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Multiscale Evaluation of Recycled Plastic Corrugated Panels for Sustainable Construction

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Abstract

The global push for sustainable building practices has intensified the search for low-carbon, recyclable alternatives to traditional roofing materials. This study investigated the structural viability of corrugated panels fabricated from 100% post-consumer recycled HDPE and PP for roofing and cladding applications under real-world loading and environmental conditions. Promising main attributes include durability, corrosion resistance, and low environmental impact. Mechanical testing revealed a flexural strength of 8.4 MPa for rHDPE and 6.3 MPa for rPP. Under impact loading, rPP retained 53% of its initial strength, while rHDPE retained 28%, as validated by drop-weight and pendulum impact tests. Vibration testing (ASTM E1876) demonstrated that rPP exhibited 18% higher longitudinal damping, whereas rHDPE outperformed in out-of-plane vibration control. XRD and SEM-EDS confirmed distinct crystalline and morphological structures responsible for the observed behavior. Findings from this investigation, supported by prototype slab testing, confirm that integrating recycled plastics facilitates the creation of durable and sustainable building envelopes for circular construction practices.

Keywords: recycled plastic corrugated panel; waste polymer valorization; sustainable roofing materials; mechanical recycling; post-consumer plastics; structural performance; circular construction; dynamic and impact testing

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1. Introduction

Corrugated panels are intensely utilized for low-cost construction, originally devised in the 1820s by Henry Palmer to reduce construction costs using timber-framed, masonry-footed systems [1]. Over the decades, advancements like the Hatschek and Magnani processes enabled mass production of fiber–cement corrugated panels [2,3]. However, with global plastic waste surging, particularly HDPE and PP, sustainable alternatives have emerged, emphasizing the use of recycled plastic for construction components [3,4]. Mechanical recycling via extrusion has enabled the development of polymer-based roofing sheets with adequate tensile and flexural properties [5]. These sheets, when fabricated using recycled plastic pellets, have shown high durability and thermal stability under various mechanical loads [6,7]. Their integration into construction materials also aligns with circular economic goals and reduces landfill pressure [8]. Research further suggests that thermoplastics can be molded into panels and sheets that meet structural demands [9]. Recent field and laboratory studies validated their energy absorption, chemical resistance, and minimal gas emissions during processing [10]. Such applications represent a paradigm shift from concrete-heavy, resource-intensive roofing to lightweight, cost-effective recycled alternatives [3,11].

A broad review of corrugated sheet materials reveals a diverse range—ranging from asbestos-reinforced fiber cement to galvanized iron and newer polymeric compounds. Classical materials such as asbestos cement had high thermal and chemical resistance but faced health and environmental concerns, prompting research into PVA, cellulose, and synthetic fiber alternatives [2]. UPVC and polymer-composite sheets, tested using FEM simulations and static load experiments, are being explored as viable replacements, offering fire resistance and structural reliability [11]. Even corrugated paper boards have seen optimization using sustainable design and simulation techniques for improved performance in packaging and building skins [3]. For metallic alternatives, corrugated steel sheets provide high load-bearing capacity but face fatigue issues, especially at bolted lap joints under cyclic stress [7]. Roof systems comprising built-up and panel designs also vary significantly in impact resistance under hail or storm conditions, guiding material selection for resilient architecture [12]. Overall, the design of corrugated sheets today is strongly influenced by ecological imperatives, economic feasibility, and mechanical behavior under loading, leading to a transition toward recycled polymers and composites in roofing and enclosure systems [13].

The properties of corrugated panels, both static and dynamic, are pivotal in determining their applications in real-world construction. Finite element modeling of UPVC hollow sheets confirms their capacity to withstand wind speeds up to 99 km/h and human installation loads [14]. Impact testing of roofing systems highlights how built-up panels behave differently under hail strike conditions, underlining the importance of ductility and surface resilience [12]. Fiber–cement sheets produced by the Hatschek process show anisotropic permeability patterns that influence vapor and gas transfer across roofing surfaces [15]. Structural shell models also show that corrugation enhances membrane stiffness while reducing in-plane deformation, contributing to improved stability under buckling loads [16]. From a material science perspective, composite sandwich panels incorporating Kevlar, PP, and thermoplastic polyurethane demonstrate high flexural stiffness and improved failure mechanisms under loading [17]. Corrugated iron buildings, historically valued for their transportability and economy, now face conservation challenges, although the same principles are being revived through recycled plastic counterparts [1]. Modern applications of recycled plastic panels, produced via hot pressing and mechanical extrusion, exhibit minimal emissions, good interfacial bonding, and performance characteristics suitable for roofing, panels, or siding systems [4,13]. These shifts suggest a growing preference for polymer-based corrugated systems capable of meeting structural and environmental standards simultaneously.

Corrugated sheets have historically provided economical roofing solutions due to their inherent structural efficiency and ease of manufacturing [1,18,19]. Traditionally, these panels were fabricated from materials such as asbestos cement, galvanized iron, or aluminum, each presenting specific challenges related to environmental impact, sustainability, or long-term durability [2,19,20]. Recently, the global emphasis on sustainability and circular economy has accelerated research into alternative roofing materials, particularly those incorporating recycled and bio-based constituents [21–23]. For instance, studies by Gaggino et al. demonstrated that roofing tiles made from recycled rubber and plastic exhibit superior insulation properties and impact resistance compared to traditional roofing tiles [24]. Similarly, corrugated sheets utilizing natural fibers, such as sugarcane bagasse, have shown promising results, offering improved moisture resistance and adequate mechanical properties for non-structural roofing [25]. Additionally, agricultural fibers such as Totora have been successfully combined with recycled low-density polyethylene to create composite panels with enhanced flexural strength and water resistance [26]. These innovative applications underline the emerging potential of waste-derived materials in roofing and cladding systems, significantly reducing environmental burdens while promoting circularity in construction practices [21,22,27].

Despite substantial advancements, the use of recycled polymers, specifically high-density polyethylene (HDPE) and polypropylene (PP), in structurally viable corrugated roofing sheets remains scarcely explored. Prior investigations have largely focused on conventional materials, such as metallic corrugated sheets under bending and dynamic loading conditions, which have been well documented [28,29]. The recent literature has started to acknowledge the structural potential of recycled plastics but primarily in non-corrugated forms, such as reinforcement bars and composite roofing tiles. Das and Ali, for example, developed recycled HDPE and PP-based reinforcement bars, proving their suitability for certain structural applications under moderate loads [30]. Similarly, innovative studies have successfully created recycled polypropylene roofing tiles reinforced with fillers such as sand and fly ash, achieving substantial compressive strength suitable for structural applications [31]. However, an extensive gap remains concerning the comprehensive evaluation of recycled polymer-based corrugated panels under flexural, impact, and dynamic loads for the construction industry. This study addresses this critical gap by fabricating corrugated panels exclusively from post-consumer recycled HDPE and PP, performing rigorous mechanical and dynamic analyses, and proposing empirical relationships between their structural characteristics. This novel approach not only contributes to structural engineering knowledge but also provides a practical framework for the sustainable and structural reuse of polymer waste, aligning closely with global environmental and circular economic strategies.

This research offers a significant contribution to the sustainable transformation of plastic waste by demonstrating the structural and functional viability of recycled rHDPE and rPP corrugated panels in construction applications [31]. Unlike conventional approaches that often limit recycled plastics to non-structural uses, this study provides empirical validation for their performance under flexural, impact, dynamic, and prototype loading conditions. The comprehensive methodology, spanning ASTM-standard mechanical testing [32], resonance-based dynamic analysis, and microstructural assessments via XRD and SEM-EDS, confirms that recycled polymers retain sufficient mechanical integrity and crystallinity for use in modular building elements. This research provides a combined quantitative and qualitative evaluation of recycled HDPE and PP under flexural and impact loading. Recycled PP retained over 50% of its flexural strength during impact, compared to approximately 28% for HDPE relating to a pattern devised with empirical equations. Qualitative observations confirmed rPP's greater toughness and deformation capacity, supporting its use in impact-sensitive structural applications. In a prototype slab, the ability of these recycled panels to resist water ingress, withstand service loads up to 1.86 kN, and exhibit material-specific damping and energy absorption profiles positions them as practical, eco-efficient alternatives for roofing and walling systems. This work not only advances engineering applications of recycled plastics but also directly supports global sustainability goals by enabling circular economic solutions in the built environment.

2. Experimental Program

2.1. Raw Materials

The plastic waste utilized in this study was systematically sourced from post-consumer municipal solid waste (MSW), with a targeted emphasis on end-of-life automotive components such as bumper covers and underbody shields, recognized as rich sources of thermoplastics. These waste streams were previously validated for structural material recovery in earlier studies, including the methodology outlined in previous research [29,31], which demonstrated an efficient material recovery pathway for construction applications. A detailed manual sorting protocol was followed to isolate recyclable thermoplastics, specifically high-density polyethylene (HDPE) and polypropylene (PP), commonly used in automotive and packaging sectors due to their favorable mechanical and environmental profiles [3,13]. The process involved removal of heterogeneous contaminants, such as metals, multilayer laminates, paper, and organic residues, to enhance the feedstock purity. The cleaned plastics were washed thoroughly using a mild alkaline solution and dried at ambient conditions to prevent thermal degradation during reprocessing. Subsequently, the materials were mechanically shredded and pelletized. Distinct coloration was used to identify the polymer types, dark gray pellets for HDPE and blue pellets for PP, as established in earlier laboratory-scale documentation [33].

These pellets were employed as the input for extrusion-based manufacturing of composite panels and rebars. Special attention was given to the extrusion of PP, which demanded tighter process control due to its sensitivity to shear and thermal fluctuations [16]. The extrusion parameters, including temperature (optimized between 150–170 °C), screw speed, and material feed ratios, were finely tuned to achieve homogeneous melt flow and ensure consistent mechanical performance of the recycled products. This collection and synthesis protocol demonstrates the scalability of a sustainable recycling framework for structural applications, aligning with global circular economy goals [33]. The process of converting post-consumer plastic waste into pellets is systematically represented in Figure 1. These pellets were utilized as feedstock in an extrusion system, where they were melted and directly injected into a custom-fabricated steel mold designed with a corrugated profile. Upon cooling and demolding, the process yielded durable corrugated plastic panels in the respective polymer colors. This method not only enables efficient material recovery but also demonstrates a sustainable approach to transforming municipal plastic waste into practical construction components.

Figure 1. Recycling of waste plastic to form recycled pellets of HDPE and PP.

2.2. Preparation of Samples

2.2.1. Preparation of Corrugated Panels

The development of Recycled Plastic Corrugated Panels (RPCP) was achieved using a controlled thermo-mechanical extrusion and molding process. Recycled HDPE and PP pellets, prepared from sorted municipal plastic waste, were first introduced into a single-screw extrusion unit equipped with a temperature-controlled barrel. The processing temperature was maintained between 150 °C and 170 °C, depending on the polymer type, to achieve a consistent molten flow without initiating thermal degradation [31]. At the extrusion outlet, a custom-engineered steel nozzle was affixed, which directed the hot, viscous polymer melt into a precision-fabricated steel mold featuring a cycloidal wave profile (Figure 2). This mold was designed to replicate the geometrical features of standard corrugated roofing sheets. As shown in Figure 2a, the mold was securely clamped to a robust steel platform and filled directly from the nozzle under manual or semi-automatic control. To ensure proper compaction and profile conformance, the mold cavity was preheated to approximately 80–100 °C, minimizing thermal shock and promoting uniform filling. Once the mold was filled with molten polymer, it was sealed and allowed to cool under ambient or assisted air-cooling conditions. The dwell time for cooling was maintained at 15–25 min, depending on panel thickness and environmental factors. Upon cooling, the mold was carefully opened, and the formed corrugated panels were demolded, exhibiting a stable profile with minimal warping or shrinkage. This direct mold-filling extrusion method allowed for the efficient and repeatable production of RPCS with consistent dimensional accuracy, surface finish, and mechanical integrity, demonstrating the feasibility of manufacturing lightweight roofing solutions from post-consumer recycled plastics. The fabricated corrugated panel had standardized final dimensions of 600 mm × 450 mm × 12 mm, as shown in Figure 2b. These panels were produced solely from post-consumer recycled HDPE or PP, with no incorporation of virgin polymers or reinforcing fibers, thereby reinforcing the principles of a closed-loop recycling approach [31]. The extrusion and molding setup employed in this process aligns with previously established methodologies for recycled plastic production [30,32] and was operated manually with strict quality control measures to ensure material consistency and to minimize environmental emissions during fabrication.

