IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Revue des Composites et des Matériaux Avancés-Journal of Composite and Advanced Materials
Vol. 35, No. 4, August, 2025, pp. 733-745
Journal homepage: http://iieta.org/journals/rcma

Multifunctional UPE Composites Reinforced with Recycled PET/HDPE Hybrids

Saad Mushtaq Hashim*, Waleed Bdaiwi

Department of Physics, College of Education for Pure Science, University of Anbar, Ramadi 31001, Iraq

Corresponding Author Email: saa23u3001@uoanbar.edu.iq

https://doi.org/10.18280/rcma.350415

Received: 15 July 2025
Revised: 15 August 2025
Accepted: 23 August 2025
Available online: 31 August 2025

Keywords:
unsaturated polyester resin (UPE), recycled PET/HDPE composites, mechanical and thermal properties, sound insulation, hybrid polymer reinforcement

ABSTRACT

This study presents the fabrication and comprehensive evaluation of hybrid polymer composites based on unsaturated polyester resin (UPE) reinforced with recycled polyethylene terephthalate (PET) and high-density polyethylene (HDPE) in a fixed weight ratio of 80:20. Varying filler contents (2.5, 5, 7.5, and 10 wt.%) were incorporated into the UPE matrix using a hand lay-up method to investigate the influence of reinforcement loading on mechanical, thermal, and acoustic properties. Results revealed that compressive strength peaked at 2.5 wt.%, while impact strength and hardness reached their highest values at 7.5 wt.%. Flexural strength declined with increasing filler content due to matrix discontinuities and interfacial stress. Notably, thermal conductivity and acoustic insulation improved progressively with filler loading, attaining maximum values at 10 wt.%, attributed to enhanced phonon transport and internal wave scattering. FTIR analysis confirmed a physically blended system without significant chemical bonding, indicating that performance enhancement was driven by dispersion quality, interfacial compatibility, and hybrid filler morphology. These findings demonstrate the feasibility of tailoring composite behavior through controlled loading of recycled hybrid fillers, offering an eco-friendly solution for multi-functional polymer materials in structural and acoustic applications.

1. INTRODUCTION

The accumulation of plastic waste, particularly polyethylene terephthalate (PET) and high-density polyethylene (HDPE), has emerged as a critical environmental issue due to their durability and resistance to degradation [1, 2]. These two polymers constitute a significant proportion of post-consumer packaging materials, and their improper disposal contributes to long-term ecological harm [3]. As global sustainability efforts intensify, recycling and reusing such plastic waste for value-added applications has become a central focus in materials engineering [4, 5].

One promising approach involves reinforcing polymer matrices with waste-derived fillers to develop eco-friendly composite materials. Unsaturated polyester resin (UPE) is a widely used thermosetting polymer valued for its processability, affordability, and mechanical rigidity [6]. However, its inherent brittleness, limited impact strength, and suboptimal thermal and acoustic insulation restrict its use in multifunctional applications [7, 8]. Integrating plastic waste fillers such as PET and HDPE into UPE systems offers a potential route to enhance its structural and functional properties while contributing to waste reduction [9].

Several recent studies have investigated PET/HDPE waste in composite systems. For example, Teixeira and De Moraes [10] reported that post-consumer PET/HDPE blends demonstrated favorable mechanical properties and thermal resistance, although their focus was on thermoplastic matrices, not thermosets like UPE. Similarly, Nursyamsi and Adil [11] showed that shredded PET and HDPE improved mechanical and acoustic performance in asphalt mixtures, but their findings were limited to infrastructure materials. While these studies highlight the potential of PET and HDPE in waste valorization, there is a noticeable lack of research examining hybrid PET/HDPE fillers in unsaturated polyester matrices, especially regarding how different filler loadings influence multiple performance attributes such as mechanical strength, thermal conductivity, acoustic damping, and molecular interactions. Furthermore, the mechanisms of interaction between UPE and plastic waste fillers remain poorly understood, particularly in systems lacking compatibilizers.

Recently, there has been a focus on improving the interfacial adhesion of recycled PET/HDPE blends with compatibilizers and surface treatment. According to Feregrino et al. [12], the flexural and impact strength of HDPE/PET composites was enhanced by the addition of ethylene-glycidyl methacrylate (E-GMA) as a compatibilizer without compromising its rigidity, thus allowing the composites to perform better in structural composites like plastic crates. Lima et al. [13] also confirmed that the bentonite clay usage may serve as the interfacial agent in the recycled blends of HDPE and PET, providing some level of compatibilization and enhancing the thermal and mechanical properties of the recycled composite materials. These recent developments highlight the increasing focus on functional additives and treatments in addressing the usefulness of recycled plastic fillers.

