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Eco-Efficient Composite Roof Tiles from Recycled PET Bottles and Lightweight Red Ash: Manufacturing, Mechanical Performance, and Durability

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Abstract

The increasing accumulation of polyethylene terephthalate (PET) bottle waste poses a growing environmental challenge and underscores the need for sustainable waste-valorization strategies within a circular economy framework. This study develops an eco-efficient composite roof tile using recycled PET as a polymeric matrix and lightweight red ash aggregate (LWA) powder as mineral filler. PET contents ranging from 0 to 100% were investigated to determine their effects on compressive strength, water absorption, density, and resistance to cyclic loading. The results revealed a distinct nonlinear relationship between PET content and compressive strength. The strength increased to approximately 35 MPa at 45% PET, indicating an optimum composition, and subsequently decreased to approximately 15 MPa at 95% PET. The improved strength at intermediate PET contents may be associated with enhanced matrix–aggregate bonding, reduced void formation, and more effective stress transfer, whereas excessive PET content reduced structural rigidity. Water absorption decreased substantially with increasing PET content, reaching approximately 1% at 75–95% PET, owing to the hydrophobic nature and pore-sealing effect of PET. The density decreased progressively from approximately 2100 to 1300 kg/m³, demonstrating the lightweighting potential of the composite. Under cyclic loading, the damage index decreased from 0.90 for the control mixture to 0.45 for the optimized composite, indicating improved resistance to damage and crack development. Overall, 45% PET provided the most balanced combination of compressive strength, moisture resistance, damage resistance, and reduced density. The findings demonstrate the potential of waste PET and red ash to be converted into value-added, lightweight, and durable roofing materials while simultaneously reducing plastic waste and dependence on conventional construction resources.

Keywords: Recycled PET, red ash, Tile composite, Circular economy, Sustainable materials, Eco-efficient manufacturing, Waste valorization.

1. Introduction

The construction sector is one of the world's most resource-intensive industries, consuming substantial quantities of virgin raw materials and contributing significantly to greenhouse-gas emissions, resource depletion, and environmental degradation [1]. Concurrently, the rapid

growth in plastic consumption has resulted in increasing quantities of post-consumer plastic waste, particularly polyethylene terephthalate (PET) from beverage bottles. PET is extensively used because of its high strength-to-weight ratio, durability, chemical resistance, transparency, and relatively low production cost. However, its high environmental persistence and increasing disposal volumes have created significant challenges for waste-management systems [2].

The continuous generation of PET waste, coupled with inadequate collection, sorting, and recycling infrastructure in many regions, highlights the need for innovative waste-valorization strategies. Conventional recycling pathways alone may be insufficient to accommodate the rapidly increasing volume of discarded plastics, creating a strong incentive to convert waste PET into value-added products [3]. At the same time, the growing demand for sustainable construction materials has encouraged the development of alternative building products that reduce dependence on virgin resources while maintaining acceptable mechanical and functional performance [4, 5]. Incorporating waste PET into construction materials therefore offers a dual benefit by diverting plastic waste from disposal while partially replacing conventional raw materials.

One promising approach is the development of polymer–aggregate composites in which molten PET functions as a thermoplastic matrix and mineral aggregates provide structural reinforcement and dimensional stability [6]. Previous studies have investigated various lightweight aggregates, including expanded clay, pumice, and perlite, in polymer-based construction composites [7]. PET–aggregate composites can potentially provide reduced weight, low water permeability, and improved resistance to moisture compared with conventional cement- or clay-based materials [8]. The conversion of waste PET into roofing products is particularly attractive because roofing components require adequate mechanical strength, resistance to environmental exposure, and relatively low weight. Thus, the use of recycled PET in roof tiles can simultaneously contribute to plastic-waste management and resource conservation in the construction sector [9].

The sustainability of such composites can be further enhanced through the incorporation of waste-derived mineral aggregates or industrial by-products. Red ash is a potentially useful secondary raw material that can be processed into a fine aggregate for composite construction applications [10]. Its incorporation can reduce the consumption of virgin aggregates while providing an additional pathway for the utilization of waste or industrial by-products. In a PET–red ash composite, the molten PET can surround and bind the fine ash particles during processing, potentially producing a dense and consolidated material with desirable mechanical and moisture-resistance characteristics [11]. The resulting composite therefore provides an opportunity to simultaneously valorize two waste-derived resources within a single construction product.

The performance of recycled PET-based composites is strongly influenced by the relative proportions and characteristics of the constituent materials. Previous investigations have shown that PET can affect the strength, toughness, crack resistance, water resistance, and durability of polymeric and cement-based composites [12–14]. However, the PET content

must be carefully optimized. Insufficient PET may result in inadequate wetting and bonding of aggregate particles, whereas excessive PET may alter the stiffness, load-transfer mechanism, and structural integrity of the composite. Similarly, aggregate particle size, surface characteristics, porosity, processing temperature, mixing conditions, and molding pressure can influence the interfacial interaction between PET and the aggregate. Consequently, optimization of the PET-to-aggregate ratio is essential for obtaining an appropriate combination of strength, moisture resistance, density, and damage resistance.

From a circular-economy perspective, the conversion of post-consumer PET into construction products provides an effective pathway for retaining material value and reducing dependence on virgin polymer resources. Rather than treating discarded PET as an environmental liability, it can be utilized as a secondary raw material in value-added products, thereby supporting waste reduction, resource efficiency, and sustainable manufacturing [15–17]. Incorporating waste-derived red ash further strengthens this circularity by simultaneously utilizing polymeric and mineral waste streams in a single composite material.

Recent studies have confirmed the potential of recycled PET for producing sustainable construction composites, while also demonstrating that its effect on mechanical and physical performance depends strongly on PET content, particle morphology, aggregate characteristics, and matrix interactions [18]. Recent reviews have emphasized the importance of optimizing PET-based formulations to achieve an appropriate balance among mechanical performance, durability, weight reduction, and sustainability [19]. PET has also been investigated in roofing applications, demonstrating its potential for producing roof tiles with modified physical and thermal characteristics [20]. Furthermore, recycled PET has been combined with other waste-derived materials, including soda-lime glass, to manufacture lightweight composite roof tiles [21]. Nevertheless, limited attention has been given to roof tiles produced from molten post-consumer PET and fine red ash, particularly regarding the systematic effect of PET–red ash composition on compressive strength, water absorption, density, impact resistance, and damage resistance. This represents an important research gap because the optimum PET content required to simultaneously achieve mechanical integrity, moisture resistance, lightweight characteristics, and resistance to damage remains insufficiently established.

