materials. The research aims to contribute to the development of sustainable and high-performance composite wall cladding for buildings in Tanzania. Successful development of these materials will significantly mitigate the environmental impact of plastic, vehicle tire, and rice husk waste. This, in turn, promotes circular economy practices and sustainability, while creating innovative solutions for the construction industry.

MATERIALS AND METHODS

Materials

The composite materials developed in this research were collected from various locally sourced materials. Fine aggregate (sand) was collected from the Kamawe River in Rukwa, Tanzania. Waste polyethylene terephthalate (PET) plastic bottles were sourced from the Nsalaga dumpsite in Mbeya, Tanzania, cleaned, dried, and cut into flakes approximately 10 centimeters by 2 centimeters. Recycled steel fibers (SFs) were recovered from waste vehicle tires sourced from the Soweto garage areas in Mbeya; these tires were incinerated for approximately two (2) hours to isolate clean fibers for use. Furthermore, rice husk ash (RHA) was produced by incinerating husks from the Kabwe dumping site in a furnace at 600°C for two hours. **Figure 1** displays the physical appearance of these materials, including Sand, recycled steel fibers, RHA and shredded PET.



Figure 1. River sand (A), recycled steel fibers (B), rice husk ash (C), shredded PET plastics (D)

Characterization of Raw Materials

A comprehensive testing program was implemented to characterize the physical and chemical properties of the materials. PET plastic was evaluated for density, melting temperature, flash, and fire points. The sand that passed through a 600 μm sieve underwent particle size distribution and chemical composition testing. Following the methodology observed by Peter Laurian et al. (2024), the SFs were measured to have an average length of 1.5 centimeters and diameter 0.3 millimeters. Similarly, the RHA was characterized for its chemical composition, specific density, specific surface area, and particle size distribution. Specifically, a Blaine air permeability apparatus was applied to characterize the specific surface area and associated physical properties of the RHA. The density of PET, Sand, and SFs materials were determined using Equation 1.

$$Density (\rho) = \frac{M}{V_2 - V_1}$$

(1)

Where M = mass of material sample, V₁ = initial volume of water in cylinder, V₂ = final volume of water and sample materials in cylinder.

Similarly, the specific density and specific surface area (SSA) of the RHA powder were measured using the method described by Siddika et al. (2021). The specific density (ρ) was determined using the volume of the Blaine tin as displayed in Equation 2.

$$\rho = \frac{2M}{V}$$

(2)

Where ρ =Specific density, M=Weight of sample at the turning point, V=Volume of the Blaine tin (1.628cm³).

The specific surface area (SSA) was subsequently measured according to Equation 3

$$SSA = K \frac{\sqrt{m_i M_i}}{\rho_{si}}$$

(3)

Where SSA=Specific surface area (cm²/g), m=Slope of the curve for air flow time versus weight of sample (sec/g), ρ_{si} =Density at turning points, M=Sample mass, K=Apparatus measurement constant (1050).

Moreover, the particle size distribution of the RHA powder was further analyzed following the methodology suggested by Vieira et al. (2020), as defined in using Equation 4 and 5.

$$G\rho_s = K \left[\frac{1}{\eta\alpha(m_1+m_2)} \right] \times \left[\frac{M_1 - \alpha M_0}{M_f - M_0} \right]$$

(4)

Where G_{ps}=Grain particle size (g), K=Constant (13,650), $\eta\alpha$ =Dynamic viscosity of air at room temperature, m₁ & m₂=gradient at the lower and middle curves, M₀=Weight of sample at zero-time, M_f=Weight of sample at second turning point, α =Factor for sample weight at zero air flow (0.99).

Additionally, the temporal characteristics of the air flow during the measurement process were measured using Equation 5

$$\%CP = 100 \frac{T_i}{T_f}$$

(5)

Where T_i = Time air for each measurement, T_f = Time air at second turning

Material densities were evaluated to forecast the theoretical weights of the wall cladding specimens prior to fabrication. As established by Omosibi and Abass (2021), any significant discrepancy between the cumulative density of individual components against the final hot-mixed specimens serve as an indicator of chemical transformations during the blending process.