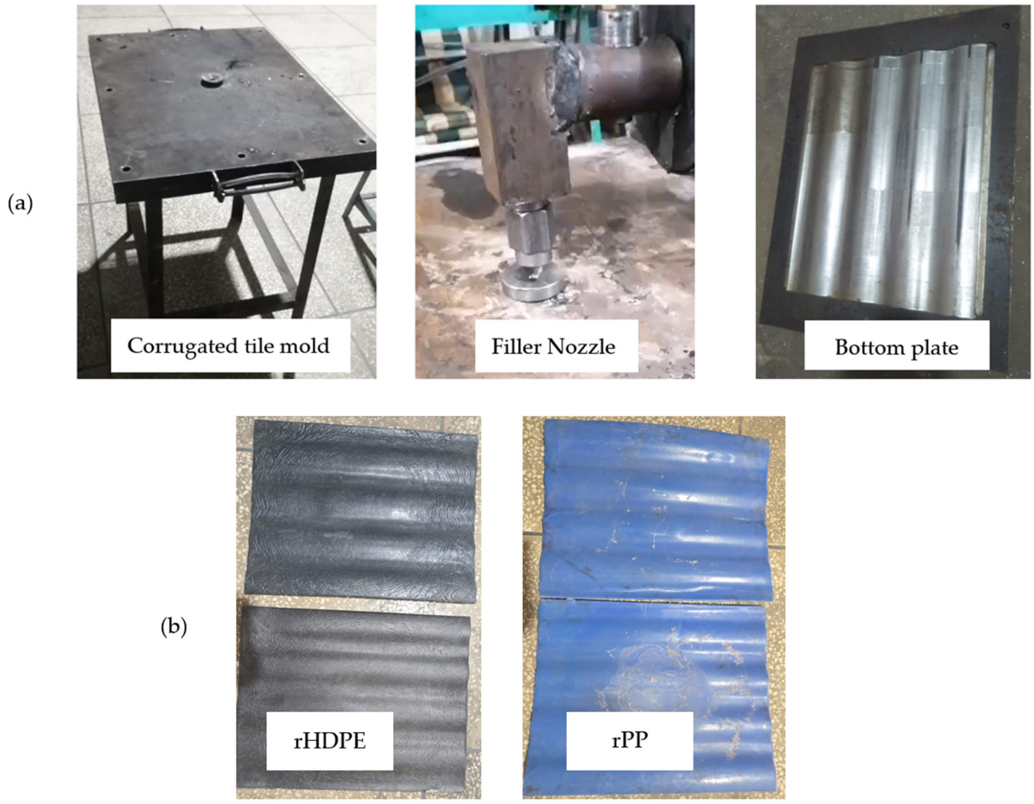


Figure 2. (**a**) Components of the molding assembly for fabrication of recycled plastic corrugated panels and (**b**) molded recycled plastic corrugated panels produced from rHDPE and rPP materials.

2.2.2. Preparation of Prototype Slab

To assess real-world applicability, a prototype slab platform measuring 1.63 m × 1.6 m was constructed using corrugated panels fabricated from recycled high-density polyethylene (rHDPE). These Recycled Plastic Corrugated Panels (RPCPs) were specifically prepared to interlock through an overlapping joint system. Each panel was machined to include edge cuts designed to provide a consistent 50 mm overlap, ensuring both dimensional continuity and load transfer integrity across panel seams [4,5]. As depicted in Figure 3, special attention was given to the shaping of the panel edges, enabling a snug and flush fit. This overlapping configuration not only minimized potential gaps that could weaken the system under load but also contributed to enhanced water resistance and structural coherence [33]. The precision in edge preparation played a crucial role in emulating real-life slab assemblies, thus allowing for accurate mechanical and impact performance testing of the composite assembly.

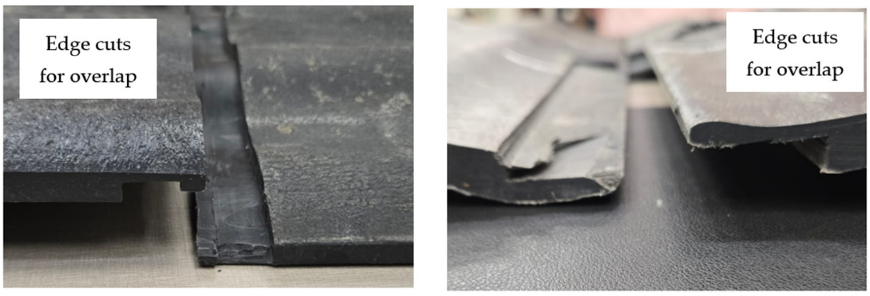


Figure 3. Edge modifications in recycled plastic corrugated panel overlapping joints for slab assembly.

2.3. Corrugated Panels Test Procedure

Table 1 presents a summarized outline of the experimental methods used to evaluate recycled plastic roofing panels, along with relevant standards and applications. Each test, mechanical, structural, or durability-focused, assesses key performance attributes such as strength, stiffness, impact resistance, and waterproofing.

Table 1. Experimental Methods, Standards, and Applicability.

Specimen	Test Type	Applicability	Standard/ Reference
Corrugated Panel	Flexural Test	Evaluate load-carrying capacity and comparative stiffness of rHDPE and rPP corrugated panels	[32]
	Dynamic Resonance	Assess out-of-plane stiffness and damping behavior of rHDPE and rPP roofing sheets	[34]
	Vertical Impact Test	Investigate dynamic impact resistance and crack development for vertical use such as claddings, etc.	[35]
	Horizontal Impact	Investigate dynamic impact resistance and crack development for horizontal use such as roofing, etc.	[36]
	XRD Analysis	Verified post-load crystallinity retention in rHDPE and rPP corrugated samples	[37]
	SEM–EDS Analysis	Characterized homogeneity, dispersion, and micro-defects in recycled plastic-based panels	[38]
Prototype Slab	Flexural Test	Full-scale slab (1.63 × 1.6 m, 12 mm) test for load-bearing capacity, deflection profile, and failure mode	[39]
	Water Leakage Test	Waterproof performance using 6 h custom ponding test, aligned with metal roof static water penetration methods	[40]

To maintain consistency in comparing the rHDPE and rPP panels, all samples were manufactured with uniform cross-sectional profiles, controlled extrusion temperatures, and standardized cooling parameters. Mechanical testing adhered strictly to ASTM procedures with consistent span lengths, support setups, and loading rates. This controlled approach prioritized material-driven assessment; however, future research could incorporate solid block testing to enhance cross-validation of component-level performance.

2.3.1. Dynamic Elastic Property Evaluation Procedure for Corrugated Panels

The dynamic mechanical characterization of the recycled plastic corrugated panels (RPCP) was carried out in accordance with ASTM E1876-15 [3], which outlines the impulse excitation technique (IET) for determining the dynamic elastic properties of the materials shown in Figure 4 [34]. Rectangular specimens of rHDPE and rPP-based corrugated panels were prepared with uniform dimensions and supported in a free–free condition to minimize boundary constraints during vibration. A calibrated impact hammer was used to excite the specimens with a light mechanical tap, and the resulting vibrational response was captured using a precision microphone or piezoelectric accelerometer placed at an optimized distance [14]. The acquired time-domain signals were processed through a data acquisition system and transformed into frequency-domain data using Fast Fourier Transform (FFT) to identify the natural resonance frequencies of the samples [17]. Specifically, three fundamental resonance modes were identified for each panel type: longitudinal mode (RFL), in-plane flexural mode (RFF(IP)), and out-of-plane flexural mode (RFF(OOP)). From these resonance frequencies, the Dynamic Elastic Moduli (DEM) were calculated using the mass, dimensions, and resonance equations defined in ASTM E1876 [34]. In addition, the damping ratio (ξ) was estimated by analyzing the decay of the resonant vibration peaks, providing insight into the energy dissipation characteristics of the materials [35,36].

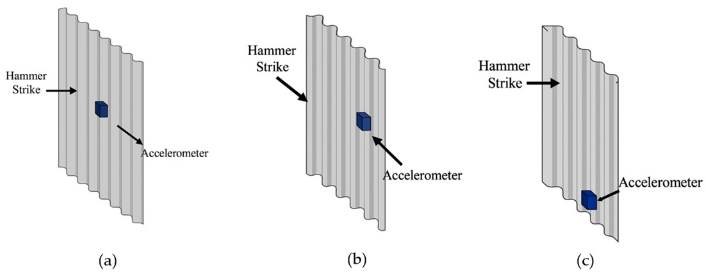


Figure 4. Schematic representation of impact response and damping behavior through (**a**) longitudinal, (**b**) In plane, and (**c**) out of plane resonance frequencies of corrugated panels.

2.3.2. Flexural Test Procedure

Flexural performance of the Recycled Plastic Corrugated panels (RPCP) was assessed using a three-point bending test setup, in accordance with the modified ASTM D790 [33] standard for determining the flexural properties of unreinforced and reinforced plastics. The tests were conducted using a calibrated Universal Testing Machine (UTM) equipped with precision load cells and deflection measurement capabilities. As shown in Figure 5, each RPCS specimen was placed horizontally on two roller supports, with a span length of 500 mm, while a centrally applied vertical load was introduced through a compression fixture mounted on the crosshead. Prior to testing, the panels were visually inspected for any surface inconsistencies or defects. The loading rate was controlled to ensure quasi-static conditions, and testing was carried out at room temperature. Real-time load–deflection data were recorded to evaluate the flexural behavior of both HDPE- and PP-based panels. Key parameters such as maximum load, stiffness (slope of the initial linear region), and deflection at failure were extracted from the resulting curves. The RPCS specimens demonstrated notable ductility and load absorption capacity, with gradual deformation observed prior to failure, indicative of a tough and energy-absorbing response. The panels fabricated from PP exhibited slightly higher stiffness, while HDPE-based panels showed more pronounced ductility. These characteristics suggest that RPCS possess the mechanical resilience required for non-load bearing structural applications, including cladding, enclosures, and other secondary construction uses where moderate flexural resistance is essential.

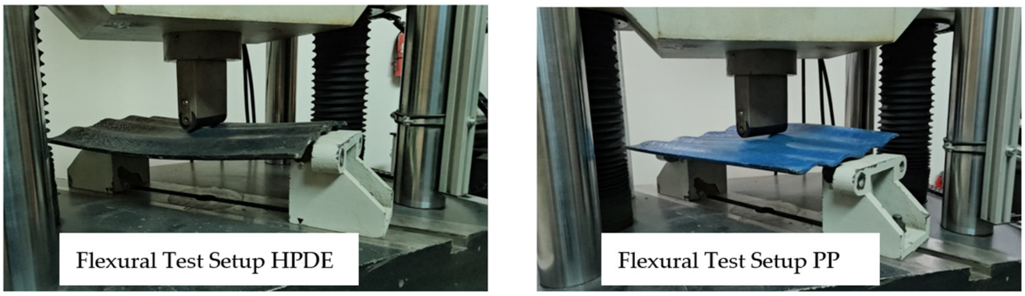


Figure 5. Flexural testing of recycled plastic corrugated panels (RPCP) under three-point bending configuration.

2.3.3. Vertical Panel Test Procedure—Modified Pendulum Impact Test

The pendulum impact apparatus consists of a steel hammer arm with a hemispherical striking head mounted on a pivot frame, allowing it to swing freely from a fixed height as shown in Figure 6. The corrugated panel specimen was clamped horizontally on a rigid steel base with minimal constraint at the edges to replicate real-life support conditions. The impact load and rebound height were recorded using a high-speed camera and deflection sensors, allowing evaluation of absorbed energy, failure modes, and damage propagation. Observations were made for crack initiation, deformation behavior, and delamination, particularly in peak regions of the corrugated profile [35,36].

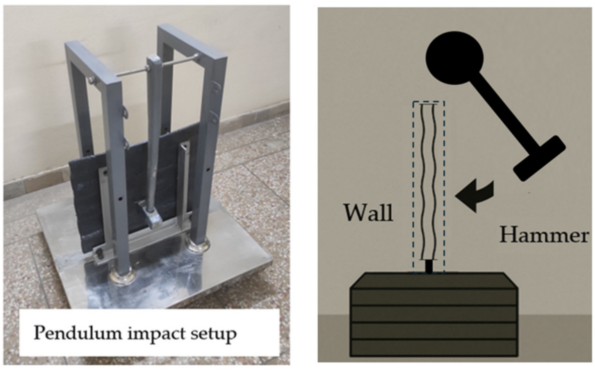


Figure 6. Experimental and schematic setup for modified pendulum impact testing.

2.3.4. Horizontal Panel Test Procedure—Modified Drop Impact Test

In the drop weight test, a cylindrical steel mass was allowed to fall vertically from set heights onto the center of the corrugated panels placed over a support shown in Figure 7. Impact energy levels were constant for drop height and mass. The failure patterns were analyzed to determine the energy absorption capacity and dynamic toughness of the materials in regard to the number of blows. Both rHDPE and rPP samples were tested under identical conditions for comparative analysis. The rPP corrugated panels generally exhibited higher peak force resistance but lower ductile deformation, whereas rHDPE panels showed greater deflection and energy absorption prior to failure, indicating their ability to withstand impact loads. This dual-impact testing framework provided a comprehensive assessment of the mechanical resilience and suitability of recycled plastic corrugated panels for applications involving dynamic loads, roofing, flooring in traffic areas, and protective barriers in construction zones in cases of hailstorms [12] and other impact loads [35,36].

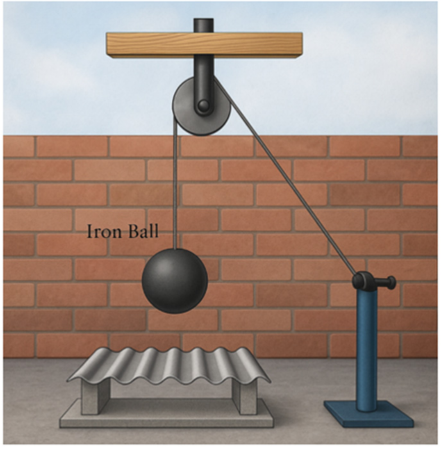


Figure 7. Schematic setup for modified drop impact testing.

2.3.5. Characterization and Microstructural Assessment

XRD Analysis Procedure

X-ray Diffraction (XRD) analysis was employed to investigate the crystallographic characteristics of the recycled HDPE and PP used in the fabrication of corrugated panels. The measurements were conducted using a θ–2θ locked-coupled scan configuration, which is widely adopted for examining semi-crystalline polymer systems [41]. A copper (Cu) anode X-ray source was utilized, generating characteristic Cu Kα radiation with an average wavelength of 1.5418 Å, suitable for resolving polymeric crystalline structures. The diffractometer was operated at an accelerating voltage of 40 kV and a current of 30 mA, providing sufficient beam intensity for the analysis of plastic-based composites [41]. Data acquisition was carried out using a goniometer with a 560 mm radius (Model 512), offering high angular precision. To optimize peak resolution and reduce axial divergence, both primary and secondary Soller slits were fixed at 2.5°. The scan range spanned from 10° to 32.2° in 2θ, effectively capturing the dominant diffraction peaks associated with the orthorhombic and monoclinic crystalline phases typical of HDPE and PP. A fine step size was applied to enhance peak definition and support reliable identification of crystallographic features. Although no monochromator or beam analyzer was used, allowing for rapid throughput, the data quality remained robust for structural analysis. This procedure adheres to standard XRD protocols for semi-crystalline polymers and enabled clear differentiation of the crystalline domains within the corrugated panels, thereby supporting the evaluation of phase composition, material structure, and degree of crystallinity in recycled polymer matrices [42].