Therefore, this study aims to develop an eco-efficient composite roof tile using waste PET as a polymeric matrix and fine red ash as a lightweight aggregate powder and to systematically evaluate its key performance characteristics. The study specifically examines the influence of PET–red ash composition on mechanical strength, water absorption, density, impact resistance, and other relevant physical and durability properties. The ultimate objective is to identify an optimized formulation capable of providing an appropriate balance between mechanical performance, durability, lightweight characteristics, and environmental sustainability. By converting two waste-derived resources of post-consumer PET and red ash into a value-added roofing material, this approach promotes waste valorization, reduces reliance on conventional raw materials, and supports circular-economy principles in sustainable construction.

2. Materials and Methods

2.1. Materials

Waste PET bottles: Post-consumer PET bottles were collected from municipal waste streams and manually sorted to remove non-PET materials, caps, labels, and visible contaminants. The bottles were thoroughly washed, dried, and mechanically shredded into PET flakes with particle sizes ranging from approximately 2 to 5 mm, as shown in Fig. 1(a). The prepared PET flakes were subsequently heated to approximately 260–280 °C to achieve sufficient melting and flowability for mixing with the lightweight red ash aggregate powder and subsequent molding of the composite roof tiles. The heating temperature was controlled to obtain adequate PET melt flow while minimizing excessive thermal degradation during processing.

Light weight red ash aggregate powder: As shown in Fig. 1(b), readily available red ash was collected from local brick-production facilities and processed for use as a lightweight aggregate. The collected material was dried and processed into a fine powder suitable for mixing with molten PET. The red ash exhibited a relatively porous structure, irregular particle morphology, and rough surface texture, characteristics that can promote mechanical interlocking and interaction with the molten PET matrix. Its relatively low density also provides potential for reducing the weight of the resulting composite roof tiles. Prior to mixing, the red ash was dried to minimize moisture-related defects and improve the consistency of the PET–red ash powder composite during processing.

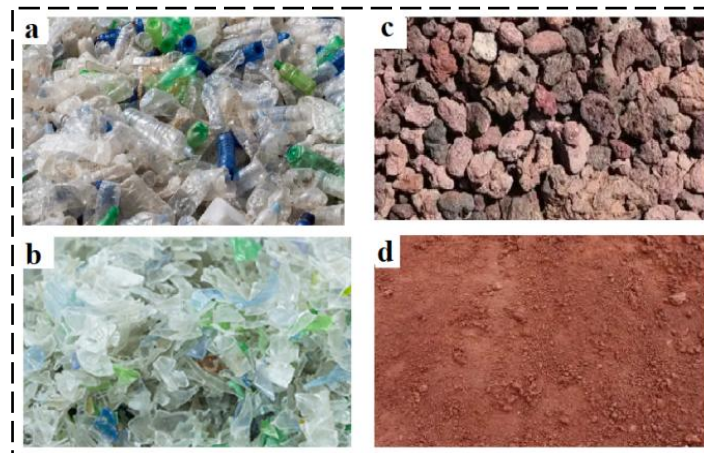


Fig. 1: Waste PET bottles (a) and its shredded flexes. Light weight red ash aggregate (c) and its powder (d).

2.2. Methodology

The experimental methodology was organized into two main phases: (i) fabrication of the composite roof tiles and (ii) characterization and performance evaluation of the developed composites. In the first phase, post-consumer polyethylene terephthalate (PET) bottles were processed into flakes and thermally melted to form a polymeric matrix, while processed

lightweight red ash was prepared as a fine mineral aggregate. The PET and red ash were subsequently combined at predetermined compositions and molded under controlled conditions to produce composite roof-tile specimens. In the second phase, the fabricated specimens were systematically characterized to determine the effects of PET content on their physical and mechanical properties, including density, water absorption, compressive strength, and resistance to impact/cyclic loading. The experimental results were then compared across the different PET–red ash compositions to determine the formulation providing the most favorable combination of mechanical performance, moisture resistance, damage resistance, and reduced density.

2.2.1. Mold Design

A rigid metallic mold was designed and fabricated for producing composite roof-tile specimens with controlled dimensions and uniform geometry. The mold consisted of two metallic plates measuring 300 mm × 200 mm × 20 mm, which were carefully aligned and firmly connected using nut-and-bolt fasteners. The assembled configuration provided a stable molding cavity and minimized dimensional variation during filling, compaction, and cooling of the PET–red ash composite, as illustrated in Fig. 2.

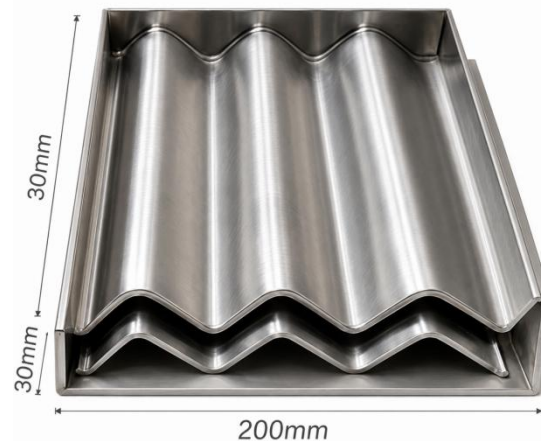


Fig. 2: Metallic mold

Before molding, the internal surfaces of the mold were cleaned to remove contaminants and, where applicable, treated with a suitable release agent to facilitate demolding after cooling. The predetermined quantities of molten PET and prepared red ash were introduced into the mold cavity and distributed as uniformly as possible. The assembly was then subjected to the specified compaction procedure to consolidate the mixture and promote intimate contact between the molten PET matrix and red ash particles. After compaction, the molded composite was allowed to cool and solidify under controlled conditions before removal from the mold. The resulting specimens were visually inspected for dimensional uniformity, surface defects, and incomplete consolidation before subsequent characterization.

2.2.2. Production Process of Eco-Efficient Roof Tiles from Waste PET and Red Ash Fine powder

The fabrication process used to produce the composite roof tiles from waste polyethylene terephthalate (PET) and fine red ash powder is illustrated schematically in Fig. 3. The process consisted of eight main stages:



Fig. 3: Schematic diagram of developing eco efficient roof tile from a mixture of waste PET and fine red ash powder.

(A) Waste PET Collection and Sorting: Post-consumer PET bottles were collected from household, commercial, and municipal waste streams. The collected bottles were manually sorted to remove non-PET components, including caps, labels, and other visible contaminants. The sorted PET bottles were retained as the polymeric matrix precursor for the composite roof tiles.

(B) Cleaning, Drying, and Shredding: The sorted PET bottles were thoroughly washed with water and, where necessary, a mild detergent to remove dirt, oil, labels, and other surface contaminants. The cleaned bottles were subsequently dried to minimize moisture during thermal processing. The dried bottles were mechanically shredded into PET flakes with a relatively uniform particle size of approximately 2–5 mm. The reduction in particle size facilitated more uniform heating and melting and promoted efficient mixing with the red ash powder.