Shredded PET plastic demonstrated a melting temperature between 240°C and 255°C. This temperature was analyzed by the hot plate method after three iterations to ensure precision. Similarly, using the Cleveland open cup method, in accordance with MoW (2000), a flash and fire points were measured at 355°C, and 360°C respectively, were observed. Pre-determining these thermal thresholds before hot mixing is critical to prevent material ignition during the fabrication of the composite. According to Laurian et al. (2024), exceeding the flash point can lead to combustion of the PET, resulting in ash formation and making it unsuitable as a binder for the composite matrix of sand, recycled steel fibers, and rice husk ash.

The elemental oxide compositions of the river sand and RHA was determined using X-ray fluorescence (XRF) analysis. The sand and RHA samples were ground to a fineness of 3656 cm²/g using a ball mill to ensure homogeneity. **Table 1** presents the elemental compositions of the RHA and sand applied in this research. The chemical composition of materials affects other material properties such as thermal resistance and mechanical strength; therefore, it is critical to assess the oxide composition of materials, particularly RHA and sand. Silica content of at least 80% in sand and 90% in RHA can withstand temperatures exceeding 600°C (Amran et al., 2021; Channa et al., 2024).

Table 1. Elemental composition of sand and RHA as done by the XRF machine

Oxides (%)	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Na ₂ O	K ₂ O	P ₂ O ₅	TiO ₂	Cr ₂ O ₃
Sand	82	6.3	6.04	0.6	0.2	0.01	0.23	1.10	0.03	0.5	0.02
RHA	91	0.3	0.5	0.6	0.2	0.02	0.11	2.01	0.2	0.03	0.02

Particle Size Distribution (PSD) of the river sand sample was carried out following the procedures outlined in MoW (2000). The river sand (sieved through a 600 µm sieve) blended with PET waste plastics, steel fibers, and RHA to make cladding and tile composites (Hamzah & Alkhafaj, 2022).

Fabrication of Composite Cladding Specimens

Composite specimens were fabricated using a thermal blending process. Initially, river sand (45%), recycled SFs (2.5%), and RHA (5%) were pre-heated in a 50 x 50 cm steel mold at 240°C for approximately 6 minutes. Pre-heating was essential to dehydrate the inorganic components, thereby resisting steam generation and subsequent pore formation in the final composite. This step also synchronized the temperature of the river sand, SFs, and RHA with the melting point of the PET (240-255°C), enhancing wetting efficiency and mitigating thermal shock. Shredded PET plastic (50% by weight) was introduced into the heated mixture. The constituents were hot mixed at a controlled temperature of 250°C and stirred continuously until the homogeneous, molten blend was achieved. The melted mixture was cast into oiled (24.4cm x 12.2cm x 2cm) mold, compressed, and cured at room temperature (Figure 2). To evaluate the effect of varying filler ratios, the RHA content was increased from 5% to 20% as a partial replacement for river sand (45% to 30%), while keeping PET and SF content constant. Melting was performed in a locally made steel pot furnace fueled by wood dust and rice husks; with firing process monitored via a 1500°C digital thermometer. The mixing temperature (250°C) provides a safety margin of 105°C below the flash point.