Spectroscopic tools such as Fourier transform infrared (FTIR) spectroscopy offer valuable insight into these interfacial interactions. Prior research by Cazan et al. [14] demonstrated that functionalization of PET can induce chemical bonding in plastic composites, while untreated PET/HDPE systems typically exhibit only physical blending. This distinction is crucial in interpreting how property enhancements are achieved in hybrid composites. Contrarily, the current study demonstrates its novelty by the systematic use of a PET:HDPE ratio of 80:20 chosen with a clear objective of reflecting the actual ratio of bottle bodies to caps found in the waste streams generated after consumers of the products (post-consumer waste streams).

Moreover, although acoustic insulation is increasingly relevant in building and automotive industries, sound attenuation performance remains underexplored in UPE-based systems with plastic fillers. Previous studies demonstrated that PET-based composites can perform well in high-frequency acoustic applications, as reported by Colorado et al. [15] and Caniato et al. [16]. However, similar studies involving PET/HDPE-filled UPE are rare.

This study addresses these gaps by developing and characterizing UPE-based composites reinforced with hybrid PET/HDPE waste fillers at varying concentrations. A fixed PET:HDPE ratio of 80:20 was deliberately selected to reflect the typical mass distribution of bottle bodies to caps in post-consumer waste streams, ensuring practical recycling relevance. The research investigates the effect of filler content on compressive, flexural, impact, and hardness properties, as well as thermal conductivity, sound insulation, and FTIR-derived structural characteristics. The goal is to determine whether property enhancements arise from chemical interactions or physical morphology, and to establish the suitability of PET/HDPE–UPE composites for functional, sustainable applications.

2. MATERIALS AND METHODS

2.1 Matrix material: Unsaturated polyester resin (UPE)

Figure 1. Unsaturated polyester resin (UPE) in liquid form prior to mixing

Unsaturated polyester resin (UPE) was employed as the base matrix for the preparation of the polymeric and composite samples. The resin was sourced from SIR Company (Saudi Arabia) and was supplied as a viscous, transparent pink liquid at room temperature, as shown in Figure 1. UPE is a thermosetting polymer that undergoes irreversible curing via crosslinking when mixed with a suitable hardener. In this study, methyl ethyl ketone peroxide (MEKP), also produced by the same manufacturer, was used as the curing agent. It was added at a fixed ratio of 2 g MEKP per 100 g of UPE, with curing reactions occurring under ambient laboratory conditions.

The key physical properties of the UPE, as provided by the supplier, are summarized in Table 1. These include moderate elastic modulus and low thermal conductivity, which make UPE suitable for structural and insulating applications.

Table 1. Key properties of the UPE matrix applied in this study

Property	Value
Modulus of Elasticity (GPa)	2.06 – 4.41
Specific Heat (J/kg·K)	710 – 920
Thermal Conductivity (W/m·°C)	0.17
Density (g/cm³)	1.20

2.2 Reinforcement materials

2.2.1 Polyethylene terephthalate (PET)

The PET used in this study was derived from post-consumer plastic waste, specifically discarded bottles from water and soft drinks, as shown in Figure 2. The bottles were cleaned, manually cut into small fragments, then melted, cooled, and ground to obtain granules with an average particle size of approximately 53 μm. PET was selected due to its high rigidity, chemical stability, and crystalline aromatic structure, which contribute to stiffness and thermal properties in the composite system.

The principal physical characteristics of PET, as reported by the supplier, are outlined in Table 2.

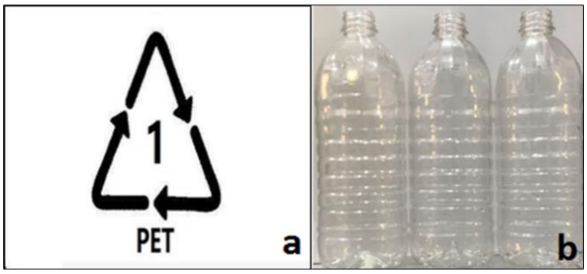

Figure 2. (a) Recycling symbol indicating polyethylene terephthalate (PET) plastic; (b) Representative PET plastic bottles collected as raw material for reinforcement preparation