(C) Melting of PET: The prepared PET flakes were gradually heated in a suitable melting unit to a temperature of approximately 260–280 °C until sufficient melt flow was achieved. The temperature was monitored throughout the melting process to maintain consistent processing conditions and minimize excessive thermal degradation. The molten PET was

mixed to obtain a relatively homogeneous polymeric phase before incorporation of the red ash powder.

(D) Preparation and Incorporation of Fine Red Ash: The collected red ash was dried to remove residual moisture and subsequently processed to obtain a fine powder suitable for composite fabrication. The prepared red ash was gradually introduced into the molten PET according to the predetermined mix proportions. The PET–red ash mixture was continuously mixed to promote uniform dispersion of the red ash particles throughout the polymeric matrix and to facilitate intimate contact between the two phases.

(E) Compression Molding: The hot PET–red ash mixture was transferred into a preheated metallic mold having the required roof-tile dimensions. The mold was subjected to controlled compression under the predetermined molding conditions to consolidate the composite and minimize the formation of internal voids. Compression also promoted intimate contact between the molten PET matrix and red ash particles and enabled the composite to conform to the desired roof-tile geometry. The molding temperature, applied pressure, and holding time were maintained consistently for all formulations.

(F) Cooling, Demolding, trimming and Finishing: Following compression molding, the formed roof tiles were allowed to cool under controlled conditions until the PET matrix solidified and the composite became sufficiently dimensionally stable for demolding. The solidified tiles were carefully removed from the mold, and excess material and irregular edges were trimmed to obtain consistent specimen dimensions. The fabricated roof tiles were subsequently conditioned prior to physical and mechanical characterization. A representative composite roof-tile specimen is presented in Fig. 4.

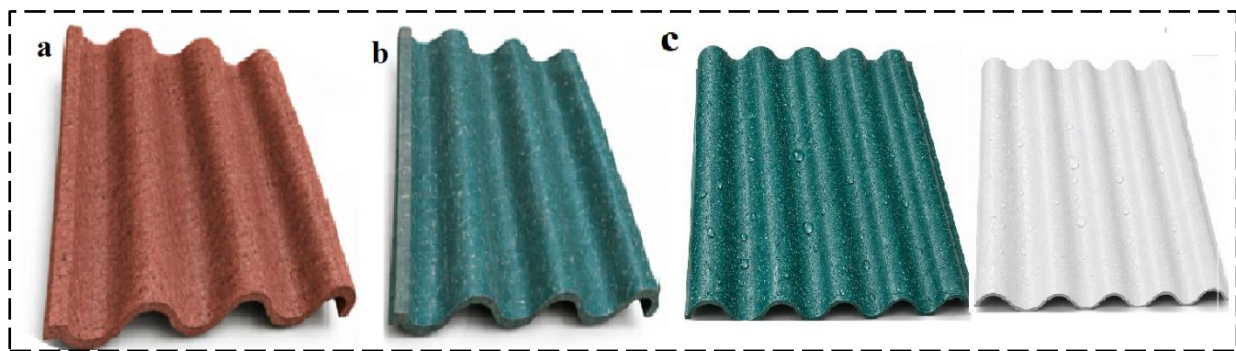


Fig. 4: prepared roof tile sample (a), metal paint tinted sample (b), and water proofed roof tile (c).

2.2.3. Mix Design and Sample Preparation

The experimental design was established by systematically varying the PET matrix content and corresponding fine red ash powder content while maintaining a total mixture composition of 100 wt.%. Eight PET–red ash formulations were investigated, containing 0, 15, 30, 45, 60, 75, 90, and 100 wt.% PET, corresponding to 100, 85, 70, 55, 40, 25, 15, 10 and 0 wt.% red ash, respectively. This systematic variation was designed to establish the effect of PET–red

ash composition on the physical, mechanical, and damage-resistance characteristics of the composite roof tiles and to identify the composition providing the most favorable overall performance.

For each formulation, the required quantities of PET flakes and dried red ash were determined on a mass basis. The PET was melted under the specified thermal conditions, after which the predetermined quantity of red ash was gradually incorporated into the molten polymer and mixed until a visually uniform composite mixture was obtained. The resulting hot mixture was then transferred to the preheated mold and compression-molded under identical processing conditions. After cooling and demolding, the specimens were trimmed and conditioned before testing. Multiple specimens were prepared for each formulation to improve the reliability and reproducibility of the measured properties.

2.3. Testing Procedures

2.3.1. SEM Microstructural Analysis

Representative fractured specimens of the PET–red ash composite were cut into small pieces (approximately 5–10 mm), cleaned, and oven-dried at 60–80 °C. The dried samples were mounted on aluminum SEM stubs using conductive carbon tape and sputter-coated with a thin gold or gold–palladium layer to minimize surface charging. SEM analysis was conducted at an accelerating voltage of approximately 5–15 kV and different magnifications to examine the microstructure. Particular attention was given to PET–red ash interfacial bonding, particle dispersion, pore structure, micro voids, cracks, and particle pull-out. The obtained micrographs were compared among different PET/red ash compositions to determine the effect of PET content on matrix compactness, interfacial adhesion, and crack resistance. Where available, EDS analysis was also used to identify the elemental composition of the red ash particles.

2.3.2. Chemical Composition Analysis (FTIR) and The Thermal Behavior (DSC)

Fourier transform infrared (FTIR) spectroscopy was employed to identify the characteristic functional groups and chemical bonding features of the PET–red ash composite. Representative samples were dried, finely ground, and analyzed using an FTIR 1000 spectrometer equipped with an attenuated total reflectance (ATR) accessory. Spectra were recorded over the range of 4000–400 cm^{-1} at a resolution of 4 cm^{-1} with 32 scans per sample. The resulting spectra were examined for characteristic absorption bands associated with PET, particularly carbonyl (C=O) and C–O groups, as well as bands attributable to mineral phases present in the red ash, including Si–O–Si and related aluminosilicate vibrations. The observed bands were interpreted in comparison with relevant literature data and, where available, the FTIR spectrum of the individual constituents.

Differential scanning calorimetry (DSC) was used to characterize the thermal behavior of the 45:55 wt.% PET–red ash composite, corresponding to the formulation identified as the optimum composition based on the overall physical and mechanical performance. The analysis was conducted using a DSC 4000 instrument. A precisely weighed sample of

approximately 2 mg was placed in a DSC pan and analyzed under a nitrogen atmosphere at a controlled heating rate of 10 °C/min over the temperature range of 22 to 350 °C. The DSC thermogram was analyzed to determine the glass-transition temperature (T_g), cold-crystallization temperature (T_{cc}), and melting temperature (T_m). Where applicable, the corresponding crystallization and melting enthalpies were also determined. The thermal transitions were used to evaluate the thermal behavior of the composite and to assess its relationship with the processing conditions.