SEM and EDS Analysis Procedure

Scanning Electron Microscopy (SEM) coupled with Energy Dispersive X-ray Spectroscopy (EDS) was employed to investigate the surface morphology and elemental composition of the recycled plastic corrugated panels (RPCP) fabricated from HDPE and PP [43]. The analysis was carried out using a field-emission SEM (FE-SEM) under high vacuum conditions to obtain high-resolution surface micrographs. Prior to imaging, the specimens were cleaned with compressed air to remove loose particles and sputter-coated with a thin layer of gold (Au) using a DC magnetron sputter coater to enhance surface conductivity and reduce charging effects during electron bombardment. The SEM images were captured at a magnification range suitable for microstructural evaluation, with an accelerating voltage set to 15 kV [44]. The working distance was optimized between 8–12 mm, and the detector mode was switched between secondary electron (SE) and backscattered electron (BSE) to resolve both topographical and compositional contrasts. Multiple regions of interest were selected for EDS analysis, identified as spectrums and others, to ensure a representative assessment of the elemental distribution across the polymer matrix. EDS spectra confirmed that carbon (C) and oxygen (O) were the dominant elements, consistent with the hydrocarbon-based composition of the polymers. Trace elements such as Ca, Si, Mg, Cl, Ti, and sputtered Au were also detected, which may arise from fillers, surface residues, or processing additives. The EDS maps provided quantitative weight percentages (wt%) for each detected element, assisting in the evaluation of purity, homogeneity, and the presence of inorganic constituents within the recycled material. This characterization protocol enabled a comprehensive understanding of the microstructural integrity and elemental uniformity of the RPCS, contributing to the assessment of their suitability for structural and environmental applications [31,45].

2.4. Prototype Slab Test Procedure

2.4.1. Water Leakage Test Procedure

A prototype slab measuring 1.63 m × 1.6 m was fabricated using RPCS HDPE panels for practical performance evaluation as per ASTM E2140 [40]. The joints of the panels were made in such a way that a 50 mm overlap was achieved. These joints were properly shaped to achieve good overlap finish. Epoxy sealant was applied along the roof joints to create a durable, watertight barrier that prevents water infiltration. Its strong adhesion and airtight joints ensured long-term protection against leakage [6].

2.4.2. Flexural Capacity Test Procedure

The prototype slab was subjected to centrally applied through incremental 10 kg bags placed at the center of the arrangement until failure [46]. Deflection at the central point was recorded by a customized arrangement with a free hanging bar fixed at the center point as per ASTM E661 [39]. The recycled plastic panels demonstrated stable performance under loads, showing controlled deflection without structural rupture during load increments [47].

This experiment validated the load-bearing capability under flexural loads of recycled plastic prototype slab RPPS and underscored their feasibility for applications in pedestrian walkways, temporary stages, lightweight decks, and low-load roofing systems [46,48]. Figure 8 illustrates a schematic setup for evaluating the structural deflection of a prototype slab (PS) under applied loading. A vertical load was applied at the center of the PS with an increment of 98.1 N to simulate service conditions, while the downward curvature indicates deflection due to bending [14]. A custom deflection gauge setup was positioned at the center to monitor deformation and measure the structural response of the prototype slab to the applied load.

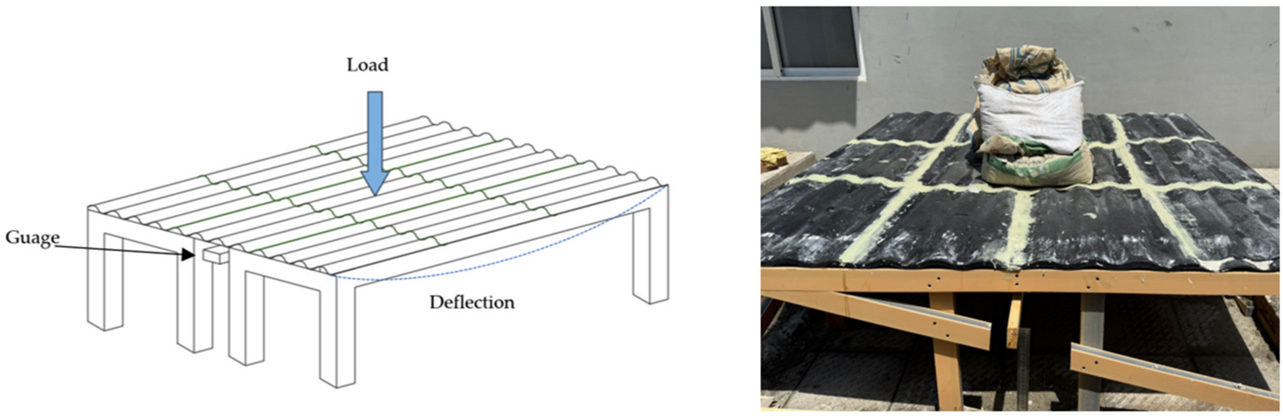


Figure 8. Schematic representation and flexural capacity test setup of corrugated panel.

2.5. Empirical Relationship Procedure Between Impact and Flexural Strength of Panel

Impact strength was determined by dividing the total absorbed energy by the area of impact. The energy absorbed during failure was measured in joules, while the impact area was calculated based on the hammer face dimensions (50.8 mm × 12.7 mm, yielding 645.16 mm^2). The resulting value, expressed in J/mm^2, was directly equivalent to megapascals (MPa), reflecting the material's ability to resist sudden applied loads. To establish a correlation between flexural and impact strength of recycled plastic materials, a systematic formulation procedure was adopted. Flexural strength was determined using standard three-point bending tests, where the maximum stress sustained by each specimen was recorded. Impact strength was assessed separately through drop-weight and pendulum impact tests, with energy absorbed during fracture measured and normalized over the impact area to express results in megapascals (MPa). The ratio of impact strength to flexural strength was then calculated for each material type, providing a dimensionless value that represents the proportion of static bending strength retained under dynamic loading. To enhance interpretability, these ratios were also expressed as percentages. This approach allowed for a direct comparison of the material's toughness relative to its bending capacity, offering both numerical and qualitative insights into its suitability for structural applications involving sudden or cyclic loads. This method provides a practical framework for evaluating recycled polymers when selecting materials for impact-prone environments. This approach provides a reliable assessment of the toughness and durability of recycled plastic panels under dynamic loading conditions. These values corresponded to flexural strength and were used to develop an empirical equation expressing the relationship between impact strength and flexural strength.

3. Results

3.1. Behavior of Corrugated Panel

3.1.1. Fundamental Frequency and Damping Behavior

The dynamic mechanical properties of recycled HDPE (rHDPE) and recycled PP (rPP) corrugated panels were assessed according to ASTM E1876-15 [34] using resonance frequency analysis to determine their stiffness and damping characteristics under flexural and longitudinal modes. Figure 4 presents the schematic arrangement. The evaluation included measurements of longitudinal resonance frequency (RFL), flexural resonance frequencies in in-plane (RFF(IP)) and out-of-plane (RFF(OOP)) directions, dynamic elastic modulus (DEM) across all corresponding modes, and material damping quantified through the logarithmic decrement (ξ). The longitudinal resonance frequency (RFL) of rHDPE was measured at 1043.1 ± 110.9 Hz, closely matched by rPP at 1042.5 ± 22.5 Hz. This parity indicates similar mass-to-stiffness ratios in longitudinal vibration for both polymers. However, a distinct difference was observed in flexural resonance behavior. While the in-plane flexural frequencies (RFF(IP)) were similar for both rHDPE and rPP (1065.3 ± 88.7 Hz vs. 1065.0 ± 0.0 Hz), the out-of-plane frequency (RFF(OOP)) revealed a substantial increase in rPP (998.6 ± 66.4 Hz) compared to rHDPE (976.1 ± 43.9 Hz), suggesting a stiffer out-of-plane response for rPP under flexural loading. The dynamic elastic modulus (DEM) data further substantiates this observation. rHDPE demonstrated a longitudinal modulus (DEML) of 1.53 ± 0.33 GPa and in-plane flexural modulus (DEMF(IP)) of 2.43 ± 0.40 GPa. Comparatively, rPP exhibited slightly lower longitudinal stiffness (1.37 ± 0.14 GPa) but demonstrated superior out-of-plane stiffness (DEMF(OOP) = 2.17 ± 0.33 GPa) versus rHDPE (2.04 ± 1.07 GPa). This indicates that rPP, though less stiff in axial loading, may offer better flexural resistance, particularly in out-of-plane structural configurations.

Damping properties, represented by the logarithmic decrement (ξ), revealed contrasting behaviors between the materials. rHDPE showed a moderate longitudinal damping ratio of 3.4 ± 0.4%, higher in-plane damping ($\xi_{F(IP)}$) of 6.9 ± 2.8%, and substantial out-of-plane damping ($\xi_{F(OOP)}$) at 8.2 ± 0.1%. This trend implies that rHDPE may be more effective in attenuating vibrational energy, especially in complex structural motions. Conversely, rPP exhibited a high longitudinal damping (ξ_L = 8.6 ± 0.7), but lower values for in-plane (5.8 ± 0.5%) and out-of-plane (4.2 ± 0.2%) damping, as summarized in Table 2. This dichotomy suggests that while rPP may absorb energy efficiently in axial resonance, it exhibits lower energy dissipation in bending modes compared to rHDPE. Overall, these results highlight nuanced differences in the dynamic behavior of rHDPE and rPP corrugated panels. rPP offers improved stiffness in flexural out-of-plane response and greater consistency in resonance behavior, while rHDPE provides superior damping in flexural configurations. These findings indicate that rPP may be more suitable for applications requiring higher flexural rigidity, whereas rHDPE could be advantageous in scenarios where vibration attenuation is critical.

Table 2. Dynamic Properties of rHDPE and rPP Corrugated Panels (ASTM E1876-15).

Sample	RF_L (Hz)	$RF_{F(IP)}$ (Hz)	$RF_{F(OOP)}$ (Hz)	DEM_L (GPa)	$DEM_{F(IP)}$ (GPa)	$DEM_{F(OOP)}$ (GPa)	ξ_L (%)	$\xi_{F(IP)}$ (%)	$\xi_{F(OOP)}$ (%)
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**
rHDPE	1043.1 ± 110.9	1065.3 ± 88.7	976.1 ± 43.9	1.53 ± 0.33	2.43 ± 0.40	2.04 ± 1.07	3.4 ± 0.4	6.9 ± 2.8	8.2 ± 0.1
rPP	1042.5 ± 22.5	1065.0 ± 0.00	998.6 ± 66.4	1.37 ± 0.14	1.91 ± 0.26	2.17 ± 0.33	8.6 ± 0.7	5.8 ± 0.5	4.2 ± 0.2

The experimental findings show that rHDPE panels possess higher damping in the out-of-plane direction, making them suitable for roofing elements subjected to dynamic loads. rPP panels, on the other hand, exhibit greater longitudinal damping and out-of-plane stiffness, supporting their use in façade or cladding systems. These material-specific properties allow engineers to assign recycled panels based on directional loading demands. The comparative evaluation of dynamic elastic modulus in the out-of-plane direction (DEM_x) revealed that rPP panels exhibited superior stiffness (2.17 ± 0.33 GPa) compared to rHDPE (2.04 ± 1.07 GPa), indicating a more rigid structural response under transverse dynamic excitation. This distinction is critical when optimizing building envelopes and lightweight roofing systems where flexural resistance and dynamic load attenuation are essential. The relatively lower DEM_x of rHDPE, coupled with its higher damping ratio (ξ_x = 8.2 ± 0.1%), suggests its effectiveness in energy dissipation rather than load bearing, making it more suitable for acoustic insulation and vibration mitigation applications. In contrast, rPP's combination of higher DEM_x and lower damping (ξ_x = 4.2 ± 0.2%) positions it as a viable material for structural skins subjected to repetitive wind or seismic excitation where stiffness and dimensional stability are prioritized. The reduced flexural damping observed in rPP is linked to its higher crystallinity and lower chain entanglement, which constrain viscoelastic energy dissipation under bending loads. In contrast, rHDPE's greater amorphous content facilitates internal friction, resulting in enhanced flexural damping. The superior longitudinal damping of rPP is attributed to its molecular alignment, which supports more efficient axial vibration attenuation. The superior mechanical performance of rHDPE arises from its semi-crystalline structure with well-distributed amorphous regions that enhance toughness and energy dissipation. Its higher molecular branching also contributes to better ductility compared to rPP. Optimizing extrusion temperature and cooling rate, and incorporating compatibilizers can further refine its microstructure and mechanical response. Both materials, however, demonstrate adequate mechanical performance as is for potential use in sustainable roofing and cladding applications where dynamic loading and acoustic insulation are the performance criteria [35,36].

3.1.2. Flexural Performance of Recycled Corrugated Panels

The flexural performance of recycled high-density polyethylene (rHDPE) and recycled polypropylene (rPP) corrugated panels was assessed through three-point bending tests, conducted in accordance with ASTM D790 [33]. The stress–strain responses, depicted in Figure 9, reveal notable distinctions in mechanical behavior between the two materials. rHDPE demonstrates a steeper stress rise and higher ultimate stress, indicating superior load resistance and structural stiffness. In contrast, rPP exhibits a more gradual increase in stress and sustains a slightly larger strain at failure, highlighting its higher ductility. Quantitative results are summarized in Table 3. From the tabulated results, rHDPE panels demonstrate superior mechanical performance relative to rPP across most critical indicators. Specifically, rHDPE panels supported a maximum load of 1.958 ± 0.098 kN, indicating higher structural capacity compared to rPP, which sustained a slightly lower peak load of 1.816 ± 0.091 kN.