Table 2. Selected physical and chemical data of PET

Property	Value
State	Solid
Density (g/cm³)	1.38
Water Absorption	0
Color	Crystalline, colorless transparent
Chemical Formula	$C_{10}H_8O_4$

2.2.2 High-density polyethylene (HDPE)

The HDPE reinforcement was also obtained from post-consumer plastic waste, specifically from the colored caps of the same PET bottles, as shown in Figure 3(a) and Figure 3(b). The caps were cleaned, cut, melted, cooled, and ground similarly to PET, to produce HDPE particles with an average size of 53 μm. HDPE was selected due to its ductility and energy absorption characteristics, which are beneficial for impact resistance and toughness enhancement in hybrid composites.

Table 3 presents the main physical properties of HDPE as specified by the manufacturer.

Figure 3. (a) Recycling symbol indicating high-density polyethylene (HDPE); (b) HDPE bottle caps collected from discarded PET bottles, utilized as a secondary reinforcement component

Table 3. Physicochemical characteristics of high-density polyethylene (HDPE)

Property	Value
State	Solid
Density (g/cm³)	0.95 – 0.98
Water Absorption	0
Color	Multi-color (varied)
Chemical Formula	$(C_2H_4)_n$

2.3 Preparation procedures

2.3.1 Preparation of reinforcement particles

The PET and HDPE reinforcement materials were prepared from post-consumer plastic waste through a multi-stage process involving cutting, melting, and grinding. Initially, the plastic waste (PET bottles and HDPE caps) was manually segmented using a locally fabricated cutting machine, as illustrated in Figure 4(a). The resulting small fragments of PET and HDPE are shown in Figure 4(b) and Figure 4(c), respectively.

Each type of reinforcement was then processed separately. PET fragments were thermally melted at 250°C, while HDPE fragments were melted at 135°C, both using the laboratory electric furnace shown in Figure 4(c). These temperatures were selected based on the respective melting points of each polymer. All melting operations were conducted under ambient laboratory conditions (25°C).

After cooling, the solidified PET and HDPE masses were crushed using a mechanical grinding machine (Figure 4(e)) to produce particulate powders. The resulting reinforcement powders for PET and HDPE had an average particle size of approximately 53 µm, as shown in Figure 4(f) and Figure 4(g), respectively. These powders were used in fixed mass ratios of 80% PET and 20% HDPE in all hybrid formulations.

2.3.2 Preparation of hybrid composite samples

The hybrid polymer composite samples were fabricated using the hand lay-up molding technique. Although vacuum-assisted molding can reduce voids, the hand lay-up method was deliberately employed to reflect low-cost, scalable recycling practices and to maintain comparability with prior PET/HDPE-UPE studies [17, 18]. A fixed PET/HDPE hybrid reinforcement ratio of 80:20 by weight was selected to reflect the typical mass distribution of bottle bodies to caps in common plastic waste streams, thereby aligning with sustainable recycling practices.

Five composite formulations were prepared with different total filler weight fractions: 0%, 2.5%, 5%, 7.5%, and 10%, while maintaining a constant total sample mass of 600 g. The hybrid filler powders were gradually added to the unsaturated polyester resin (UPE) and mixed manually using a glass rod until a uniform mixture was achieved. A methyl ethyl ketone peroxide (MEKP) hardener was then added at a ratio of 2 g per 100 g of UPE, initiating the crosslinking reaction under room temperature conditions.

Figure 4. Stages of preparation of PET and HDPE reinforcing materials: (a) Locally fabricated cutting machine used for initial shredding of plastic bottles PET; (b) PET fragments after cutting; (c) HDPE fragments after cutting; (d) Electric furnace used for melting PET (at 250°C) and HDPE (at 135°C); (e) Grinding machine used to pulverize the cooled melted materials; (f) PET granules after grinding (particle size≈53 µm); and (g) HDPE granules after grinding (particle size≈53 µm); (h) Locally fabricated cutting machine used for initial shredding of plastic bottles caps HDPE or another HDPE

The composite paste was poured into aluminum and glass molds with predefined dimensions based on the testing requirements. The molds were left undisturbed to cure at ambient temperature until full solidification.

The reinforcement weight fraction (Ψ) quantifies the proportion of reinforcement within a composite relative to its total mass. It is expressed as a percentage and provides a direct measure of how much of the composite is occupied by the reinforcing phase compared to the matrix.