2.3.3. Flexural strength

The flexural strength of the PET–red ash roof-tile composite was determined using a three-point bending configuration. Specimens were cut from the molded roof tiles, and their width and thickness were measured before testing. Each specimen was positioned on two supports of a universal testing machine and loaded at its midpoint at a constant crosshead speed of [insert value] mm/min until failure or the specified maximum deformation was reached. The maximum applied load was recorded. For a rectangular specimen, the flexural strength was calculated using:

$$\sigma_f = \left(\frac{3PL}{2bd^2} \right) \text{-----(1)}$$

where P is the maximum load (N), L is the support span (mm), b is the specimen width (mm), and d is the specimen thickness (mm). Three specimens were tested for each formulation, and the mean value and standard deviation were reported.

2.3.4. Compressive Strength Tests

The compressive strength of the PET–red ash composite was determined using a universal testing machine. The specimens were prepared to the specified dimensions and positioned centrally between the compression platens in accordance with ASTM C109 standards [22]. Load was applied at a controlled rate of [insert value] until failure or significant deformation occurred. The maximum compressive load was recorded. The compressive strength was calculated from:

$$CS = \left(\frac{F}{A} \right) \text{-----(2)}$$

Where, Cs is compressive strength, F is force and A is area of samples

2.3.5. Water Absorption Test

Water absorption was evaluated using a procedure based on ASTM D570-22, which provides a standardized method for determining water absorption of plastics [23]. Specimens measuring 60 × 60 × 10 mm³ were prepared from the composite roof tiles. Five specimens were tested for each formulation. The specimens were dried under the specified conditioning conditions, cooled to room temperature in a desiccated environment, and weighed to obtain

their initial dry mass (W_i). The specimens were subsequently immersed in distilled water at 22 ± 2 °C for the specified exposure period. After immersion, excess surface water was removed using a standardized procedure, and the specimens were immediately weighed to obtain the final mass (W_f). Water absorption was calculated as:

$$WA\% = \left(\frac{W_f - W_i}{W_i} \right) * 100 \text{-----} (3)$$

Where, WA% is water absorption %age, W_f is final sample Wight and W_i , is initial sample weight. The mean and standard deviation were calculated for each formulation.

2.3.6. Density Reduction and Self-Weight Analysis

The bulk density of the fabricated composite roof tiles was determined using the mass-to-volume relationship. After conditioning, each tile was weighed using a calibrated digital balance, and its length, width, and thickness were measured at multiple locations. The average dimensions were used to calculate the specimen volume. The mass of each complete roof tile was also recorded to assess its potential contribution to structural dead load. ASTM C29/C29M-23 [24] is specifically a test method for the bulk density and voids of aggregate; therefore, if it is cited, it should be described as a basis or adapted procedure rather than as a direct standard for the finished composite roof tile. The density reduction relative to the selected conventional reference roof tile was calculated as:

$$\rho = \left(\frac{M}{V} \right) \text{-----} (4)$$

Where, ρ is density, m is mass and V is volume of the sample

2.3.7. Durability and Environmental Resistance

The resistance of the PET–red ash composites to cyclic environmental exposure was evaluated using controlled cycling conditions. Where freeze–thaw exposure was employed, the procedure was adapted from ASTM C666/C666M-26 [25], which specifies laboratory procedures for evaluating the resistance of concrete to repeated freezing and thawing. Because the developed roof tile is a non-cementitious polymer–aggregate composite, the applicable procedure and any modifications to the ASTM protocol should be explicitly described. A total of 50 cycles were applied under the selected environmental exposure conditions. Before and after cycling, specimens were evaluated for changes in mass, dimensions, visible surface cracking, surface deterioration, and residual mechanical strength. The percentage retention of mechanical strength was calculated by comparing the post-exposure strength with the corresponding initial value. Where a damage index was used to quantify deterioration, it was calculated using the following expression:

$$DI = 1 - \left(\frac{P_N}{P_0} \right) \text{-----} (5)$$

where P_0 is the initial performance and P_N is the performance after N cycles

3. Result and Discussions

3.1. SEM Microstructural Analysis

The scanning electron microscopy (SEM) micrographs provide direct evidence of the multiphase morphology of the PET–red ash composite and reveal the distribution and interaction of the polymeric matrix with the mineral aggregate. As shown in Fig. 4, the red ash particles exhibit an irregular morphology and inherently porous structure, while the molten PET forms a continuous matrix around and between the red ash particles. At regions where adequate PET wetting occurred, the polymer closely conformed to the irregular surfaces of the red ash particles, resulting in intimate matrix–aggregate contact and mechanical interlocking.

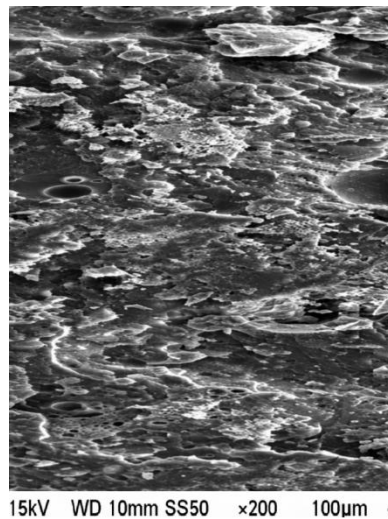


Fig. 54: SEM image of the developed Composite materials

The micrographs also reveal localized microvoids and porous regions within the composite. These features may be associated with entrapped air during mixing and molding, the inherent porosity of the red ash particles, residual moisture, or incomplete consolidation of the PET–red ash mixture. The extent and distribution of these defects are important because voids can act as stress-concentration sites and provide preferential locations for crack initiation and propagation under mechanical loading.

The quality of red ash powder dispersion also varied with PET content. At relatively low PET contents, insufficient polymer coverage of the red ash particles can result in exposed fine powder surfaces and discontinuities within the matrix, potentially limiting effective stress transfer. With increasing PET content, greater matrix coverage and improved filling of interparticle spaces can promote a more continuous composite structure. However, excessive PET content may produce a polymer-dominated morphology with a reduced fraction of load-bearing mineral phase. Thus, the SEM observations support the existence of a composition-

dependent balance between matrix continuity, red ash powder reinforcement, and void formation.

The microstructural characteristics observed at the optimum composition are particularly relevant to the measured mechanical performance. A relatively continuous PET matrix surrounding well-dispersed red ash particles can facilitate stress transfer between the two phases, while reduced interfacial gaps and voids can limit localized stress concentration. Conversely, poorly bonded particles, large voids, or particle pull-out regions can provide preferential sites for crack initiation and propagation. These observations provide a microstructural basis for interpreting the variation in compressive and flexural strength with PET content.

3.2. Fourier Transform Infrared Spectroscopy (FTIR) and The Thermal Behavior (DSC)

The FTIR spectrum of the developed PET–red ash composite is presented in Fig. 5 (a). The spectrum exhibits characteristic absorption bands associated with both the organic PET matrix and the inorganic red ash phase, confirming the presence of the two principal constituents in the composite.