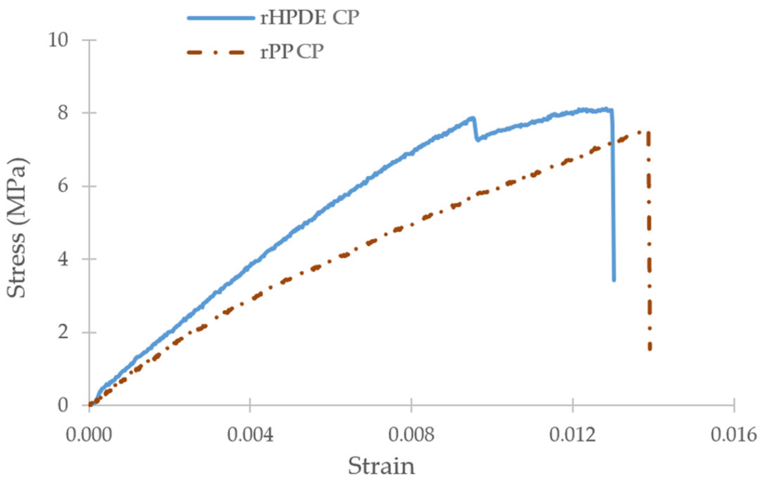


Figure 9. Stress—strain behavior of rHDPE and rPP corrugated panels.

Table 3. Summary of Results of Flexural Behavior of Corrugated Panels.

Material	Weight (kg)	Max Load (kN)	Max Deflection (mm × 10)	Max Stress (MPa)	Max Strain (×10^{-2})	Total Energy Absorption (MJ/m^3 × 10^{-2})	Toughness Index
rHDPE	3.100 ± 0.155	1.958 ± 0.098	2.860 ± 0.143	8.136 ± 0.407	1.302 ± 0.065	6.826 ± 0.341	1.017 ± 0.051
rPP	3.200 ± 0.160	1.816 ± 0.091	3.051 ± 0.153	7.546 ± 0.377	1.391 ± 0.070	5.918 ± 0.296	1.000 ± 0.050

This enhanced load-bearing capacity in rHDPE is further supported by its maximum stress value of 8.136 ± 0.407 MPa, which surpasses that of rPP at 7.546 ± 0.377 MPa. The higher stress resistance is indicative of better stiffness and internal bonding in rHDPE-based composites. In terms of deformation behavior, rPP panels experienced greater deflection (3.051 ± 0.153 mm × 10) compared to rHDPE panels (2.860 ± 0.143 mm × 10), suggesting relatively lower rigidity in rPP composites. Corresponding strain values further confirm this trend, with rPP reaching a strain of 1.391 ± 0.070 × 10^{-2}, slightly exceeding rHDPE's 1.302 ± 0.065 × 10^{-2}. Despite the higher strain, rPP's capacity to absorb energy under load remains lower, with total energy absorption recorded at 5.918 ± 0.296 MJ/m^3 × 10^{-2} for rPP, compared to 6.826 ± 0.341 MJ/m^3 × 10^{-2} for rHDPE. Furthermore, the toughness index, an indicator of post-yield energy absorption relative to yield strength, was marginally higher for rHDPE (1.017 ± 0.051) than rPP (1.000 ± 0.050), reinforcing the former's better energy dissipation and crack-resistance properties. Overall, these findings highlight rHDPE's mechanical superiority for structural applications requiring higher flexural resistance, energy absorption, and toughness [49]. These comparative results are visually consolidated in Figure 10, where the bar chart illustrates the relative performance of both materials across all key parameters, including load, deflection, stress, strain, energy absorption, and toughness index. Collectively, the data suggest that while both rHDPE and rPP corrugated panels exhibit promising flexural characteristics, rHDPE offers enhanced strength and energy absorption, making it more suitable for structural applications demanding higher resistance to flexural stress. rPP, on the other hand, may be preferred in scenarios requiring greater flexibility and ductility.

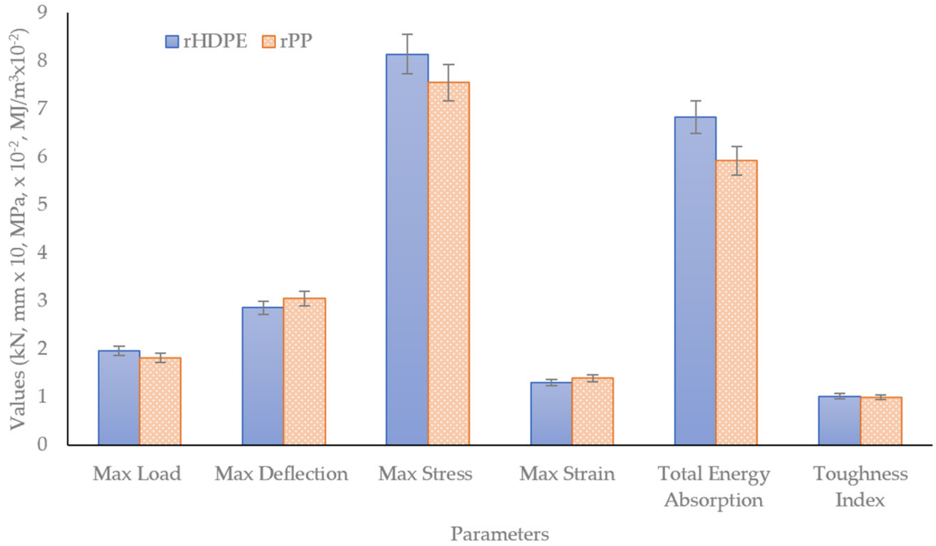


Figure 10. Summary of behavior of rHDPE and rPP corrugated panels.

3.1.3. Behavior of Vertical Panel Under Pendulum Impact

The impact energy and toughness properties of recycled HDPE and PP panels were evaluated through both drop-weight and pendulum impact tests. The energy per impact was calculated using the potential energy equation $E = mgh$, assuming no energy loss (ideal conditions), with the mass of the falling body being 2.94 kg, gravitational acceleration $g = 9.81$ m/s^2, and drop heights of 1.8 m for the drop test and 0.6 m for the pendulum test. These values yielded individual blow energies of 52.06 J (0.052 kJ) and 17.35 J (0.017 kJ), respectively. By multiplying these by the number of impacts sustained before failure, the total energy absorption for each sample was calculated. The total energy was then normalized by the specimen volume (0.00354 m^3) to derive the material toughness in kJ/m^3. Figure 11 illustrates the failure patterns of rPP and rHDPE corrugated panels subjected to a modified pendulum impact test. The rPP sample (top row) exhibits a characteristic radial cracking pattern extending across a 75 mm radius from the impact center, indicative of localized tensile failure and material ductility under dynamic load. In contrast, the rHDPE sample (bottom row) displays a projectile-like disintegration at the impact zone, suggesting a brittle fracture mode with minimal crack propagation and energy absorption. These visual differences confirm the superior impact toughness of rPP over rHDPE in resisting high-strain-rate deformation. Under high strain rate impact, rPP exhibits radial cracking due to its higher crystallinity and localized stress concentration, leading to brittle fracture paths. In contrast, rHDPE undergoes a more distributed failure characterized by projectile-like fragmentation, attributed to its ductile matrix and energy dissipation through fibrillation and cavitation. These contrasting behaviors reflect fundamental differences in their molecular architecture and deformation mechanisms.

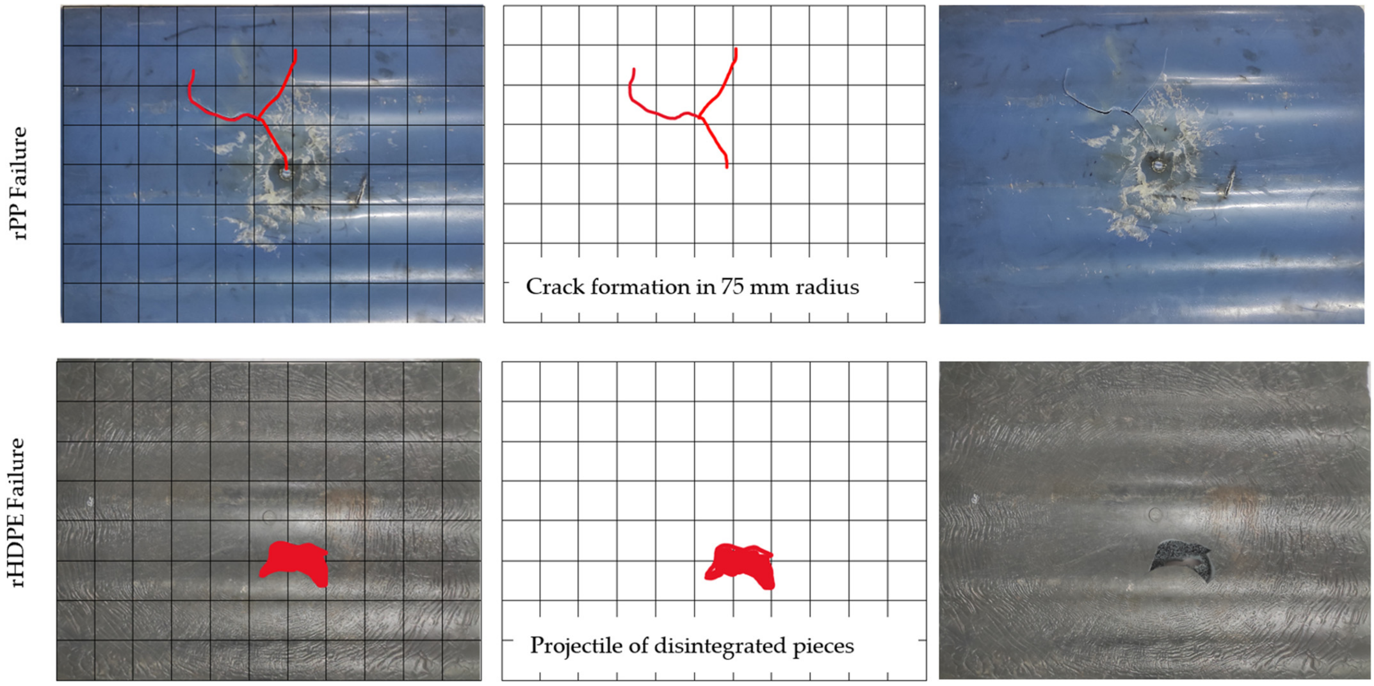


Figure 11. Failure of corrugated panels in modified pendulum impact test.

3.1.4. Behavior of Horizontal Panel Under Drop Impact

In the drop-weight tests, rHDPE withstood 28 ± 3 blows, resulting in a total energy absorption of 1.458 ± 0.156 kJ and a material toughness of 411.85 ± 44.13 kJ/m^3. In contrast, rPP absorbed significantly more energy, withstanding 51 ± 4 blows and absorbing 2.655 ± 0.208 kJ, corresponding to a toughness of 750.15 ± 58.84 kJ/m^3. Under pendulum impact conditions, rHDPE absorbed 0.816 ± 0.069 kJ from 47 ± 4 blows, with a toughness of 230.44 ± 19.61 kJ/m^3, whereas rPP exhibited enhanced performance again, absorbing 1.770 ± 0.156 kJ over 102 ± 9 blows, yielding a toughness of 500.10 ± 44.13 kJ/m^3. Figure 12 depicts the failure morphology of rPP and rHDPE corrugated panels subjected to a modified drop impact test. The rPP sample (top row) demonstrates a clean longitudinal split along the length of the panel, signifying a ductile tearing behavior that maintains structural continuity at the edges. This indicates a gradual energy dissipation mechanism characteristic of more flexible thermoplastics. Conversely, the rHDPE sample (bottom row) exhibits a brittle failure pattern with fragmentation into three distinct sections, denoting a sudden loss of load-bearing capacity upon impact. The fracture propagation across multiple directions highlights the material's limited toughness and resistance under high-energy impact loading.

In recent research [35,36], the same mechanism was adopted to evaluate impact resistance, observing significant gains in energy absorption and dynamic resilience [35,36]. Their empirical modelling underlined the relevance of repeated blow analysis in quantifying dynamic load behavior. These findings clearly indicate that recycled polypropylene exhibits better impact resistance and toughness compared to recycled HDPE under both dynamic testing regimes. The results are summarized in Table 4 and Figure 13 for both the tests. The higher energy absorption and toughness values of the rPP highlight its potential as a sustainable and resilient material for construction applications, particularly in environments subject to repeated or high-intensity impacts. Its durability makes it a promising candidate for recycled corrugated roofing and cladding elements, supporting the transition toward circular and high-performance construction materials.