It is mathematically defined as:

$$\Psi = \left(\frac{w_p}{w_c}\right) \times 100 \tag{1}$$

with

$$w_c = w_p + w_m \tag{2}$$

where,

- w_p=mass of the hybrid reinforcement (PET + HDPE) [g],
- w_m=mass of the UPE matrix [g],
- w_c=total mass of the composite [g].

The detailed formulation of all samples is summarized in Table 4.

Table 4. Composition of hybrid UPE composites reinforced with 80% PET and 20% HDPE

Sample No.	Total Mass (g)	Filler Content (wt.%)	UPE Mass (g)	PET (80%) (g)	HDPE (20%) (g)
1	600	0	600	0	0
2	600	2.5	585	12	3
3	600	5	570	24	6
4	600	7.5	555	36	9
5	600	10	540	48	12

2.4 Mechanical and physical testing procedures

All tests were conducted on five specimens per group, as required by the minimum levels of the applicable ASTM standards. The sample size chosen (n = 5) might be deemed small. However, it is standard in the characterization of composites and was chosen to maximize reproducibility within the limitations of material availability. Duplication assured consistent findings and mean values were given along with standard deviations to establish reliability.

2.4.1 Compressive strength test

The compressive strength test was conducted to evaluate the material's ability to withstand axial compressive loads. This test was performed using a LARYEE Universal Testing Machine, capable of performing compression, bending, and tensile tests. In this test, each sample was subjected to a gradually increasing axial compressive load until failure occurred. The loading rate was maintained at 5 mm/min, and the compressive strength was recorded directly from the machine's data acquisition system. All tests were conducted according to the ASTM D695 standard [19].

2.4.2 Flexural strength test

The flexural test was conducted to assess the material's resistance to combined compressive and tensile stresses under bending. A three-point bending method was employed using the same LARYEE testing machine described above. All samples were tested at the same strain rate until failure, and flexural strength was measured directly from the machine's output. Testing procedures were carried out in accordance with the ASTM D790 standard [20].

2.4.3 Impact strength test

Impact resistance was evaluated to determine the material's ability to absorb energy during sudden loading or shock without fracturing. An Izod impact tester was used for this purpose, in which a pendulum strikes a vertically mounted specimen from one side. The energy absorbed during fracture is indicated by the machine's dial. Samples were prepared and tested in accordance with the ISO 180 [21] standard. This test provides insight into the toughness and dynamic durability of the composite material.

2.4.4 Surface hardness test

Surface hardness was assessed to determine the material's resistance to localized surface deformation, such as scratching or indentation. The test was performed using a Shore D durometer. For each sample, five readings were taken at different points, and the average value was calculated. The test followed the ASTM D2240 standard [22], which is widely used for polymers and composites to quantify surface resilience.

2.4.5 Thermal conductivity test

The purpose of this test was to determine the material's ability to conduct heat. A Lee's Disk Apparatus, manufactured by Griffin & George, was used to measure thermal conductivity. In this setup, heat flows from the heating element through a stack of metal disks, with the composite sample placed between them. The temperatures of the three disks (T_A, T_B, T_C) were measured using inserted thermocouples.

Thermal conductivity was calculated using the following equations [23]:

$$K\left(\frac{T_{B-}T_A}{T_S}\right) = e\left[T_A + \frac{2}{r}\left(d_A + \frac{1}{4}d_s\right)T_A + \frac{1}{2r}d_S d_B\right] \tag{3}$$

$$\begin{aligned} H = IV = \pi r^2 e(T_A + T_B) \\ + 2\pi re\Big[d_A T_A + d_s \cdot \frac{1}{2}(T_A + T_B) \\ + d_B T_B \quad + d_C T_C\Big] \end{aligned} \tag{4}$$

where,

K: Thermal conductivity (W/m·°C)
e: Heat energy per unit area per unit time (W/m²·°C)
T_A, T_B, T_C: Disk temperatures (°C)
d_A, d_B, d_C: Thicknesses of disks A, B, and C (mm)
d_s: Thickness of the composite sample (mm)
r: Radius of disks (mm)
H: Power input, calculated by H = IV
I: Current (0.25 A)
V: Voltage (6 V)

2.5 Sound insulation test

Sound insulation testing was conducted to assess the composite's ability to attenuate acoustic wave transmission. A locally fabricated sound insulation test system was used in accordance with the ASTM E336 standard. The apparatus consisted of four main units: a wave generator (Unit 092812), an amplifier (Model AV298), a loudspeaker, and a wave receiver (measuring range: 30–130 dB). Figure 5 shows the sound insulation setup and the tested samples.