A strong absorption band at approximately 1715 cm^{-1} is attributed to the C=O stretching vibration of the ester groups in PET. The characteristic absorption bands near 1240 and 1100 cm^{-1} are associated primarily with C–O stretching vibrations of the PET structure. The persistence of these characteristic PET bands after thermal processing indicates that the principal PET functional groups remain detectable in the fabricated composite.

The red ash contribution is particularly evident in the broad absorption region around $1000\text{--}950\text{ cm}^{-1}$, which can be associated with Si–O stretching vibrations characteristic of silicate- and aluminosilicate-containing mineral phases. The precise assignment of these bands depends on the mineralogical composition of the red ash and should therefore be interpreted together with its chemical or mineralogical characterization, where available.

Minor changes in peak position, intensity, or band shape in the fingerprint region may indicate changes in the local molecular environment resulting from the incorporation of red ash into the PET matrix. Such changes may reflect interfacial interactions between the polymer and mineral phases; however, FTIR evidence alone is insufficient to conclusively establish the formation of new covalent bonds or to distinguish specific interactions such as hydrogen bonding or van der Waals forces. The overall spectrum therefore suggests that the composite retains the characteristic chemical features of both PET and red ash while exhibiting possible changes associated with their interfacial interaction.

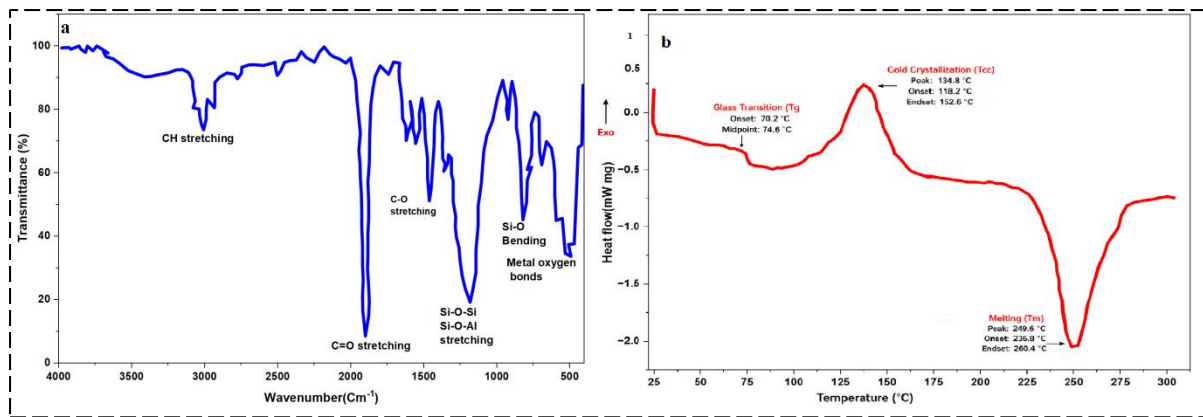


Fig. 5: FTIR and DSC analysis of developed composite materials

The DSC thermogram of the optimized 45 wt.% PET–55 wt.% red ash composite is presented in Fig. 5(b). The thermogram exhibits the characteristic thermal transitions of the PET phase, including the glass transition, cold crystallization, and melting processes. A baseline shift occurs at approximately 70–80 °C, corresponding to the glass-transition temperature T_g of the PET phase. This transition represents an increase in molecular mobility within the amorphous regions of PET as the material changes from a relatively rigid glassy state to a more mobile rubbery state.

A broad exothermic region observed at approximately 120–150 °C is attributed to cold crystallization T_c , which occurs when previously disordered PET chains rearrange into more ordered crystalline regions during heating. The dominant endothermic peak at approximately 245–255 °C corresponds to the melting temperature T_m of the crystalline PET phase.

The incorporation of 55 wt.% red ash can influence the thermal transitions of the PET phase by restricting polymer-chain mobility and altering the crystallization environment. The mineral particles may also provide heterogeneous nucleation sites that affect PET crystallization. However, the magnitude of these effects should be interpreted from the measured transition temperatures and enthalpy values rather than inferred solely from the presence of the red ash.

The observed melting transition is particularly relevant to the processing of the composite roof tiles. The melting region centered on approximately 250 °C indicates that the PET phase becomes sufficiently molten within this temperature range to permit flow and wetting of the red ash particles. The processing temperature used during fabrication, approximately 260–280 °C, was therefore above the observed melting transition and provided sufficient melt flow for mixing and molding. Nevertheless, the processing temperature and residence time should be controlled carefully because unnecessarily prolonged exposure to elevated temperatures may promote thermal degradation of PET.

Overall, the DSC results demonstrate that the characteristic thermal transitions of PET are retained after incorporation of red ash. The thermal analysis therefore provides useful information for understanding the behavior of the composite during heating and for

establishing an appropriate processing window for melting, mixing, and compression molding.

3.3. Flexural strength

The flexural strength of the composite roof tiles produced from waste PET and fine red ash at different compositions is presented in Fig. 6. A distinct nonlinear relationship was observed between PET content and flexural strength. The flexural strength increased from approximately 5.8 MPa at 5 wt.% PET to a maximum of 13.8 MPa at 45 wt.% PET and 55 wt.% red ash, representing the optimum composition. Beyond this composition, the flexural strength progressively decreased to approximately 12.6, 10.1, 7.4, and 4.9 MPa at 60, 75, 90, and 95 wt.% PET, respectively.

The increase in flexural strength at intermediate PET contents can be attributed to improved wetting and encapsulation of the red ash particles by the molten PET matrix. The continuous polymer phase promotes intimate matrix–aggregate contact and facilitates stress transfer across the composite, while the irregular and rough morphology of the red ash can provide mechanical interlocking with the PET matrix. The combination of matrix continuity and mineral reinforcement therefore contributes to improved resistance to tensile stresses generated during bending. In addition, the ductile PET phase may contribute to energy dissipation and delay crack propagation by deforming around the mineral particles.

At low PET contents, the limited amount of polymer matrix may be insufficient to adequately wet and bind the red ash particles, resulting in discontinuous matrix regions and a greater likelihood of interfacial defects. These defects can act as stress-concentration sites and facilitate crack initiation under flexural loading. As PET content increased toward 45 wt.%, improved matrix continuity and the red ash powder encapsulation resulted in a more consolidated composite structure, consistent with the relatively high flexural strength observed at this composition.