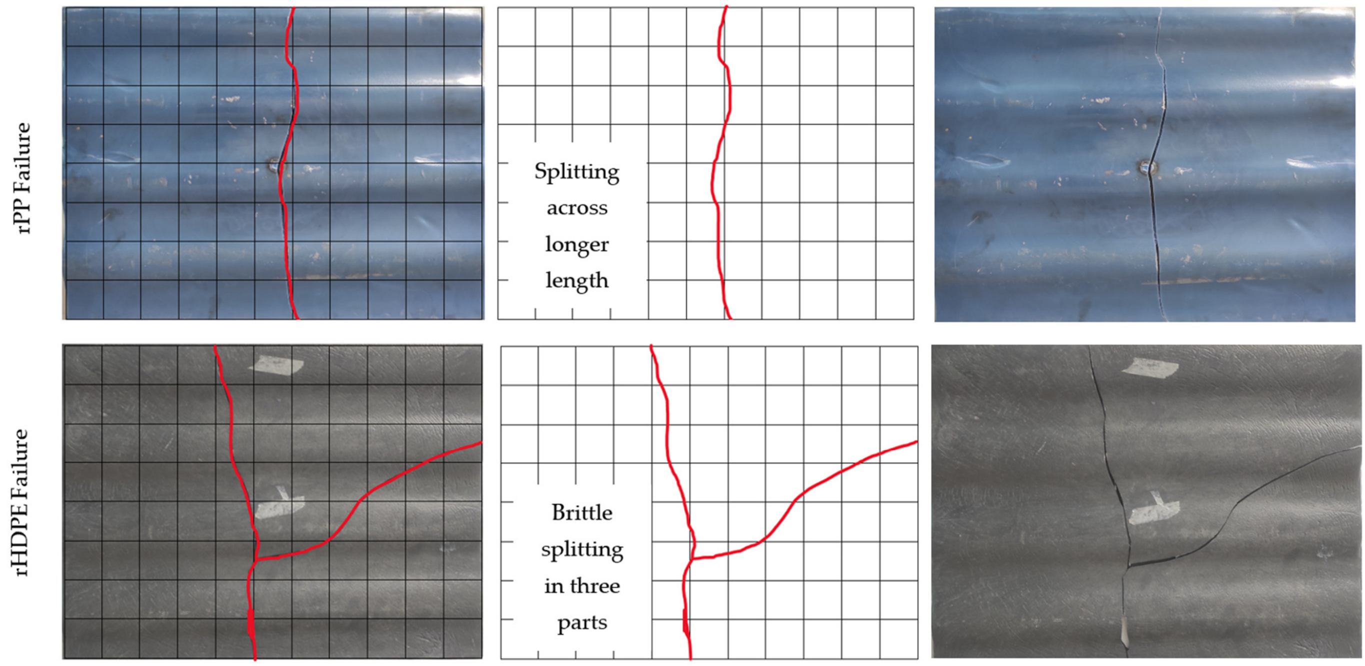


Figure 12. Failure of corrugated panels in modified drop impact test.

Table 4. Summary of Impact Strength Results of rHDPE and rPP Corrugated Panels.

Test Type	Sample	Impact Height (m)	Angular Distance (m)	Impact Energy (J/Blow)	Impact Strength (Blows)	Total Energy (kJ)	Impact Strength (MPa)	Material Toughness (kJ/m^3)
Drop Weight	rHDPE	1.8	-	52.06	28 ± 3	1.45 ± 0.15	2.25 ± 0.23	411.84 ± 44.12
	rPP	1.8	-	52.06	51 ± 4	2.65 ± 0.20	4.11 ± 0.31	750.15 ± 58.83
Pendulum	rHDPE	-	0.6	17.35	47 ± 4	0.81 ± 0.06	1.26 ± 0.09	230.43 ± 19.61
	rPP	-	0.6	17.35	102 ± 9	1.77 ± 0.15	2.74 ± 0.23	500.10 ± 44.12

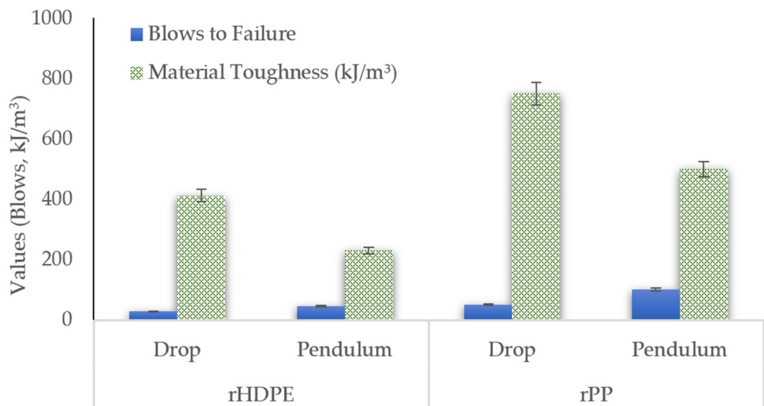


Figure 13. Comparison of results of blow to failure and material toughness of rHDPE and rPP on the modified pendulum and modified drop test.

Table 5 summarizes the failure morphology of the corrugated panels. Under pendulum impact testing, recycled polypropylene (rPP) panels exhibited radial crack propagation extending approximately 75 mm from the center of impact, forming a star-like fracture pattern with angular spacing of around 60° between primary cracks. In contrast, recycled high-density polyethylene (rHDPE) panels displayed a highly localized failure, limited to a central impact zone with negligible crack extension—confined within a crater roughly 100 mm in diameter—indicating a brittle fragmentation mode. During drop-weight impact testing, rPP panels developed a single dominant longitudinal crack spanning nearly the entire panel length (~450 mm), while the remainder of the panel remained intact, suggesting a ductile tearing mechanism with minimal material loss. Conversely, rHDPE panels fractured into three sizable sections due to two prominent cracks (~450 mm and ~250 mm), diverging at approximate angles of 0° and 60°, characteristic of brittle fracture propagation. Despite the severe cracking, rHDPE showed minimal fine debris, and the fragmented zones were composed of cleanly separated sections rather than pulverized material, indicating that the disintegration area was limited to macroscopic divisions.

Table 5. Failure Morphology of Impact Strengths of rHDPE and rPP Corrugated Panels.

Material	Test	Approx. Crack Lengths	Disintegration Area	Crack Orientation
rPP	Pendulum	~75 mm radial cracks (2–3 emanating)	Negligible (no pieces detached)	Radial from impact (~60° apart)
	Drop Weight	One crack ~450 mm (along panel length)	None (intact except for split)	~0° (along corrugation/length)
rHDPE	Pendulum	Minimal crack propagation (<20 mm)	~100 mm diameter impact crater	Localized shatter at center
	Drop Weight	Two cracks ~450 mm and ~250 mm	No small debris (broke into 3 large sections)	~0° and ~60° (diverging paths)

3.1.5. Microstructural Behavior

XRD Analysis

The presented XRD patterns were obtained from recycled HDPE and PP samples post-failure under flexural loading, as part of a structural assessment study. Despite undergoing mechanical deformation and fracture during flexural testing, both polymers retained distinct crystalline peaks, suggesting that their core crystalline regions remained largely unaffected. However, minor peak broadening and reduced intensity, particularly in the rHDPE pattern, may indicate localized structural disorder or microcrack formation induced by mechanical loading. Figure 8 presents X-ray diffraction (XRD) patterns of recycled high-density polyethylene (rHDPE) and recycled polypropylene (rPP), highlighting their respective crystalline structures. The graph in Figure 14a corresponds to rHDPE, showing two prominent diffraction peaks located at approximately 21.6° and 23.9° 2θ, which are indexed to the (110) and (200) crystallographic planes. These peaks are characteristic of the orthorhombic crystal structure typical of semi-crystalline HDPE, indicating a moderate degree of crystallinity retained in the recycled polymer. Figure 14b displays the XRD pattern of rPP, which exhibits multiple well-defined peaks, including reflections at around 13.9°, 16.7°, 18.6°, 21.2°, and 25.7° 2θ. These peaks correspond to the (110), (111), (040), and (041) planes of the monoclinic α-phase of polypropylene. The intensity and multiplicity of peaks in rPP suggest a relatively higher crystalline order compared to rHDPE. The pronounced peak intensities reflect the semi-crystalline nature of the polymer and indicate that the recycling process preserved significant structural integrity [31].

The influence of recycling processes, such as melting, extrusion, and remolding, can also impact the degree of crystallinity by altering the molecular alignment. Nonetheless, the preservation of prominent diffraction peaks in both rHDPE and rPP implies that the recycling process did not significantly compromise their crystalline structure. This structural resilience, even after flexural failure, highlights the potential of mechanically recycled polymers to maintain functional integrity in load-bearing applications. Overall, the XRD analysis confirms the presence of distinct crystalline domains in both recycled polymers, validating their suitability for structural applications. The identifiable peaks further reinforce the retention of polymer-specific lattice arrangements, crucial for ensuring mechanical performance in recycled plastic products [37].

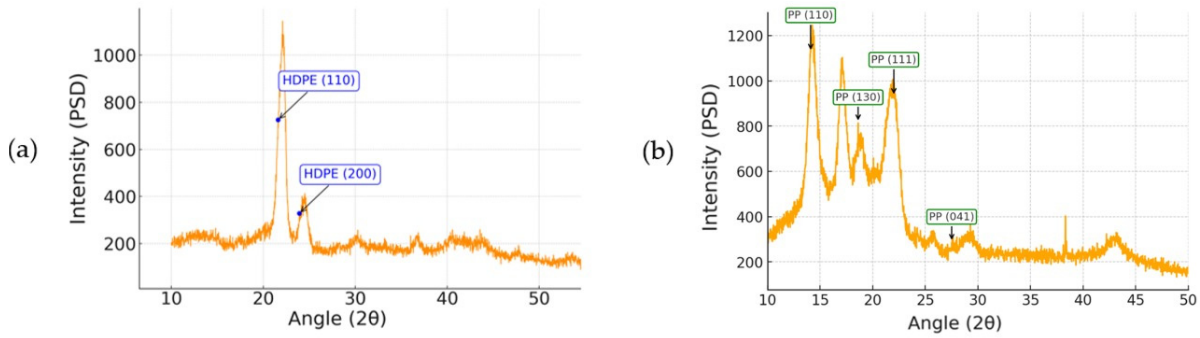


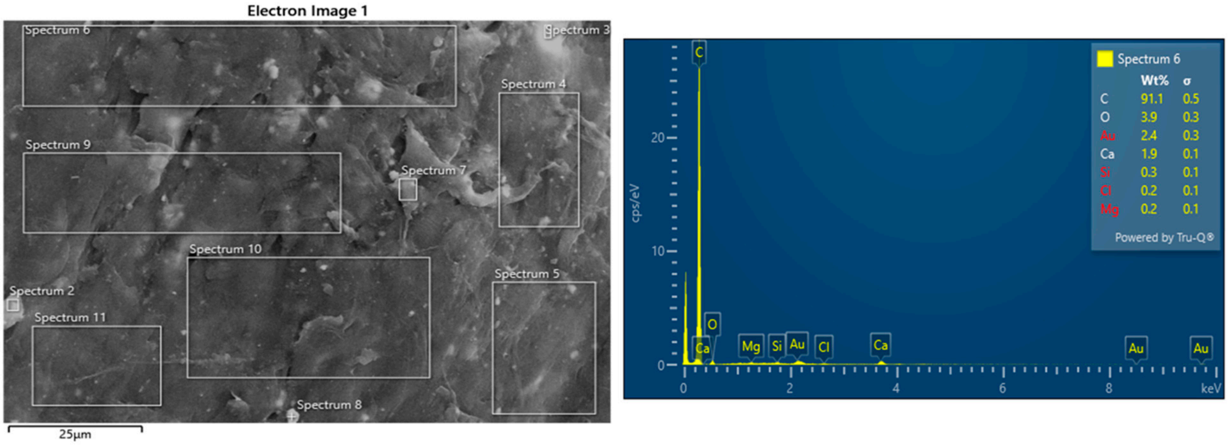
Figure 14. X-ray diffraction (XRD) patterns of recycled (**a**) HDPE and (**b**) PP corrugated panels after flexural failure.

Crystallinity indices derived from XRD analysis, based on Gaussian fitting and baseline-corrected integration, indicated values of 22.12% for rPP and 17.20% for rHDPE. The XRD patterns exhibited by rHDPE and rPP indicate notable microstructural differences. rHDPE showed broader and less intense peaks, suggesting lower crystallinity and a higher amorphous fraction, which may enhance its ductility and energy absorption under impact. Conversely, rPP displayed sharper and more defined peaks, pointing to a more ordered structure that contributes to higher stiffness but reduced impact tolerance. These differences support the contrasting mechanical behaviors observed during high strain rate testing.

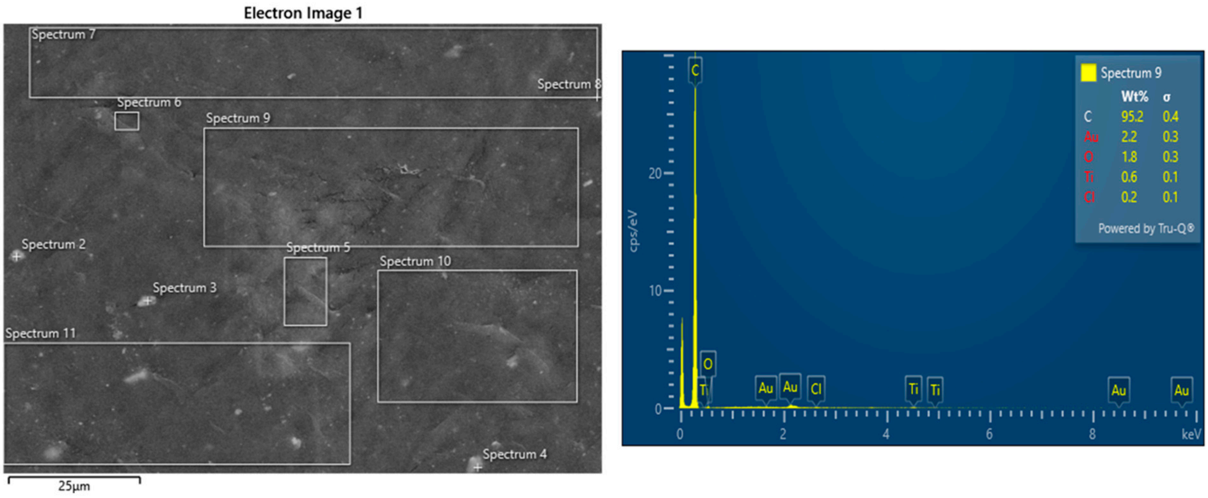
SEM and EDS Analysis

The scanning electron microscopy (SEM) images and energy-dispersive X-ray spectroscopy (EDS) analysis of recycled high-density polyethylene (rHDPE) and recycled polypropylene (rPP) following mechanical testing is shown in Figure 15. SEM-EDS analysis was conducted on post-failure fracture surfaces to examine microstructural distortions, filler distribution, and compositional variations induced by mechanical stress, offering insight into material failure mechanisms. The SEM micrographs offer insight into the surface morphology of both materials, while the EDS spectra provide detailed elemental composition from selected regions. The SEM image of rHDPE (Figure 15a) reveals a rough and uneven surface with visible micro-voids and surface irregularities, which likely developed during flexural loading or because of inhomogeneities introduced during recycling. The distribution of rectangular boxes labeled Spectrum indicates multiple areas analyzed for chemical composition. These morphological features suggest the presence of embedded fillers or incomplete fusion of polymer chains, characteristic of recycled thermoplastics [49].