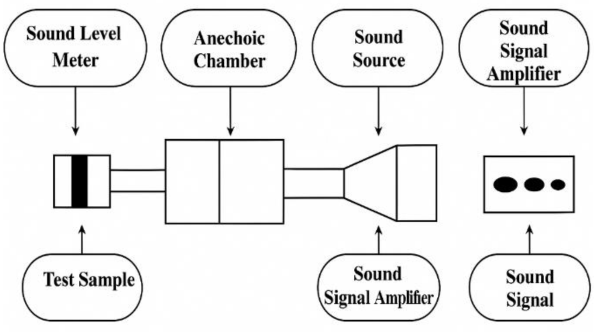

Figure 5. Schematic representation of the acoustic insulation testing setup used to evaluate sound transmission

The test procedure involved generating sound waves at defined frequency bands and transmitting them through a closed wooden box in which the sample was mounted at the center. The sound intensity was measured before and after wave transmission using the receiver. Measurements were taken at three characteristic frequencies (e.g., 100 Hz, 1000 Hz, 10,000 Hz). The test environment was maintained as static and quiet as possible to ensure accuracy and reproducibility.

2.6 Fourier transform infrared (FTIR) spectroscopy

FTIR spectroscopy was employed to identify the functional groups present in the neat UPE matrix and in the PET/HDPE-reinforced composites. This analytical technique enables qualitative identification of chemical bonds, assessment of structural changes, and detection of impurities or additives. Spectra were collected in the range of 4000–400 cm^{-1} using an FTIR spectrometer. The resulting spectra were analyzed to compare the molecular fingerprint of the pure UPE with that of the composites, allowing evaluation of matrix–filler interactions and confirmation of physical blending behavior.

3. RESULTS AND DISCUSSION

3.1 Compressive strength

The compressive strength of UPE-based hybrid composites reinforced with PET/HDPE waste particles was measured to evaluate their resistance to static loading and dimensional deformation. As shown in Figure 6, the compressive strength varied significantly with filler content, reflecting a non-linear relationship between reinforcement level and mechanical performance.

The unfilled UPE matrix exhibited a baseline compressive strength of approximately 70 MPa. Remarkably, the addition of 2.5 wt.% PET/HDPE resulted in a substantial improvement in compressive strength, reaching approximately 115 MPa, indicating a ~64% enhancement. This peak performance is attributed to the optimal dispersion of rigid PET particles and the energy-dissipating contribution of HDPE at low filler loading. A similar enhancement was observed by Xu et al. [24], who reported compressive strengths up to 107 MPa in PET-derived UPE composites used for wood reinforcement. However, at 5 wt.%, compressive strength dropped sharply to approximately 68 MPa, nearly matching that of the neat resin. This reduction may be attributed to filler agglomeration or inadequate wetting at higher particle concentrations, which can introduce interfacial defects and act as stress concentrators under compressive loads. Comparable behavior was reported in cementitious composites where compressive strength declined beyond 7.5% HDPE replacement due to particle clustering [25]. Upon increasing the filler content further to 7.5 wt.%, the compressive strength recovered to about 80 MPa, indicating partial restoration of structural reinforcement. The improvement suggests better filler–matrix interaction or redistribution of agglomerates due to increased polymer chain entanglement and plastic phase buffering from HDPE. This is consistent with the findings of Kambai et al. [26], who observed recovery and reinforcement in PET/HDPE blends through hybrid filler systems. At the highest tested concentration (10 wt.%), the compressive strength rose further to ~95 MPa, reflecting an overall enhancement of ~36% compared to the neat matrix. This behavior implies that beyond a critical threshold (~5–7.5%), the PET/HDPE hybrid system regains efficiency in load-bearing, likely due to improved percolation of the rigid phase and favorable stress distribution. Comparable hybrid UPE systems with optimized filler content showed sustained or recovered compressive performance through improved interface quality and dispersion [27].