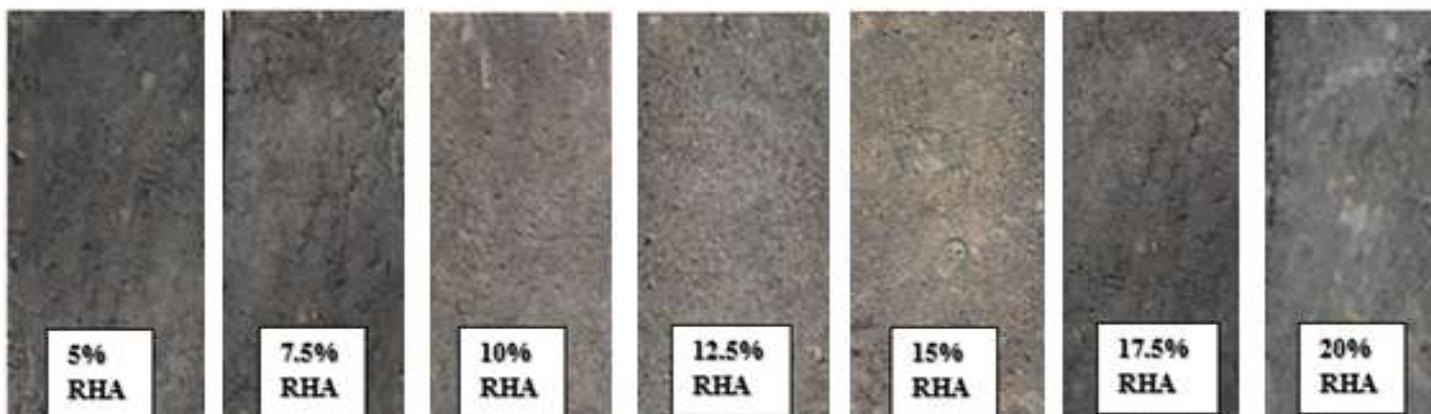


Figure 2. Cladding specimens with different RHA contents

Physical Properties Characterization

The densities of the cladding specimens were determined in accordance with the procedures from MoW (2000). Density of the cladding specimens is a critical parameter for understanding their dead load imposed on

structures and the logistics of transportation. Specimen densities were measured using Equation 1

Water absorptions of the specimens were performed following MoW (2000) and Sahu & Gupta (2022) to assess the material's resistance to moisture ingress and internal dampness. Specimen water absorption was calculated using Equation 6. This analysis is essential for determining the quantity of water uptake, also aids in managing internal dampness within structures.

$$\text{Water absorption (\%)} = \frac{(M_2 - M_1)}{M_1} \times 100 \quad (6)$$

Where M_1 = the mass of the specimen before water immersion, M_2 = mass of the specimen after water immersion.

Mechanical Properties Characterization

Compressive strength of specimens was evaluated using the rebound hammer method to describe the material's resistance to breakage during handling and installation. Nine rebound readings were taken per specimen: three at the central region, and three at the two sides of the edges and corners. The mean rebound hammer readings were converted into compressive strengths in MPa via Equation 7 (Kumavat et al., 2021).

$$C \text{ (Mpa)} = 0.788N^{1.03} \quad (7)$$

Where C = compressive strength of specimen (MPa), N = rebound hammer reading, Mpa= Mega Paschal

Impact strength of the composite specimens was determined via a drop-ball test utilizing a 338.8 g steel ball (4.54 cm diameter). The steel ball was released from heights of 100 cm onto six points on each specimen surface, two at each edge, and two at the center. A ruler was applied to measure the rebound height (H_{rebound}) to determine the energy dissipated. The impact energy absorption was calculated using Equation 8 (Finnerty et al., 2023).

$$IE \text{ (Joules)} = M \times G \times H \quad (8)$$

Where IE = impact energy absorbed (Joules), M = mass of steel ball (kg), G = acceleration due to gravity (10m/s^2), H = drop height (m). H ($H_{\text{initial}} - H_{\text{rebound}}$)

RESULTS

Material Characterization

PET plastics indicated a density of 1.305 g/cm^3 , a flash and fire points of 355°C , and 360°C , respectively (Peter Laurian et al., 2024), and a melting range of $240\text{-}255^\circ\text{C}$, align with its semi-crystalline nature (Guclu et al., 2022; Slezák et al., 2023). Recycled steel fibers had a density of 7.788 g/cm^3 , while river sand and RHA demonstrated densities of 2.59 g/cm^3 and 2.139 g/cm^3 , respectively. XRF analysis (Table 1) confirmed high silica content in both RHA (91%) and sand (82%), validating their suitability and thermal stability for composite applications (Emah et al., 2024).

Physical Properties

Density was inversely related to RHA content (Figure 3), decreasing from 2.469 g/cm^3 (0% RHA) to 1.495 g/cm^3 (20%). This reduction is related to RHA's lower specific gravity (Selvaranjan et al., 2021). Water absorption (Figure 4) raised proportionally from 1.80% to 3.12%. Notably, most composite specimens remained within the ASTM C373 'Vitreous' range (0.5%-3.0%). The 12.5% RHA mix falls under the 3% threshold, while the 20%RHA mix may be classified as 'semi-vitreous'.