In contrast, the SEM image of rPP (Figure 15b) displays a relatively smoother and denser surface morphology, although minor rough patches and particulate residues are also visible. This may indicate better flow and dispersion during reprocessing, although the presence of surface inclusions still reflects its recycled nature [38]. In the EDS spectra, for rHDPE, Spectrum 6 shows that the dominant element is carbon (91.1 wt%), followed by oxygen (3.9 wt%), gold (2.4 wt%), calcium (1.9 wt%), and trace amounts of silicon (0.3 wt%), chlorine (0.2 wt%), and magnesium (0.2 wt%). For rPP (Spectrum 9), the carbon content is higher at 95.2 wt%, with oxygen at 2.2 wt%, and trace levels of gold (0.6 wt%), titanium (0.6 wt%), chlorine (0.2 wt%), and iron (0.1 wt%), summarized in Table 6. The peaks in both samples arise from the conductive sputter coating used during SEM imaging. The presence of calcium, silicon, and magnesium in rHDPE and titanium and iron in rPP suggests residual inorganic fillers, pigments, or impurities retained from the recycling stream or previous use. The SEM-EDS analysis confirms that both rHDPE and rPP retain significant carbon-based polymer structure after flexural failure, while also containing minor elemental residues indicative of additives, contamination, or process-related modifications. This highlights the complexity of recycled plastic compositions and the importance of microstructural and compositional evaluation in assessing their mechanical reliability and consistency for reuse in structural applications [31].



(a) SEM and spectrum analysis of r HDPE



(b) SEM and spectrum analysis of rPP

Figure 15. SEM and composition analysis of (**a**) rHDPE and (**b**) rPP.

Table 6. Elemental Composition (wt%) of Recycled HDPE and PP from EDS Analysis.

Sample	C (wt%)	O (wt%)	Au (wt%)	Ca (wt%)	Si (wt%)	Cl (wt%)	Mg (wt%)	Ti (wt%)	Fe (wt%)
rHDPE	91.1 ± 0.5	3.9 ± 0.3	2.4 ± 0.3	1.9 ± 0.1	0.3 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	—	—
rPP	95.2 ± 0.4	2.2 ± 0.3	0.6 ± 0.3	—	—	0.2 ± 0.1	—	0.6 ± 0.1	0.1 ± 0.1

3.2. Behavior of Prototype Slab

3.2.1. Water Leakage Behavior of Prototype Slab

The structural performance and water resistance of recycled corrugated plastic prototype slabs was evaluated through experimental procedures, as depicted in the Figure 16. Initially, edge modifications were made to facilitate overlapping joints between adjacent panels. These modifications, visible in Figure 16, involved precise edge-cutting techniques designed to enhance interlocking capability and prevent water ingress at junctions. The overlapping design mimics conventional roofing practices, offering both mechanical interlock and coverage continuity. This detailing is critical for achieving long-term waterproofing and structural integrity in roofing applications using recycled plastic components.

Subsequently, to assess the water resistance performance of the assembled system, a water leakage test was conducted on a mock-up frame covered with the joined corrugated panels, as shown in Figure 15b. The test setup included a soil-bound reservoir filled with water over the surface of the assembled prototype slab. The setup was kept for 6 h, and no water leakage was observed, as compiled in Table 7. Observations revealed that the modified edges effectively minimized water leakage, validating the proposed joint design for practical use in roofing or cladding systems subjected to rainfall or wet environmental conditions.

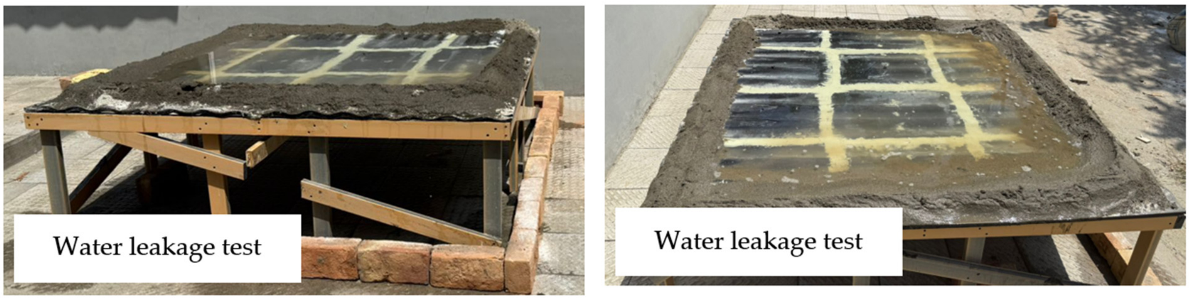


Figure 16. Water leakage testing of recycled plastic corrugated prototype slabs test.

Table 7. Water Leakage Test Results for rHDPE Prototype Slabs.

Time Interval (h)	Water Head * (cm)	Water Leakage Observed	Water Collected Below (Liters)	Remarks
0	7.67	0%	0	No leakage
2	7.67	0%	0	No leakage
4	7.67	0%	0	No leakage
6	7.67	0%	0	No leakage

* Note: 200 L water on slab top.

3.2.2. Recycled Plastic Prototype Slab (RPPS) Flexural Capacity

In the next phase of evaluation, load testing was performed to investigate the structural response of the recycled prototype slab assemblies under applied loads. Figure 17a from the second image set presents the experimental configuration used to simulate service loading by applying stacked sandbags centrally on the surface. Deflection was recorded using a calibrated measuring scale, both at mid-span and at the supports, to monitor the elastic and plastic deformation response of the prototype slab assembly. Pre-failure conditions exhibited a gradual increase in deflection without visible cracking, indicating satisfactory energy dissipation and flexibility within the safe load-bearing range. However, upon exceeding the material's ultimate strength, the prototype slab exhibited visible failure modes, as captured in Figure 17b. A cracking sound was heard before failure and the failure was not sudden. The failure patterns were predominantly characterized by significant mid-span sagging and the opening of joints, particularly at the interfaces between overlapping panels. These failures point to the necessity for additional reinforcement or improved joint treatment in future designs to enhance structural continuity and overall durability. The observations gathered from this testing provide critical insights into the mechanical behavior, joint reliability, and application feasibility of recycled plastic corrugated panels for structural use in sustainable construction solutions [50,51].

The structural performance of recycled corrugated plastic prototype slabs was quantitatively assessed through a load–deflection test, as illustrated in Figure 18. The graph demonstrates the nonlinear relationship between the applied load and vertical deflection, with the prototype slab exhibiting progressive deformation under incremental loading until failure. The curve shows a gradual increase in deflection corresponding to the applied load, reaching a maximum value near 190 kg (1.86 kN) at approximately 27 mm of deflection, indicating ductile behavior and considerable energy absorption capacity prior to failure. Table 8 presents a summarized evaluation of the panel’s geometric and mechanical performance parameters. The tested prototype slab had a width of 1.6 m, a length of 1.68 m, and a thickness of approximately 12.7 mm. The prototype slab withstood a peak load of 1.86 kN, corresponding to substantial flexural resistance in the context of lightweight roofing applications. The recorded maximum deflection was 27 mm, reflecting its ability to undergo elastic deformation without immediate fracture. Furthermore, the calculated energy absorption was 26.8 N-m, emphasizing its capacity to absorb energy under load without catastrophic failure. These findings affirm the feasibility of using mechanically recycled plastic panels in structural applications where moderate loading and impact resistance are required, such as affordable housing and temporary shelter systems.

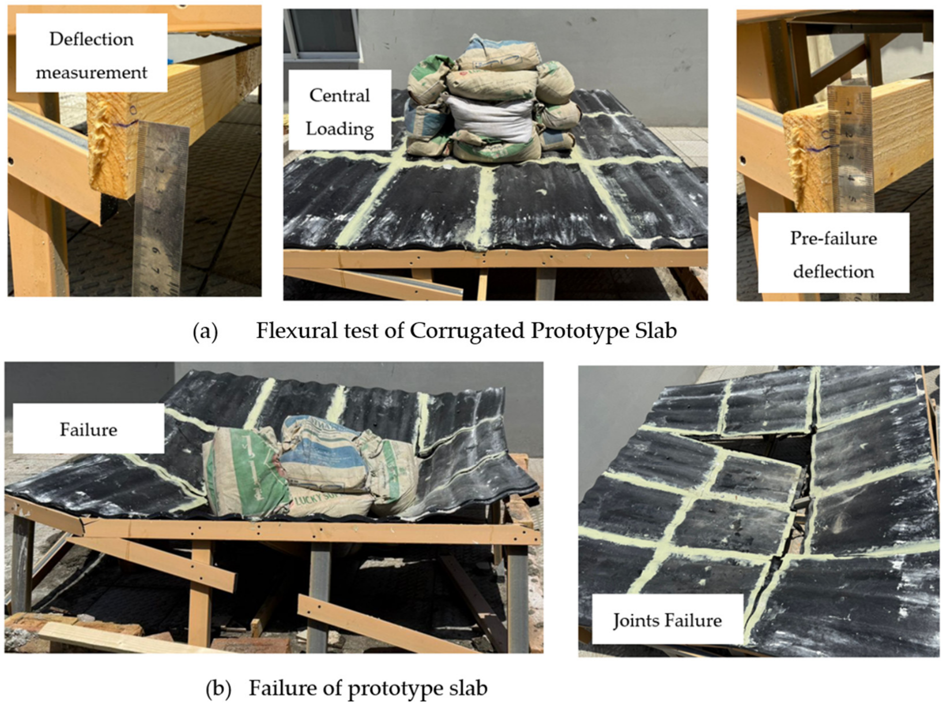


Figure 17. Testing of recycled plastic prototype slabs. (**a**) Test setup and (**b**) failure of prototype slab.

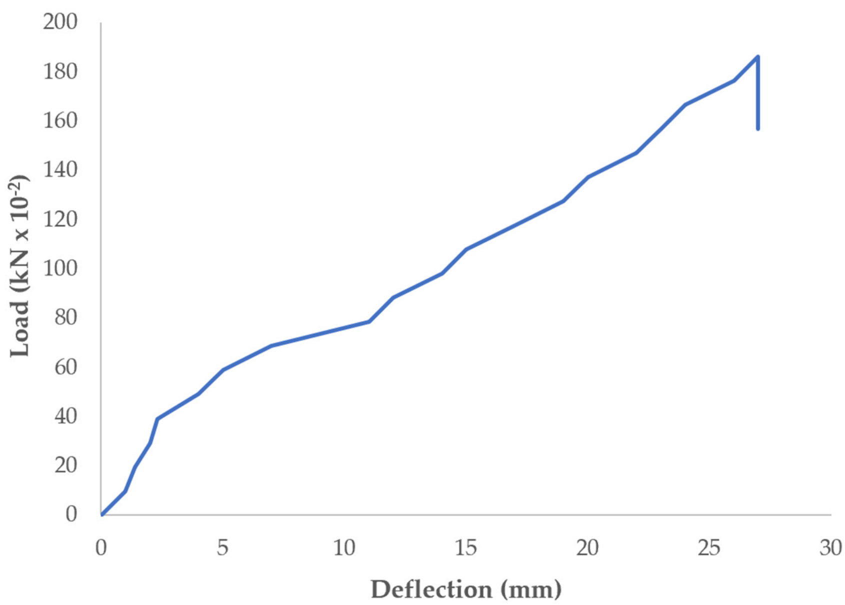


Figure 18. Load–deflection behavior of the recycled rHDPE prototype slab.

Table 8. Summary of Load Deflection Behavior of Prototype Slab Testing.