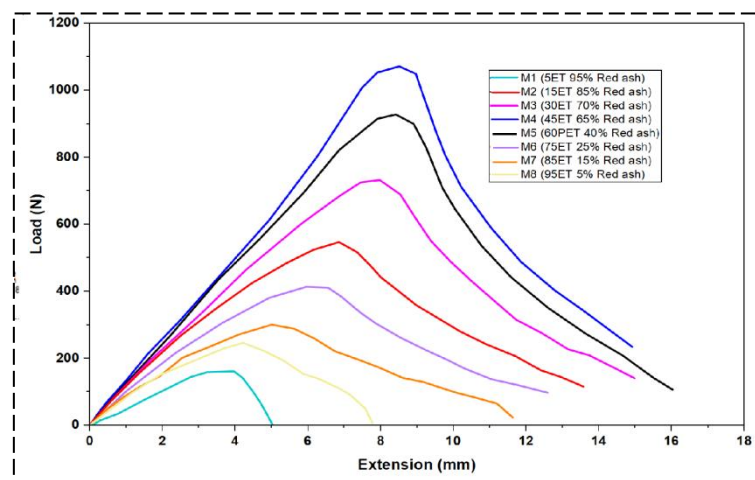


Fig. 6: flexural strength of the composite roof tile

However, further increases in PET content beyond 45 wt.% resulted in a progressive reduction in flexural strength. This behavior is attributed primarily to the decreasing proportion of rigid red ash reinforcement within the composite. Although the higher PET content provides greater polymer continuity, the reduced mineral fraction limits the contribution of the rigid aggregate phase to load bearing and can result in a more polymer-dominated structure with lower flexural stiffness and strength. Consequently, an optimum balance exists between PET matrix continuity and red ash reinforcement.

The observed flexural-strength trend is consistent with the microstructural characteristics discussed in the SEM analysis, where effective PET coverage, particle dispersion, interfacial contact, and reduced internal defects contribute to improved mechanical performance. Overall, the 45 wt.% PET–55 wt.% red ash formulation exhibited the highest flexural strength of approximately 13.8 MPa, indicating that this composition provides a favorable balance between polymer–aggregate bonding, matrix continuity, and rigid-phase reinforcement for the developed composite roof tiles.

Compressive Strength Behavior

The compressive strength of the developed roof tiles at different PET contents is presented in Fig. 7. A distinct nonlinear relationship was observed between PET content and compressive strength, with the strength increasing to an optimum value and subsequently decreasing as the PET fraction increased further. The compressive strength increased from approximately 28 MPa at 15 wt.% PET to 32 MPa at 30 wt.% PET, reaching a maximum of approximately 35 MPa at 45 wt.% PET. Beyond this optimum composition, the compressive strength decreased progressively to approximately 30 MPa at 60 wt.% PET, 22 MPa at 75 wt.% PET, and 15 MPa at 100 wt.% PET.

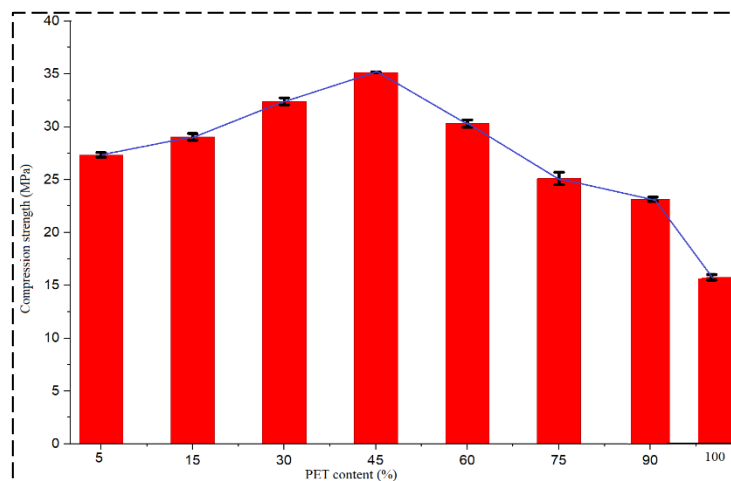


Fig. 7: Compression strength

The increase in compressive strength up to 45 wt.% PET can be attributed to the development of a more consolidated PET–red ash composite structure. At intermediate PET contents, the molten polymer can effectively wet and surround the irregular red ash particles, improving matrix–aggregate contact and facilitating stress transfer between the polymeric and mineral

phases. The PET matrix can also occupy interparticle spaces, potentially reducing large voids and improving the continuity of the composite. These effects, together with the rigid red ash phase, contribute to greater resistance to compressive deformation and explain the relatively high strength obtained at 45 wt.% PET. The SEM observations provide supporting evidence for the role of matrix continuity, aggregate dispersion, and interfacial contact in determining the mechanical response.

The maximum compressive strength of approximately 35 MPa at 45 wt.% PET and 55 wt.% red ash indicates that this composition provides a favorable balance between the binding capacity of the polymer matrix and the load-bearing contribution of the rigid mineral phase. At lower PET contents, the amount of polymer may be insufficient to adequately coat and bind the red ash particles, resulting in less continuous matrix regions and a greater potential for interfacial defects. Consequently, stress transfer through the composite may be less efficient, limiting the compressive strength.

In contrast, increasing the PET content beyond 45 wt.% progressively reduced the compressive strength. This decline is primarily associated with the decreasing proportion of rigid red ash reinforcement and the increasing dominance of the polymeric phase. Although PET provides matrix continuity and contributes to toughness, the reduction in mineral reinforcement decreases the rigid load-bearing framework of the composite. Under compressive loading, the polymer-rich structure can undergo greater deformation than the mineral-reinforced structure, resulting in lower effective stiffness and compressive strength. Excessive PET may also reduce aggregate-to-aggregate contact and mechanical interlocking, further contributing to the observed reduction in strength.

The lowest compressive strength, approximately 15 MPa, was obtained for the 100 wt.% PET formulation, demonstrating that a polymer-rich composition without mineral reinforcement does not provide the same compressive load-bearing capability as the optimized PET–red ash composite. Overall, the results demonstrate that PET content plays a critical role in controlling the compressive performance of the developed roof tiles. The 45 wt.% PET–55 wt.% red ash formulation exhibited the highest compressive strength, indicating an optimum balance among matrix continuity, aggregate reinforcement, interfacial contact, microstructural consolidation, and stress transfer.

3.2. Water Absorption and Moisture Resistance

The water absorption characteristics of the developed PET–red ash composite roof tiles are presented in Fig. 8. A clear reduction in water absorption was observed with increasing PET content, indicating that incorporation of the hydrophobic polymer phase substantially reduced the accessibility and connectivity of water-transport pathways within the composite. At relatively low PET contents (15–30 wt.%), water absorption remained comparatively high, which can be attributed primarily to the porous nature of the lightweight red ash aggregate and the presence of accessible interparticle voids. These features provide pathways through which water can enter and be retained within the composite.