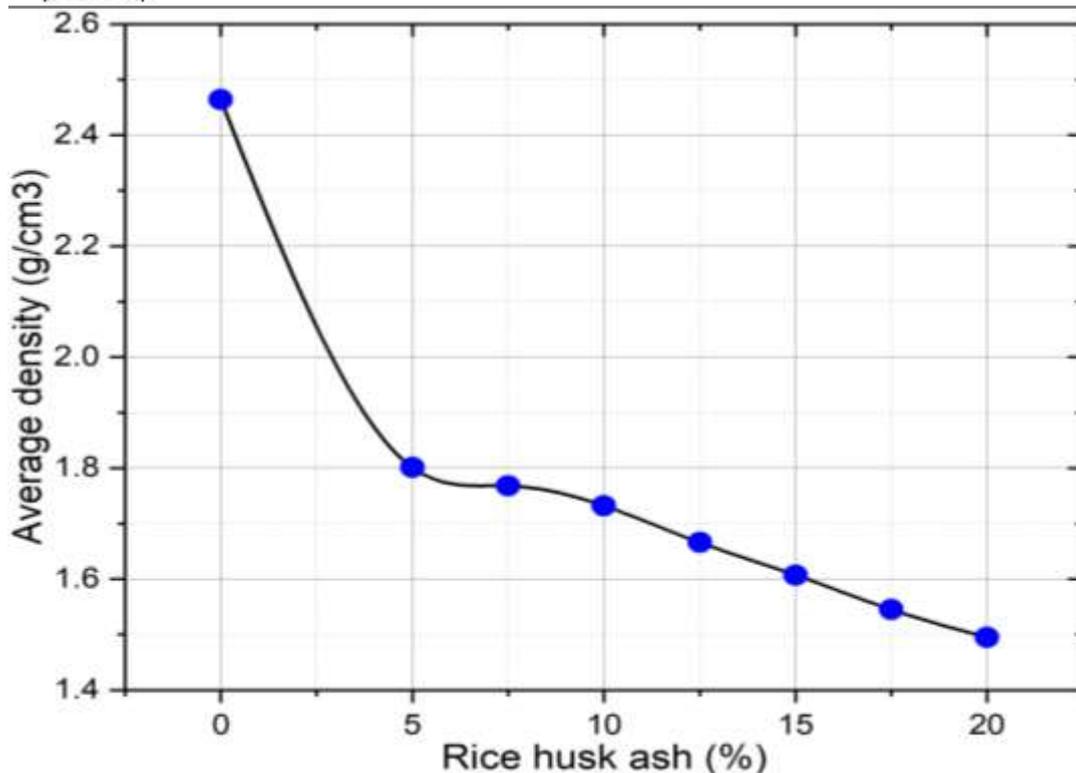


Figure 3. Density variation in the Composite cladding material

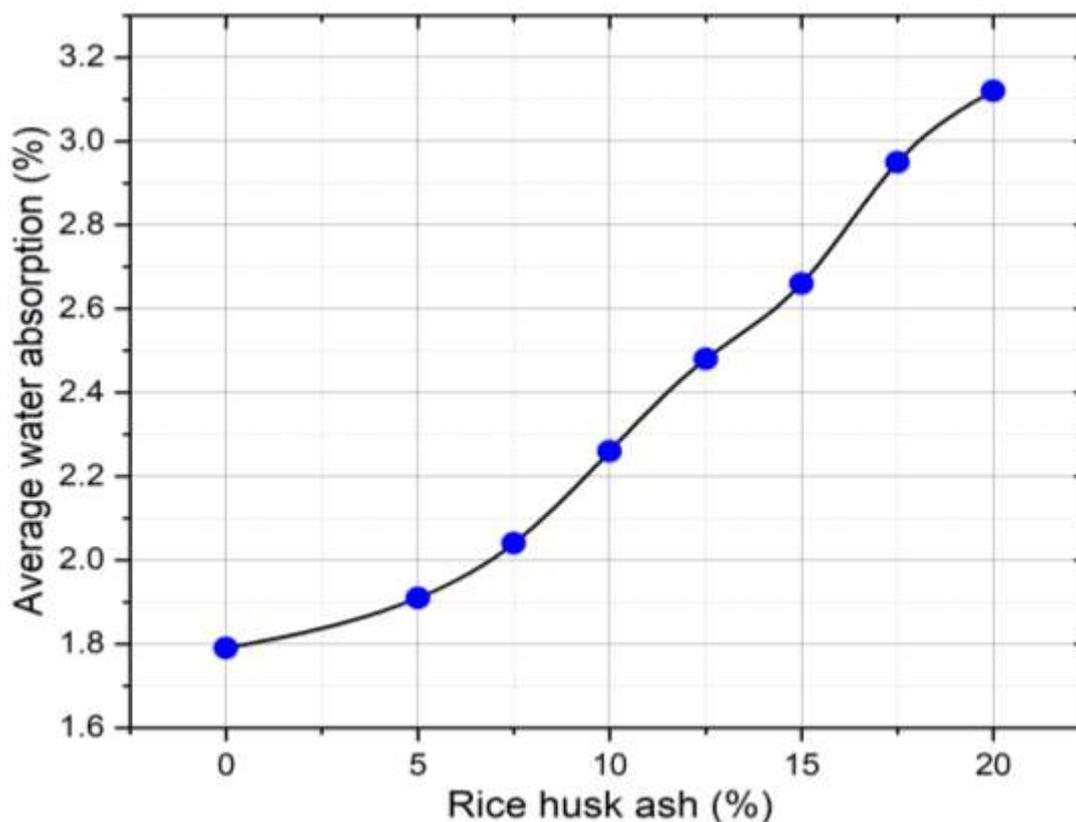


Figure 4. Water absorption of composite cladding material

Mechanical Properties Composite Cladding Materials

Compressive strength followed a non-linear trend (Figure 5), peaking at 24.1 MPa with 12.5% RHA content. Impact testing revealed no visible damage at 100 cm drop heights across all composites. The 12.5% RHA specimen exhibited the highest energy absorption at 3.29 Joules.

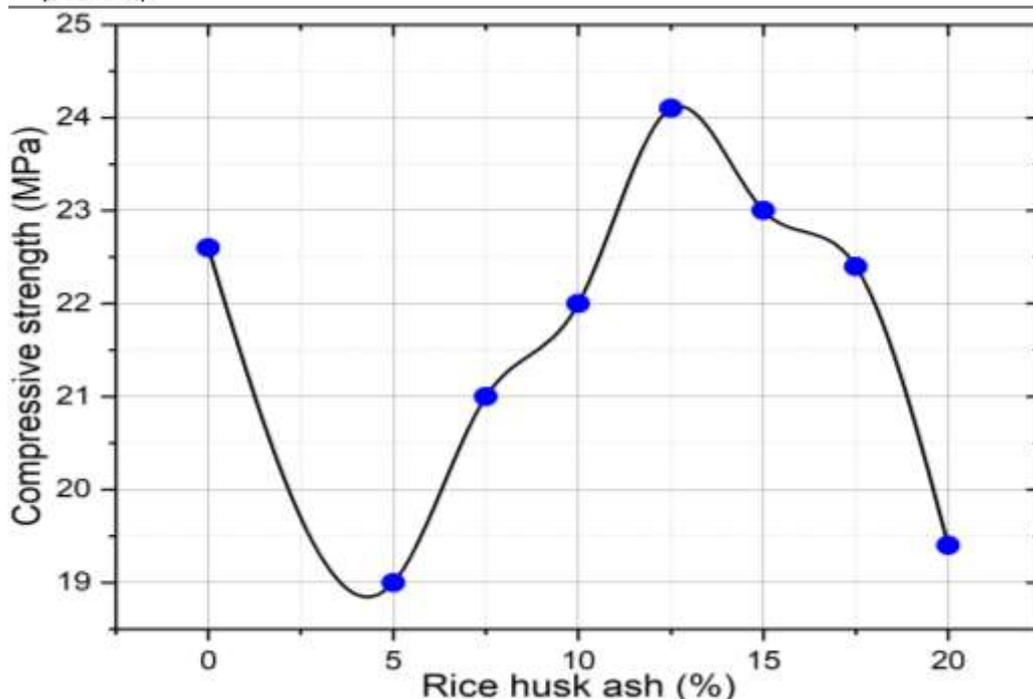


Figure 5. Compressive strength of composite cladding materials

DISCUSSION

Mechanistic Interpretation of Properties

The reduction in density confirms RHA as an effective lightweight filler, providing easier logistics for rural construction. The 40% weight reduction enables for manual handling without heavy machinery, which is a major benefit in developing regions. The increase in water absorption at higher RHA contents (20%) is likely caused by the hydrophilic nature of silica and crucial interfacial voids between the reinforcement fibers and polymer binder.