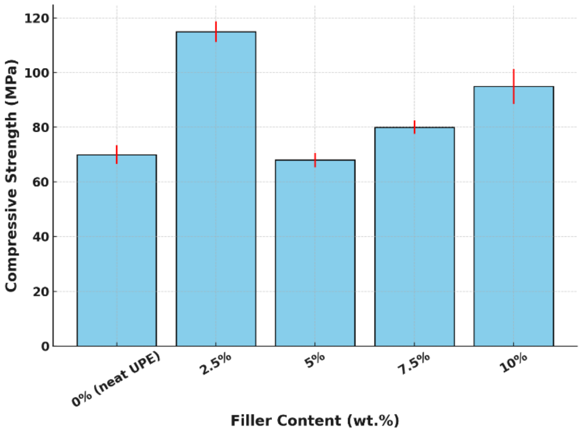

Figure 6. Variation of compressive strength (MPa) of UPE-based composites with different filler contents (0–10 wt.%) of hybrid PET/HDPE reinforcements

The observed non-monotonic trend underscores the importance of controlling filler dispersion and interfacial adhesion in multi-phase polymer systems. Percolation theory can be used to justify this behavior because it is predicted that at low filler contents (<5 wt.%), well-dispersed PET/HDPE particles create isolated reinforcement sites in the stress field, resulting in a maximum compressive strength. But beyond the percolation threshold, clustering of the particles and poor wetting indicate discontinuities, which decrease strength until increased loading resumes partial connectivity once again [28].

3.2 Flexural strength

Flexural strength testing provides insight into the bending resistance of the hybrid composites, which is critical for load-bearing applications involving paneling, casing, or structural frames. The results are presented in Figure 7, showing a significant decrease in flexural strength with increasing filler content.

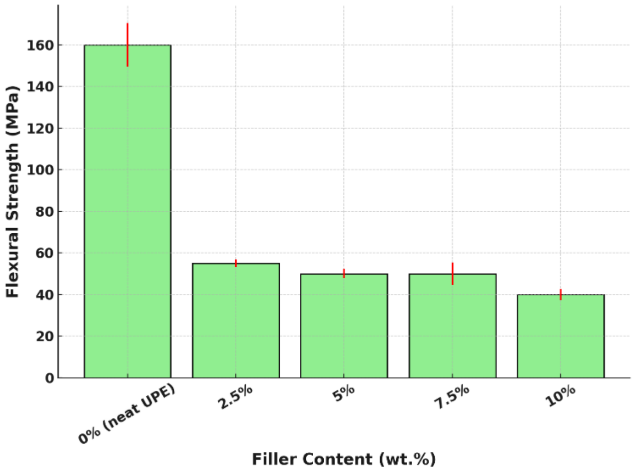

Figure 7. Variation of flexural strength (MPa) of UPE-based composites with different filler contents (0–10 wt.%) of hybrid PET/HDPE reinforcements

The neat UPE matrix exhibited the highest flexural strength, approximately 160 MPa, reflecting the inherent rigidity and crosslinked nature of cured polyester resin. Upon incorporation of 2.5 wt.% PET/HDPE hybrid filler, flexural strength dropped sharply to about 55 MPa, a reduction of more than 65% compared to the unreinforced resin. This significant decline contrasts with the trends seen in other composite systems where proper surface treatment or fiber reinforcement mitigated strength loss. For instance, Ahmad et al. (2008) found that while sawdust-reinforced PET-UPE composites showed reduced flexural strength, the decline was less severe when alkali treatment improved filler–matrix adhesion [29].

Further increases in filler content to 5 wt.% and 7.5 wt.% did not result in substantial improvements, with flexural strength remaining around 50 MPa in both cases. At 10 wt.%, a further decline to approximately 40 MPa was observed. This consistent reduction across the composition range suggests that PET/HDPE particles, in their untreated or irregular morphology, do not effectively reinforce UPE under flexural loading. The phenomenon is similarly reported in polymer mortar systems, where PET-based UPE composites exhibited reduced flexural strength unless enhanced with additional fillers or compatibilizers [27].

Several contributing factors may explain the performance drop:

Poor filler–matrix interfacial adhesion, especially with HDPE, likely causes stress discontinuities during bending. Comparable studies highlight this issue, where flexural strength improved significantly only after compatibilization of PET or HDPE waste with maleic anhydride or surfactants [14].

Particle agglomeration, especially at higher loadings, creates localized stress concentration zones that act as crack initiators. This was also observed in short PET fiber–HDPE composites, where flexural strength improved only with fiber dispersion and compatibilization techniques [30].

Disruption of matrix continuity due to the rigid, non-fibrous nature of the fillers reduces the efficiency of load transfer along the polymer chains.