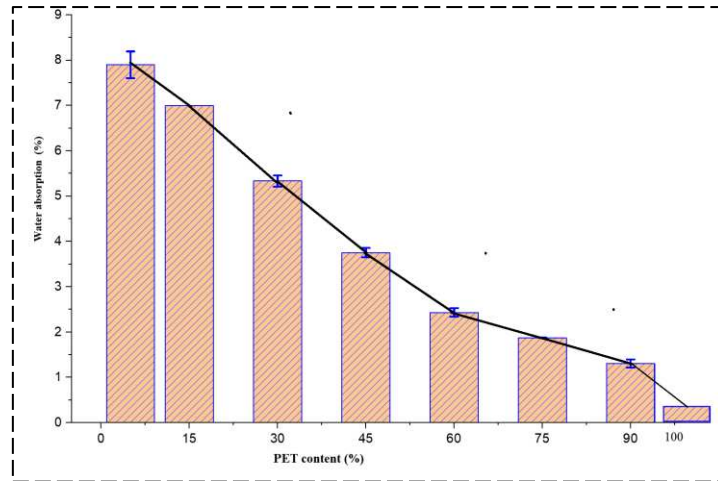


Fig. 8: Water absorption trend showing decreasing values with increasing PET content

As the PET content increased, water absorption progressively decreased. The reduction became particularly evident at intermediate and high PET contents, where the molten polymer was able to more effectively wet and encapsulate the red ash particles and occupy interparticle spaces. This improved matrix continuity can reduce the volume of accessible pores and interrupt interconnected pathways through which water can penetrate. Consequently, the composite exhibited progressively lower moisture uptake as the PET fraction increased.

At high PET contents (approximately 75–100 wt.%), water absorption approached a minimum value of approximately 1%. This behavior is consistent with the hydrophobic nature of PET and the formation of a more continuous polymer-rich phase. The increased polymer coverage limits direct exposure of the porous red ash particles to water and reduces the connectivity of accessible surface pores. Therefore, the observed reduction in water absorption provides indirect evidence of improved matrix continuity and aggregate encapsulation with increasing PET content.

The water-absorption behavior also demonstrates the complementary roles of PET and red ash in the composite. Although the porous red ash contributes to lightweighting, its internal pore structure can increase water uptake. Increasing PET content partially offsets this disadvantage by coating the aggregate surfaces and filling accessible interparticle spaces. This combination is potentially beneficial for roofing applications because limiting water ingress can reduce moisture-related deterioration and may contribute to improved long-term environmental resistance.

Importantly, the composition exhibiting the lowest water absorption does not necessarily represent the optimum formulation for the overall roof-tile performance. Although the high-PET formulations exhibited water absorption approaching 1%, their compressive and flexural strengths decreased substantially beyond 45 wt.% PET. In contrast, the 45 wt.% PET–55 wt.% red ash formulation exhibited a water absorption of approximately 4% while providing the highest compressive strength and flexural strength. Therefore, considering the combined

mechanical and moisture-related performance, the 45 wt.% PET–55 wt.% red ash formulation provides a more favorable overall balance than the polymer-rich formulations.

For further enhancement of moisture resistance, particularly under prolonged outdoor exposure, application of a surface waterproofing treatment may be considered. A polyurethane coating can form a continuous hydrophobic barrier over the roof-tile surface, potentially sealing accessible surface pores and microcracks and further restricting water ingress. However, the effect of polyurethane coating should be evaluated experimentally through comparative tests on coated and uncoated specimens before its contribution to water resistance and weathering durability is quantitatively claimed.

3.3. Density Reduction and Self-Weight Analysis

The density of the developed PET–red ash composite roof tiles at different PET contents is presented in Fig. 9. A clear and progressive reduction in density was observed with increasing PET content, demonstrating the potential of waste PET to reduce the mass per unit volume of the developed roofing composite. The density decreased from approximately 2100 kg/m³ at 15 wt.% PET to approximately 1300 kg/m³ at high PET contents, corresponding to an overall reduction of approximately 38%.

At 15 wt.% PET, the relatively high density can be attributed to the high proportion of red ash within the composite and the comparatively limited volume fraction of the lower-density PET phase. As the PET content increased from 30 to 60 wt.%, the density progressively decreased as the composition shifted toward a greater fraction of the lower-density polymeric phase. The change in density is therefore governed primarily by the relative proportions and intrinsic densities of PET and red ash, together with the degree of consolidation and internal void structure of the molded composite.

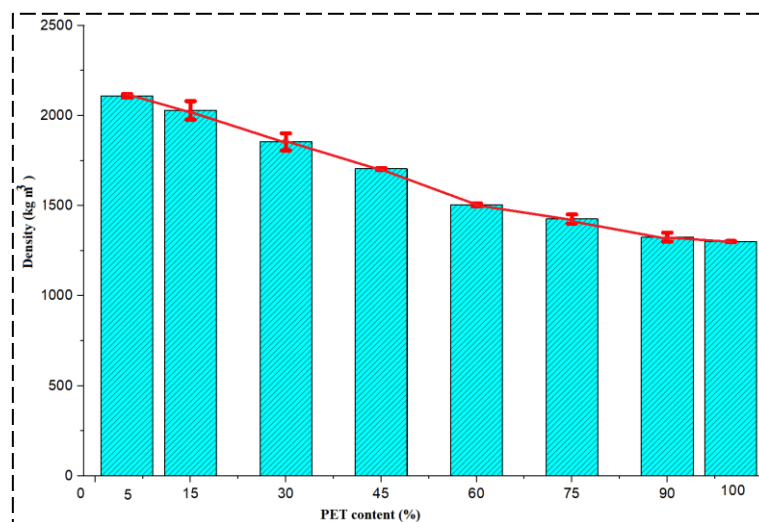


Fig. 9: Density reduction as a function of lightweight aggregate content.

At PET contents above approximately 75 wt.%, the density approached a relatively stable value of around 1300 kg/m³. The observed plateau indicates that further increases in PET

content produced comparatively small changes in the measured mass-to-volume ratio. This behavior may reflect the increasingly dominant contribution of the PET phase to the composite volume, together with the relatively stable density of the polymer-rich material at the investigated compositions.

The reduction in density is advantageous for roofing applications because lower-density tiles can reduce the dead load imposed on supporting structural members. In addition, lighter tiles can facilitate handling, transportation, and installation. The approximately 38% reduction in density observed across the investigated composition range therefore demonstrates the potential of PET incorporation as an effective lightweighting strategy for waste-derived roofing materials.

However, the lowest density does not necessarily correspond to the optimum formulation. Increasing PET content beyond 45 wt.% produced further reductions in density but was accompanied by a substantial decrease in compressive and flexural strength. Therefore, the lightweighting benefit must be evaluated together with mechanical and moisture-related performance. In the present study, the 45 wt.% PET–55 wt.% red ash formulation provides a more balanced combination of mechanical strength, moisture resistance, and reduced density, whereas the higher-PET formulations primarily offer advantages in lightweighting and water resistance.