	Max Load (kN × 10^{-2})	Slab Width (m)	Slab Length (m)	Slab Thickness (mm)	Max Deflection (mm × 10)	Energy Absorption (N-m)
Value	186.33	1.6	1.68	12.7	2.7	26.8

3.3. Empirical Relationship of Flexural Strength to Impact Strength of Recycled Panels

To evaluate the relationship between the flexural and impact performance of recycled polymer panels, a comparative analysis was conducted using normalized ratios. Flexural strength was determined through three-point bending tests, while impact strength was assessed via drop-weight and pendulum impact methods. For each material type—recycled high-density polyethylene (rHDPE) or recycled polypropylene (rPP)—the ratio of impact strength to flexural strength was calculated, offering insight into the material's dynamic response relative to its static bending capacity. The ratios were expressed both in decimal and percentage form, facilitating a clearer interpretation of impact performance as a proportion of flexural capacity. Table 9 provides a summary to establish a quantitative relationship between static and dynamic mechanical performance; the impact strength of the recycled plastic panels was normalized with respect to their flexural strength. This approach enables a direct comparison of the material's ability to resist a sudden impact relative to its bending resistance. The formulation was based on the ratio $R = \sigma_{impact}/\sigma_{flexural}$, where both strengths are expressed in megapascals (MPa). The resulting dimensionless ratios were further converted to percentage form to enhance interpretability. For recycled polypropylene (rPP), the impact-to-flexural strength ratio under drop-weight impact testing was 0.5449 (54.49%), while for pendulum impact testing, it was 0.3632 (36.32%). These values indicate that rPP retains a substantial portion of its flexural strength under dynamic loading, suggesting tough and energy-absorbing behavior. In contrast, recycled high-density polyethylene (rHDPE) exhibited lower ratios of 0.2765 (27.65%) and 0.1549 (15.49%) under drop and pendulum tests, respectively. These results point toward a more brittle or stiff response under impact despite relatively strong flexural resistance. Overall, the significantly higher ratios observed for rPP demonstrate its superior adaptability to impact stresses, making it more suitable for applications requiring combined structural rigidity and impact tolerance. The following empirical equation was developed to understand the correlation between impact and flexural strengths:

$$\sigma_{impact} = 0.155 \times A \times B \times \sigma_{flexural} \quad (1)$$

The differences between drop and pendulum tests further highlight the influence of loading configuration and strain rate on the dynamic response of recycled plastic materials. Where in the above equation σ_{impact} is impact strength, $\sigma_{flexural}$ is flexural strength and A is 1 for HDPE and 2 for rPP, while B is 1 for vertical panel and 2 for horizontal panel; the corresponding values are presented in Table 9. The predictive equation using constant 0.155 was evaluated against experimental data for both recycled HDPE and PP in vertical and horizontal panel configurations. The coefficient value of 0.155 was selected after iterative evaluation to ensure that the percentage error across all test configurations remained within ±15%. This optimized value enhances the reliability and generalizability of the empirical model, shown in Figure 19. The coefficient 0.155 corresponds to a corrugated panel with similar geometric parameters and configuration, including pitch count, crest height, span length, and impact location. The results showed minimal error for the rHDPE vertical panel (+0.08%) and a reasonably good approximation for the rHDPE horizontal panel (+12.09%). For rPP, the horizontal panel condition slightly overpredicted (+13.83%), while the vertical panel configuration showed a larger underprediction (−14.62%). Overall, the formulation offers reliable accuracy, particularly for rHDPE, with potential refinement needed for rPP vertical panel scenarios.

Table 9. Summary of Relationships of Impact Load and Flexural Load.

Material	Panel	Test Type	Impact Strength Original (MPa)	Impact Strength Empirical (MPa)	Percentage Error
rHDPE	Horizontal	Drop test	2.25 ± 0.23	2.52 ± 0.13	+12.09%
	Vertical	Pendulum Test	1.26 ± 0.09	1.26 ± 0.06	+0.08%
rPP	Horizontal	Drop Test	4.11 ± 0.31	4.68 ± 0.23	+13.83%
	Vertical	Pendulum Test	2.74 ± 0.23	2.34 ± 0.12	−14.62%

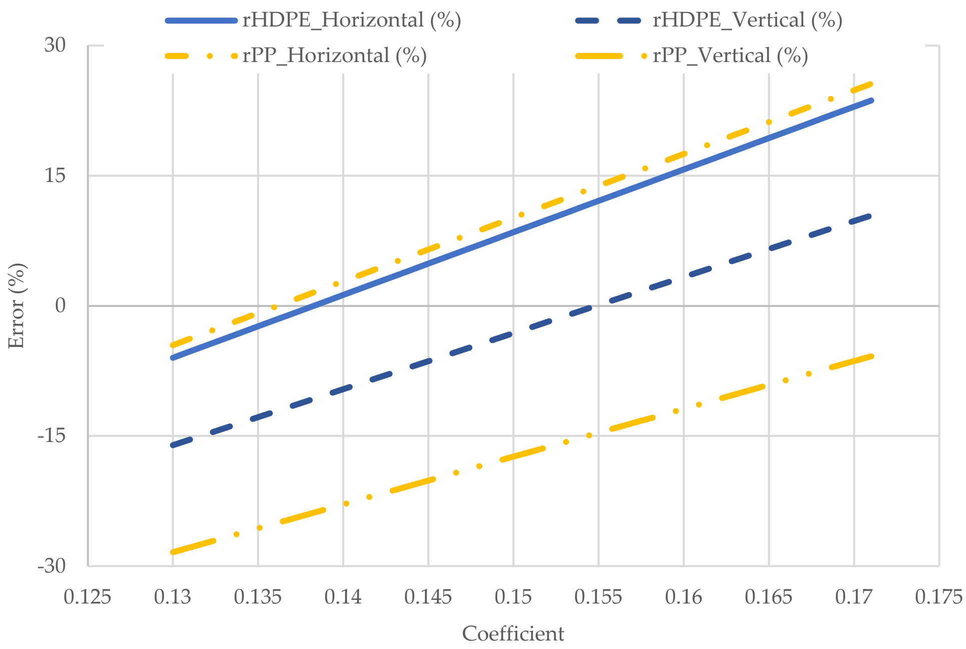


Figure 19. Variation of percentage error in empirical impact strength with respect to coefficient values for rHDPE and rPP corrugated panels under different configurations.

4. Challenges in Practical Applications and Their Solutions

This study demonstrates that recycled high-density polyethylene (rHDPE) and recycled polypropylene (rPP) corrugated panels possess considerable potential as sustainable materials for structural applications, especially in roofing and cladding systems. Through a comprehensive experimental program encompassing flexural, impact, dynamic, microstructural, and prototype slab evaluations, both materials have shown promising mechanical integrity, durability, and performance consistency under various load conditions. Flexural testing revealed that rHDPE offered higher maximum stress (8.136 ± 0.407 MPa) and energy absorption capacity (6.826 ± 0.341 $MJ/m^3 \times 10^{-2}$), underscoring its stiffness and load-bearing capability. In contrast, rPP exhibited enhanced ductility, with greater deflection (3.051 ± 0.153 mm × 10) and strain (1.391 ± 0.070 × 10^{-2}), indicating its suitability for applications where flexibility and post-yield resilience are critical. These material distinctions provide opportunities for designers to tailor solutions based on specific structural performance requirements, be it rigidity for static loading or ductility for dynamic environments. Dynamic mechanical analysis further enriched this perspective. rPP displayed higher longitudinal damping (ξ_L = 8.6 ± 0.7%), suggesting superior energy dissipation during vibrational excitation, while rHDPE performed better in out-of-plane damping ($\xi_{F(OOP)}$ = 8.2 ± 0.1%), which is advantageous in minimizing vertical resonance. These complementary traits underscore the feasibility of using either material in contexts where acoustic insulation, shock absorption, or vibration control is desired. Impact resistance was a defining metric where rPP outperformed rHDPE across both pendulum and drop-weight tests. It exhibited significantly higher blows-to-failure (102 ± 9) and material toughness (750.15 ± 58.84 kJ/m^3), along with ductile fracture patterns characterized by distributed crack formation. Conversely, rHDPE experienced brittle failure with disintegration into fragments, a behavior less ideal for high-strain-rate conditions. These findings reflect rPP's ability to dissipate energy more effectively and maintain structural continuity, key for components subject to repeated or sudden impacts in hailstorms and abnormal weather conditions for use in construction industry. Recycled polypropylene (rPP) showed a greater ability to retain its flexural strength under impact, with ratios of 54.49% in drop tests and 36.32% in pendulum tests. In contrast, recycled HDPE demonstrated lower retention, with corresponding values of 27.65% and 15.49%. These results quantitatively highlight rPP's superior toughness and its potential for use in applications involving dynamic or sudden loading.

Microstructural investigations via SEM and EDS revealed differences in morphological texture and elemental distribution. rPP exhibited a smoother and more homogenous surface with minimal voids, while rHDPE showed roughness and embedded particulate clusters, likely due to incomplete polymer fusion during recycling. Nonetheless, XRD analysis confirmed the retention of crystalline peaks in both polymers post-failure, validating that their semi-crystalline structure was largely preserved despite mechanical deformation. The robust crystallinity underscores the mechanical reliability of the recycled material and suggests long-term dimensional and structural stability under service conditions. The prototype slab fabricated from recycled panels endured peak loads of up to 1.86 kN with a deflection of 27 mm, validating its ability to sustain service loads without abrupt failure. The failure observed near mid-span and joints indicates the importance of improving the inter-panel connections, yet the ductile failure mode observed implies predictable and non-catastrophic performance. The water leakage test further affirmed the practicality of the proposed edge-modified panels, where six-hour submersion of overlapped panels showed no leakage. This indicates that simple, yet precise edge detailing can effectively maintain watertight integrity, mimic traditional roofing practices and enhancing real-world application viability. For structural elements exposed to cyclic loading, a performance-driven selection is recommended: rHDPE offers superior load-bearing capacity, making it suitable for flexural-critical regions, while rPP provides higher ductility, ideal for zones requiring energy dissipation. A hybrid assembly combining both materials can effectively balance strength and deformability in long-term applications.

Despite these promising outcomes, several challenges must be addressed to ensure successful real-world deployment. Variability in feedstock quality, contamination during recycling, inconsistencies in extrusion, and interfacial weaknesses at joints remain notable concerns. Environmental factors, such as prolonged UV exposure, moisture cycling, and temperature fluctuations, could degrade material performance over time. Incorporating UV stabilizers, fiber reinforcement, or advanced compatibilizers may be necessary to overcome these limitations. Nonetheless, the collective findings from this study affirm that recycled polymer corrugated panels are not merely alternatives but serious contenders for sustainable construction materials. Their favorable balance of strength, ductility, energy absorption, and manufacturability, combined with validation and predictive modeling, illustrates their readiness for application in sustainable housing, temporary shelters, and resilient infrastructure. These insights support broader adoption in line with circular economic principles, where waste is valorized into high-performance building components. With continued refinement in processing and joint design, recycled plastics can transition from environmental liabilities into engineered solutions that meet both structural and sustainability goals [31].

5. Conclusions

This study comprehensively assessed the structural, mechanical, and dynamic behavior of recycled high-density polyethylene (rHDPE) and polypropylene (rPP) corrugated panels to determine their suitability for construction applications. The results underscore that both materials retain promising mechanical properties after recycling, though their performance characteristics differ significantly based on loading conditions and failure mechanisms.

- The following conclusions are drawn from the evaluation of the corrugated panels.
    - rPP exhibited higher out-of-plane flexural stiffness (2.17 ± 0.33 GPa) and lower damping ($\xi_{F(OOP)}$ = 4.2 ± 0.2%), suggesting improved rigidity under vibration-sensitive applications. Conversely, rHDPE showed greater damping capacity ($\xi_{F(OOP)}$ = 8.2 ± 0.1%) but lower stiffness (2.04 ± 1.07 GPa), indicating superior vibration attenuation. This divergence supports material-specific usage based on required mechanical responses.
    - rHDPE demonstrated higher flexural strength (8.136 ± 0.407 MPa) and energy absorption (6.826 ± 0.341 MJ/m^3), while rPP showed superior strain capacity ($1.391 \pm 0.070 \times 10^{-2}$), making it more ductile. Thus, rHDPE is preferred for rigid load-bearing applications, whereas rPP is optimal for flexible elements.
    - Impact response analysis revealed rPP's superior ductility, with radial cracks and higher energy absorption, while rHDPE displayed brittle failure with minimal crack propagation. Toughness analysis corroborated rPP's resilience under dynamic loading.
    - Drop-weight and pendulum impact testing confirmed rPP's greater toughness (750.15 ± 58.84 kJ/m^3) and total energy absorption (2.65 ± 0.20 kJ). In contrast, rHDPE showed brittle fragmentation, validating rPP for impact-prone systems.
    - Microstructural analysis via XRD showed retained semi-crystalline structure for both polymers. rPP displayed higher crystallinity than rHDPE. SEM-EDS revealed more homogenous and cleaner morphology for rPP, suggesting superior recycling consistency.
- The following conclusions are drawn from the evaluation of the recycled plastic corrugated prototype slabs.
    - Water leakage testing confirmed the watertight performance of edge-modified slabs with overlapping joints under a continuous 6 h test, validating their roofing application.
    - Flexural slab evaluation showed ductile deformation with a peak load of 1.86 kN and 27 mm maximum deflection. Energy absorption of 26.8 N-m indicates structural adequacy for lightweight structural systems.
- An empirical model relating flexural and impact strengths showed that rPP retained over 50% of its flexural strength post-impact, versus 27.65% for rHDPE. A coefficient of 0.155 provided a consistent predictive value across all datasets.

Overall, rPP emerges as a more flexible and impact-resilient material, ideal for use in structures exposed to dynamic or repetitive loading. rHDPE, with its superior stiffness and damping capacity, is more suitable for static load bearing or vibration-sensitive applications. Both materials, when properly processed and assembled, show strong potential for integration into sustainable construction solutions, especially in sustainable housing, temporary shelters, and cladding systems where mechanical efficiency, durability, and environmental resilience are critical. Future research can explore the modification of rPP with additives to improve its response to dynamic loading. The goal is to enhance impact resistance and deformation capacity, enabling its effective use in applications requiring higher toughness and durability. This will further expand to facilitate the production of sustainable products and full-scale behavior in housing. While the current study demonstrates the potential of rHDPE and rPP panels, future investigations should benchmark these materials against conventional options such as UPVC and galvanized steel to assess trade-offs in cost, strength-to-weight ratio, and durability. The application of Grey Relational Analysis (GRA) [52] is recommended as a robust decision-making tool for evaluating such alternatives under sustainability criteria.