Lack of mechanical anchoring, as PET and HDPE particulates do not behave like traditional fiber reinforcements, such as glass or carbon fibers.

Interestingly, although increasing filler content beyond 2.5 wt.% did not severely worsen flexural properties, the values remained significantly below the performance of neat UPE. This plateauing effect suggests a stabilized internal structure, but one that fails to replicate the network needed for strong flexural resistance.

This pattern aligns with prior findings that suggest untreated PET or HDPE fillers can weaken composite bending resistance unless reinforced with proper surface treatment or used in fiber form the study [31]. Similarly, the monotonic reduction of flexural strength follows the Halpin Tsai model of short rigid particles with weak interfacial bonding where the theoretical modulus is predicted to decrease with increased filler concentration. The model points out that in contrast with fiber reinforcements, particulate fillers with poor adhesion have little effect on bending strength, which may explain the difference between compressive reinforcement and flexural degradation seen in this study [32, 33].

3.3 Impact strength

The impact strength test evaluates a composite's ability to absorb and dissipate energy under sudden or dynamic loading conditions, a property especially important in protective and structural applications. As shown in Figure 8, the addition of PET/HDPE hybrid fillers led to a clear improvement in impact resistance at low to moderate filler content, followed by degradation at higher levels.

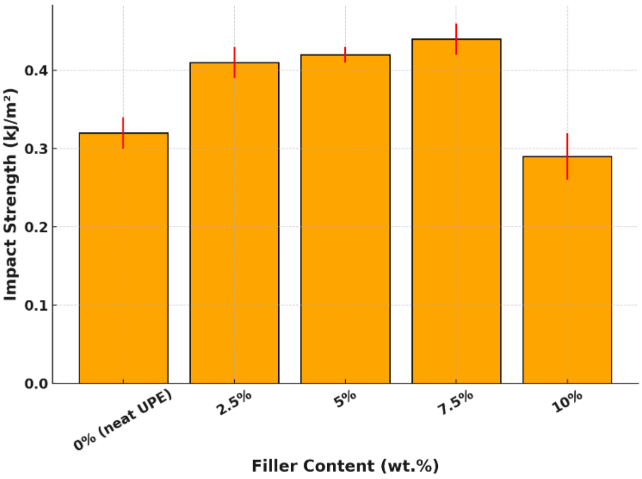

Figure 8. Variation of impact strength (kJ/m²) of UPE-based composites with different filler contents (0–10 wt.%) of hybrid PET/HDPE reinforcements

The neat UPE matrix exhibited a baseline impact strength of approximately 0.32 kJ/m², which is typical for brittle thermosets. Incorporation of 2.5 wt.% PET/HDPE increased the impact strength to ~0.41 kJ/m² (a 28% improvement), attributed to the synergistic toughening mechanisms of the fillers—rigid PET particles inhibit crack propagation, while ductile HDPE particles absorb energy through plastic deformation. Further increases in filler content to 5% and 7.5% yielded slightly higher values, with a maximum of ~0.44 kJ/m² at 7.5 wt.%, suggesting a continued benefit from enhanced microstructural energy dissipation.

This improvement aligns with literature reports showing that PET and HDPE additives can increase impact resistance when adequately dispersed and bonded. For example, Cazan et al. [14] demonstrated that surface-functionalized PET and

HDPE fillers significantly enhanced impact resistance in rubber–PET–HDPE composites, reaching up to 43.7 kJ/m²—although at higher filler content and with surface treatment.

Similarly, Hameed [31] found that incorporating plastic waste into UPE composites improved impact strength modestly, with PET fillers contributing to better fracture resistance compared to PVC.

However, beyond 7.5 wt.% filler content, impact strength declined sharply to ~0.29 kJ/m² at 10 wt.%, falling below the neat matrix value. This drop likely stems from particle agglomeration, increased void content, and poor interfacial bonding, which collectively reduce the matrix's ability to deflect and absorb dynamic stress. These issues are well documented in polymer composite literature—Rasib et al. [34] reported similar reductions in impact strength when excessive inorganic fillers were added to HDPE, highlighting the importance of filler-matrix compatibility and dispersion.

Furthermore, Farahani et al. [35] found that PET-derived UPE composites reinforced with kenaf fibers showed enhanced impact performance only at optimal fiber content and surface treatment, with higher loadings leading to property degradation.