The maximum compressive strength at 12.5% RHA shows an optimal particle packing density. At this threshold, RHA particles serve as secondary reinforcement, refining the matrix and reducing micro-cracks (Ezenkwa et al., 2022). However, beyond 12.5% RHA likely resulting to “binder starvation”, where the PET matrix cannot fully cover the high surface area of the ash (4948.424 m²/g), leading to a reduction in strength and increased voids.

The specific surface area of RHA needs a proportional increase in PET quantity to ensure fully particle coating. Beyond 12.5% RHA, the constant 50% PET volume becomes insufficient to lubricate and bind the entire surface area, leading to the identified drop in compressive strength.

Structural Robustness and Sustainability

The high impact resistance is credited to the bridging effect of the recycled steel fibers, which transfer loads and mitigates crack extension (Nurazzi et al., 2021; Sharma et al., 2023). Compared to conventional cement-based claddings (which typically range from 7-15 MPa), this PET-RHA composite contributes to a superior strength (24.1 MPa) and lower moisture absorption. By substituting high-cost river sand with zero-cost agricultural residue (RHA), the formulation embodies a “waste-to-resource” model that integrates structural integrity with significant economic feasibility.

Methodological Acknowledgement

Non-destructive rebound hammer testing was implemented to characterize surface hardness. While effective for identifying the optimal 12.5% mix ratio, the authors acknowledge that future destructive testing using

Universal Testing Machines (UTM) is required to validate absolute structural values and long-term durability against UV and thermal cycling.

CONCLUSION AND RECOMMENDATIONS

Conclusions

This research validated a thermal mixing framework for converting recycled PET plastic, sand, recycled steel fibers (SFs), and rice husk ash (RHA) into a high-performance cladding composite. The following conclusions are drawn:

- **Mechanical Thresholds:** A potential optimal point for RHA integration was observed at 12.5%. At this content, the composite achieved a maximum compressive strength of 24.1 MPa and Impact energy absorption of 3.29 Joules. This characteristic exceeds traditional fiber-cement benchmarks, suggesting that RHA acts as an effective micro-filler that enhances matrix density until the binder-to-filler ratio reaches a point of “binder starvation.”
- **Physical Optimization:** RHA replacement successfully converted the material into a lightweight option, minimizing density by approximately 40% (from 2.469 g/cm³ to 1.495 g/cm³). This yields a material with excellent strength-to-weight ratios suitable for seismic-resistant or minimal-load cladding applications.
- **Moisture Performance:** Despite the hydrophilic nature of RHA, the PET-bound limited the matrix’s water absorption levels to less than 3.12%. This suggests that the polymeric binder effectively seals the porous ash, ensuring the material meets the criteria for “Vitreous” classification under the ASTM C373 protocol.
- **Technical Viability:** The thermal alignment between the PET melting phase (240-255°C) and the silica-rich RHA enables homogeneous blending without the need for high-cost chemical additives, establishing a feasible waste-to-resource pathway.

Recommendations

To facilitate the industrial adoption of this material from lab-scale, the following methodological frameworks are recommended to maintain material integrity and regulatory compliance at volume:

- **Standardized Compressive Testing:** While the rebound hammer established a valuable comparative baseline for mix optimization, future studies should incorporate destructive crushing tests to calibrate and validate absolute structural performance. It is acknowledged that the shape factor of cladding (2cm thickness) may influence rebound values compared to standard 150mm cubes.
- **Long-term Durability:** Empirical assessment of UV degradation, thermal fatigue, and fire performance is essential. Given the 355°C flash point of PET, research into fire-retardant mineral-based coatings is recommended for applications in high-occupancy building use.
- **Microstructural Analysis:** Future research involving SEM (Scanning Electron Microscopy) is recommended to visualize the interfacial bonding between the steel fibers and the PET/RHA matrix, providing a clear understanding of the energy dissipation mechanisms during impact. Specifically looking for “Fiber pull-out” versus “Fiber rupture”.
- **Standardization:** Tanzania construction authorities such as NEMC and NCC should formalize technical guidelines for recycled plastic composites to facilitate the transition toward a circular economy solution within national housing projects.

Conflict Of Interest Statements

The authors have declared that there is no conflict of interest related with this publication.

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