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Abbreviations

The following abbreviations are used in this manuscript:

DEML	Longitudinal Dynamic Elastic Modulus
DEMF(IP)	In-plane Flexural Dynamic Elastic Modulus
DEMF(OOP)	Out-of-plane Flexural Dynamic Elastic Modulus
rHDPE	Recycled High-Density Polyethylene
rPP	Recycled Polypropylene
RFL	Longitudinal Resonance Frequency
RFF(IP)	In-plane Flexural Resonance Frequency
RFF(OOP)	Out-of-plane Flexural Resonance Frequency
ξ_L	Longitudinal Damping
$\xi_{F(IP)}$	In-plane Flexural Damping
$\xi_{F(OOP)}$	Out-of-plane Flexural Damping

References

1. Thomson, N.; Banfill, P. Corrugated-Iron Buildings: An Endangered Resource within the Built Heritage. *J. Archit. Conserv.* **2005**, *11*, 71–87. [CrossRef]
2. Delvasto, S.; Toro, E.F.; Perdomo, F.; De Gutiérrez, R.M. An Appropriate Vacuum Technology for Manufacture of Corrugated Fique Fiber Reinforced Cementitious Sheets. *Constr. Build. Mater.* **2010**, *24*, 187–192. [CrossRef]
3. Haba, B.; Djellali, S.; Abdelouahed, Y.; Boudjelida, S.; Faleschini, F.; Carraro, M. Transforming Plastic Waste into Value: A Review of Management Strategies and Innovative Applications in Sustainable Construction. *Polymers* **2025**, *17*, 881. [CrossRef]
4. Besir, A.B.; Cuce, E. Green Roofs and Facades: A Comprehensive Review. *Renew. Sustain. Energy Rev.* **2018**, *82*, 915–939. [CrossRef]
5. Kumaraswamy, J.; Vijay Praveen, P.M.; Alzahrani, H.A.H.; Sharma, S.; Shetty, V.; Shabari Shedthi, B. Experimental Investigation of Heat Transfer Rate for Building Roof with Corrugated Sheets Using Phase Change Material (PCM). *Case Stud. Therm. Eng.* **2024**, *59*, 104508. [CrossRef]

6. Almodóvar-Melendo, J.-M.; La Roche, P. Thermal Evaluation of a Water-to-Air Heat Exchanger Combined with Different Roof Configurations for Passive Cooling. *Buildings* **2025**, *15*, 1098. [CrossRef]
7. Mohammed, H.; Kennedy, J.B. Fatigue Resistance of Corrugated Steel Sheets Bolted Lap Joints under Flexture. *Pract. Period. Struct. Des. Constr.* **2009**, *14*, 242–245. [CrossRef]
8. Malek, S.; Williams, C. The Equilibrium of Corrugated Plates and Shells. *Nexus Netw. J.* **2017**, *19*, 619–627. [CrossRef]
9. Yang, M.; Gao, C.; Pang, J.; Li, S.; Hu, D.; Li, X.; Zhang, Z. High-Cycle Fatigue Behavior and Fatigue Strength Prediction of Differently Heat-Treated 35CrMo Steels. *Metals* **2022**, *12*, 688. [CrossRef]
10. Henderson, D.J.; Ginger, J.D. Response of Pierced Fixed Corrugated Steel Roofing Systems Subjected to Wind Loads. *Eng. Struct.* **2011**, *33*, 3290–3298. [CrossRef]
11. Brochu, M.; Verreman, Y.; Ajersch, F.; Bouchard, D. High Cycle Fatigue Strength of Permanent Mold and Rheocast Aluminum 357 Alloy. *Int. J. Fatigue* **2010**, *32*, 1233–1242. [CrossRef]
12. Thakre, G.; Kaushal, V.; Najafi, M. A Comparative Impact Assessment of Hail Damage to Tile and Built-Up Roofing Systems: Technical Review and Field Study. *Preprints* **2024**. [CrossRef]
13. Da Silva, T.R.; De Azevedo, A.R.G.; Cecchin, D.; Marvila, M.T.; Amran, M.; Fediuk, R.; Vatin, N.; Karelina, M.; Klyuev, S.; Szelag, M. Application of Plastic Wastes in Construction Materials: A Review Using the Concept of Life-Cycle Assessment in the Context of Recent Research for Future Perspectives. *Materials* **2021**, *14*, 3549. [CrossRef] [PubMed]
14. Setyanto, D. Design and FE Modeling of UPVC Corrugated Hollow Roofing Sheet. *MATEC Web Conf.* **2019**, *258*, 01017. [CrossRef]
15. De Mello Innocentini, M.D.; Vieira De Faria, M.A.; Rosseto Crespi, M.; Batista Andrade, V.H. Air Permeability Assessment of Corrugated Fiber-Cement Roofing Sheets. *Cem. Concr. Compos.* **2019**, *97*, 259–267. [CrossRef]
16. Soto, F.R.C.; Bueno, J.D.J.P.; Mendoza López, M.L.; Chavela, M.H.; Ramos, M.E.P.; Manzano-Ramírez, A. Hydrothermal Evaluation of Vernacular Housing: Comparing Case Studies of Waste PET Bottles, Stone, and Adobe Houses. *Buildings* **2022**, *12*, 1162. [CrossRef]
17. Lin, M.-C.; Lin, J.-H.; Lin, J.-Y.; Lin, T.A.; Lou, C.-W. Fabrication, Properties, and Failure of Composite Sandwiches Made with Sheet Extrusion Method. *J. Sandw. Struct. Mater.* **2020**, *22*, 689–701. [CrossRef]
18. Talib, R.; Boyd, D.; Hayhow, S.; Ahmad, A.G.; Sulieman, M. Investigating Effective Waterproofing Materials in Preventing Roof Leaking; Initial Comparative Study: Malaysia, U.K. *Procedia Manuf.* **2015**, *2*, 419–427. [CrossRef]
19. Okamoto, S. Water Leak Testing of Japanese Tiled Roofs under Vibration and Scattering. *IERI Procedia* **2012**, *1*, 47–52. [CrossRef]
20. Afizah Asman, N.S.; Dullah, S.; Ayog, J.L.; Mirasa, A.K.; Djamila, H. The Hydrological Performance of Lightweight Green Roofs Made From Recycled Waste Materials As the Drainage Layer. *MATEC Web Conf.* **2017**, *103*, 04011. [CrossRef]
21. Cascone, S. Green Roof Design: State of the Art on Technology and Materials. *Sustainability* **2019**, *11*, 3020. [CrossRef]
22. Saba, M.; Coronado-Hernández, O.E.; Gil, L.K.T. Energy Efficiency in Subtropical Homes: Replacing Asbestos–Cement Roofs with Sustainable Alternatives. *Buildings* **2024**, *14*, 4082. [CrossRef]
23. Gaggino, R.; Kreiker, J.; Filippín, C.; Sánchez Amono, M.P.; González Laría, J.; Peisino, L.E. The Comprehensive Comparison of Thermal and Physical-Mechanical Properties of the Recycled Rubber and Plastic Roofing Tiles versus Roofing Tiles Made with Different Traditional Materials. *Adv. Civ. Eng.* **2018**, *2018*, 7361798. [CrossRef]
24. Kittisak, B.; Prayoon, S. Properties of Corrugated Roofing Sheet Material from Sugarcane Bagasse Fibers. *J. Phys. Conf. Ser.* **2021**, *1860*, 012007. [CrossRef]
25. Jara-Vinueza, O.; Pavon, W.; Remache, A.; Arroyo, F.; Gutiérrez, M.; Mora Figueroa, E. Evaluation of Mechanical Behavior and Application Potential of Totora (Schoenoplectus Californicus)-and-Recycled Low-Density Polyethylene–Aluminum (LDPE–Al) Hybrid Panels. *Buildings* **2025**, *15*, 2212. [CrossRef]
26. Yoshino, Y.; Kimura, Y. Strength and Stiffness of Corrugated Plates Subjected to Bending. *Buildings* **2025**, *15*, 469. [CrossRef]
27. Xia, Y.; Friswell, M.I.; Flores, E.I.S. Equivalent Models of Corrugated Panels. *Int. J. Solids Struct.* **2012**, *49*, 1453–1462. [CrossRef]
28. Abd El-Latif, M.Y.; Yossef, M.; Chen, A.; Elsayad, M. Behavior of Stressed Skin Corrugated Sheet under Hydrostatic Loads. *Case Stud. Constr. Mater.* **2024**, *20*, e03343. [CrossRef]
29. Das, A.J.; Ali, M. Sustainable Development and Assessment of Low-Strength/High-Toughness Recycled Plastic Rebars for Structural Elements Under Light Loads. *Sustainability* **2025**, *17*, 4997. [CrossRef]
30. Karedla, A.B.; Schuster, J.; Shaik, Y.P. Possibility of Making Plastic Roof Tiles from Waste Plastic, Sand, and Fly Ash. *Constr. Mater.* **2024**, *4*, 597–610. [CrossRef]
31. Das, A.J.; Ali, M. Prospective Use and Assessment of Recycled Plastic in Construction Industry. *Recycling* **2025**, *10*, 41. [CrossRef]
32. *ASTM D790-17*; Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials. ASTM International: West Conshohocken, PA, USA, 2017.
33. Fitas, R.; Schaffrath, H.J.; Schabel, S. A Review of Optimization for Corrugated Boards. *Sustainability* **2023**, *15*, 15588. [CrossRef]
34. *ASTM E1876-15*; Standard Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio by Impulse Excitation of Vibration. ASTM International: West Conshohocken, PA, USA, 2015.

35. Ahmed, S.; Ali, M. Use of Agriculture Waste as Short Discrete Fibers and Glass-Fiber-Reinforced-Polymer Rebars in Concrete Walls for Enhancing Impact Resistance. *J. Clean. Prod.* **2020**, *268*, 122211. [CrossRef]
36. Hussain, T.; Ali, M. Improving the Impact Resistance and Dynamic Properties of Jute Fiber Reinforced Concrete for Rebars Design by Considering Tension Zone of FRC. *Constr. Build. Mater.* **2019**, *213*, 592–607. [CrossRef]
37. Li, D.; Zhou, L.; Wang, X.; He, L.; Yang, X. Effect of Crystallinity of Polyethylene with Different Densities on Breakdown Strength and Conductance Property. *Materials* **2019**, *12*, 1746. [CrossRef]
38. Sutar, H.; Sahoo, P.C.; Sahu, P.S.; Sahoo, S.; Murmu, R.; Swain, S.; Mishra, S.C. Mechanical, Thermal and Crystallization Properties of Polypropylene (PP) Reinforced Composites with High Density Polyethylene (HDPE) as Matrix. *Mater. Sci. Appl.* **2018**, *09*, 502–515. [CrossRef]
39. *ASTM E661-15*; Standard Test Method for Performance of Panel-Type Wall Constructions. ASTM International: West Conshohocken, PA, USA, 2023.
40. *ASTM E2140-22*; Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors and Curtain Walls by Uniform Static Air Pressure Difference. ASTM International: West Conshohocken, PA, USA, 2022.
41. Abubaker, S.A.; Chaqmaqchee, F.A.; Taha, A.H. X-Ray Fluorescence Techniques. *ARO* **2021**, *9*, 22–25. [CrossRef]
42. Pang, A.L.; Husin, M.R.; Arsad, A.; Ahmadipour, M. Effect of Graphene Nanoplatelets on Structural, Morphological, Thermal, and Electrical Properties of Recycled Polypropylene/Polyaniline Nanocomposites. *J. Mater. Sci. Mater. Electron.* **2021**, *32*, 9574–9583. [CrossRef]
43. Liço, E.; Rapa, V.; Drushku, S.; Chatzitheodoridis, E. Morphological and Chemical Study of Recycled Plastic Materials by Using Scanning Electron Microscopy and Energy Dispersive Analysis. *Zašt. Mater.* **2011**, *52*, 231–236.
44. Hu, B.; Guo, P.; Han, S.; Chen, S. Distribution Characteristics of Microplastics in the Soil of Mangrove Restoration Wetland and the Effects of Microplastics on Soil Characteristics. *Ecotoxicology* **2022**, *31*, 1120–1136. [CrossRef]
45. Jones, H.; McClements, J.; Ray, D.; Kalloudis, M.; Koutsos, V. High-Density Polyethylene–Polypropylene Blends: Examining the Relationship Between Nano/Microscale Phase Separation and Thermomechanical Properties. *Polymers* **2025**, *17*, 166. [CrossRef] [PubMed]
46. Kassab, R.A.; Sadeghian, P. Effects of Material Non-Linearity on the Structural Performance of Sandwich Beams Made of Recycled PET Foam Core and PET Fiber Composite Facings: Experimental and Analytical Studies. *Structures* **2023**, *54*, 1259–1277. [CrossRef]
47. Wang, M.; Zhang, J.; Yuan, H.; Guo, H.; Zhuang, W. The Plastic Behavior in the Large Deflection Response of Fiber Metal Laminate Sandwich Beams under Transverse Loading. *Materials* **2022**, *15*, 439. [CrossRef] [PubMed]
48. Talukder, M.K.; Haque, M.N. Experimental investigation of flexural capacity and deflection of low strength RCC beam strengthened with flexural steels and steel shear key. *Asian J. Civ. Eng.* **2023**, *24*, 29–56. [CrossRef]
49. Tesfaw, S.; Bogale, T.M.; Fatoba, O. Evaluation of Tensile and Flexural Strength Properties of Virgin and Recycled High-Density Polyethylene (HDPE) for Pipe Fitting Application. *Mater. Today Proc.* **2022**, *62*, 3103–3113. [CrossRef]
50. Cheng, Q.; Li, Z.; Deng, S.; Jiang, H.; Tian, Y.; Geng, J. Full-Scale Experimental Study on Flexural Performance of the New Precast UHPC Diaphragm Slab in Utility Tunnels. *Buildings* **2023**, *13*, 1349. [CrossRef]
51. Acharya, M.; Gurung, K.; Mashal, M. Full-Scale Flexural Testing of Slabs Made of Modular Structural Concrete Insulated Panels. *PCI J.* **2022**, *67*, 55–76. [CrossRef]
52. Asadoullahtabar, S.R.; Asgari, A.; Tabari, M.M.R. Assessment, Identifying, and Presenting a Plan for the Stabilization of Loessic Soils Exposed to Scouring in the Path of Gas Pipelines, Case Study: Maraveh-Tappeh City. *Eng. Geol.* **2024**, *342*, 107747. [CrossRef]