3.4. Durability and Environmental Resistance

The durability performance of the developed PET–red ash roof tiles at different PET contents is presented in Fig. 10. The results show a progressive improvement in the measured durability index with increasing PET content, indicating that incorporation of the polymer phase enhances the resistance of the composite to the investigated cyclic environmental exposure. The improvement is particularly pronounced at intermediate-to-high PET contents, suggesting that increasing polymer coverage modifies the internal structure and reduces the accessibility of moisture-transport pathways.

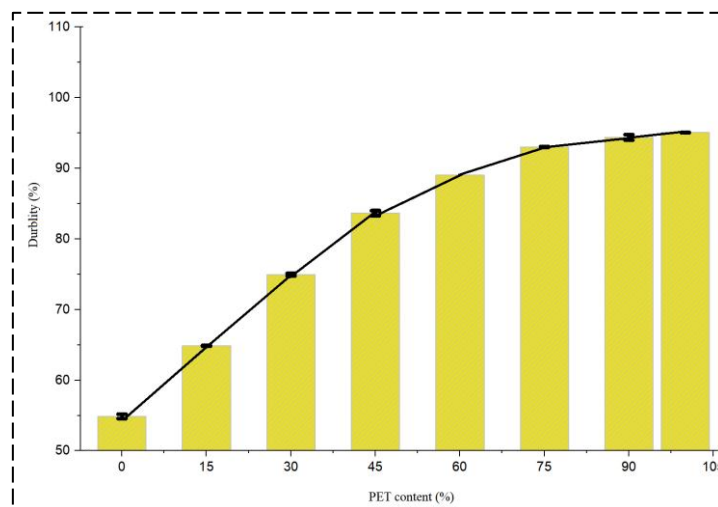


Fig. 10: Overall durability

The improved durability can be primarily attributed to the ability of the molten PET to wet and encapsulate the red ash particles and occupy interparticle spaces [26, 27]. As the PET content increases, greater matrix continuity can reduce the number and connectivity of accessible voids, thereby limiting water penetration into the composite. This interpretation is consistent with the observed decrease in water absorption at higher PET contents and with the SEM observations of the PET–red ash interface. Because moisture penetration is an important contributor to deterioration during cyclic environmental exposure, the reduction in accessible water pathways can contribute to improved retention of mechanical integrity.

The durability improvement becomes particularly evident at PET contents of approximately 60 wt.% and above, where the increasing polymer fraction produces a more continuous matrix. The corresponding reduction in water accessibility may limit moisture-related damage during repeated environmental cycling. However, the durability results should be interpreted specifically in relation to the exposure conditions used in this study; resistance to other degradation mechanisms, such as chemical attack or prolonged ultraviolet exposure, would require separate experimental evaluation.

In addition to its moisture-barrier effect, the PET phase may contribute to damage tolerance through its ability to undergo localized deformation and redistribute stresses within the composite. This behavior can reduce the severity of local stress concentrations at the polymer–aggregate interface and may delay the development of microcracks during cyclic loading. The effect is particularly relevant for a composite containing porous red ash, where local defects and aggregate–matrix interfaces can serve as potential sites for crack initiation.

At high PET contents, the durability index approaches a relatively stable value, indicating that further increases in PET provide progressively smaller improvements. This plateau suggests that a substantial fraction of the accessible moisture-transport pathways has already been restricted by the polymer phase and that additional PET produces diminishing returns in durability enhancement. Nevertheless, the highest durability index should not be considered sufficient by itself for selecting the optimum formulation.

The overall performance of the developed roof tiles demonstrates a clear trade-off among durability, mechanical strength, water absorption, and density. Although high PET contents provide superior moisture resistance and durability, excessive PET incorporation results in a substantial reduction in compressive and flexural strength. In contrast, the 45 wt.% PET–55 wt.% red ash formulation provides a more balanced combination of mechanical performance, moisture resistance, density reduction, and durability. Therefore, the optimum composition should be selected based on the combined performance of the material rather than maximizing PET content for durability alone [26, 28].

Conclusion

This study demonstrated the feasibility of producing an eco-efficient composite roof tile by valorizing post-consumer polyethylene terephthalate (PET) waste and fine red ash lightweight aggregate powder. The PET–red ash ratio had a pronounced influence on the

mechanical, physical, moisture-related, and durability performance of the developed composite. Among the investigated formulations, the 45 wt.% PET–55 wt.% red ash composition provided the most favorable overall balance of properties.

At the optimum composition, the composite achieved a compressive strength of approximately 35 MPa and a flexural strength of approximately 13.8 MPa, while maintaining a water absorption of approximately 4% and a density of approximately 1700 kg/m³. Increasing PET content beyond 45 wt.% further reduced water absorption and density but resulted in a progressive reduction in compressive and flexural strength because of the decreasing fraction of rigid red ash reinforcement. These results demonstrate that the optimum performance is governed by a balance between PET matrix continuity and red ash reinforcement, rather than by maximizing the content of either constituent.

Microstructural observations indicated that adequate PET content improved the red ash aggregate powder encapsulation and matrix continuity, while the thermal and chemical analyses confirmed the retention of the characteristic PET structure and its principal thermal transitions after incorporation of red ash. The improved moisture resistance at higher PET contents is consistent with the hydrophobic nature of PET and its ability to reduce the accessibility of internal water-transport pathways. The durability results further indicated improved resistance to the investigated environmental cycling with increasing PET content, although the highest PET content did not provide the best overall mechanical performance.

From a waste-valorization perspective, the developed composite provides a promising pathway for converting two waste-derived resources—post-consumer PET and red ash—into a value-added roofing material. The approach has the potential to reduce dependence on virgin construction materials, divert waste from disposal streams, reduce roofing-component weight, and support circular-material utilization in the construction sector. However, the present results should be regarded as a laboratory-scale demonstration, and further validation is required before full-scale structural or commercial applications.

Future Work

Although the present results demonstrate promising performance, further research is required to establish the long-term reliability and scalability of the developed composite. Future studies should investigate interfacial bonding between PET and the powdered red ash aggregate phase through surface modification, compatibilization, or the incorporation of nano-scale additives such as nano-silica. These approaches may further improve stress transfer and mechanical performance while reducing interfacial defects.

Long-term field exposure and accelerated aging studies should also be conducted to evaluate the effects of prolonged sunlight, rainfall, temperature fluctuations, moisture cycling, and other environmental conditions on mechanical and durability performance. In addition, comprehensive life-cycle assessment (LCA) and techno-economic analysis should be performed to quantify the environmental benefits, carbon-emission reduction potential, resource savings, and economic feasibility of the proposed recycling route.

Further investigation into fire resistance and thermal behavior is particularly important before large-scale construction applications. Finally, industrial-scale manufacturing technologies, including continuous extrusion, automated mixing, molding, and high-throughput pressing systems, should be optimized to improve production consistency, energy efficiency, dimensional accuracy, and economic competitiveness. Such developments would facilitate the transition from laboratory-scale production toward commercial manufacturing and broader implementation of waste-derived composite roofing materials.

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