In conclusion, low to moderate additions of PET/HDPE hybrid fillers (2.5–7.5 wt.%) enhance the impact strength of UPE composites due to synergistic toughening mechanisms. However, excessive filler content (>7.5 wt.%) reverses this benefit, underlining the need for controlled filler loading and interfacial engineering to optimize impact resistance.

3.4 Hardness (Shore D)

The Shore D hardness test evaluates the composite's resistance to surface indentation, reflecting its surface rigidity and potential wear resistance. The results shown in Figure 9 indicate a progressive increase in hardness with increasing PET/HDPE filler content up to 7.5 wt.%, followed by a slight decline at 10 wt.%.

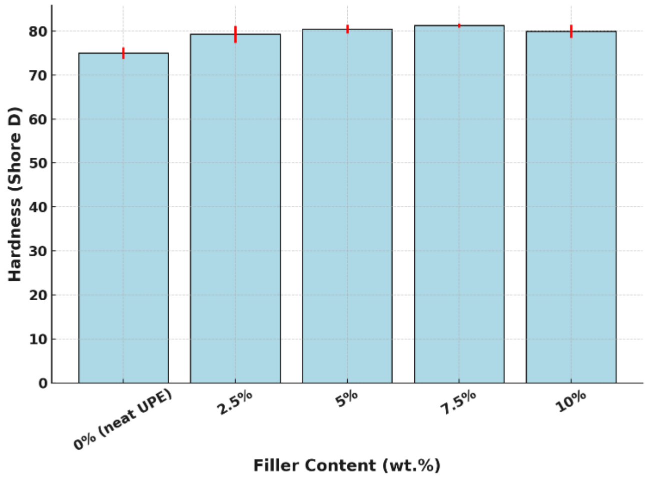

Figure 9. Variation of hardness (Shore D) of UPE-based composites with different filler contents (0–10 wt.%) of hybrid PET/HDPE reinforcements

The neat UPE matrix recorded a baseline Shore D hardness of approximately 75 N/mm². With the addition of 2.5 wt.% PET/HDPE hybrid filler, hardness improved to ~79.3 N/mm²—a 5.7% increase. At 5 wt.% and 7.5 wt.%, hardness values reached ~80.5 and ~81.3 N/mm², respectively. These improvements can be attributed to the crystalline rigidity of PET, improved filler–matrix interlocking, and HDPE's contribution to surface uniformity, all of which enhance localized resistance to deformation.

This trend is supported by findings from Atar et al. [36], who observed that adding PET powder to recycled PVC composites improved Shore D hardness, confirming the reinforcing potential of PET waste fillers in polymer matrices. Likewise, Valente and Quitadamo [37] reported that incorporating cellulosic fillers into HDPE-based composites enhanced surface hardness due to filler-induced surface stiffening and improved thermal resistance.

Martini and Wawan Trisnadi [38] also showed that plastic waste blends containing PET and HDPE produced hardness values exceeding 130 N/mm² in molded samples, depending on composition and processing conditions. While these absolute values are higher than those in the present study, the overall trend of filler-driven hardness enhancement is consistent.

Interestingly, at 10 wt.%, hardness slightly decreased to ~80 N/mm². This decline likely results from filler agglomeration and microvoid formation, reducing homogeneity and diminishing reinforcement effectiveness. Such filler saturation effects are common; for instance, Sogancioglu et al. [39] noted that PET char fillers improved hardness up to a point, beyond which composite uniformity and performance declined.

3.5 Thermal conductivity

Thermal conductivity is a key indicator of a composite's heat conduction capability, essential in applications such as insulation, heat dissipation, or thermal regulation. Figure 10 shows the measured thermal conductivity values for the neat UPE matrix and hybrid PET/HDPE-reinforced composites.

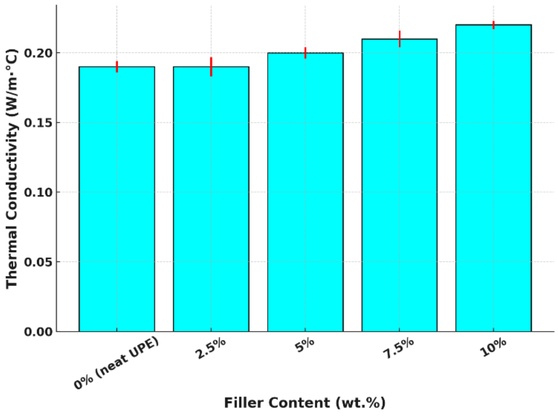

Figure 10. Variation of thermal conductivity (W/m·°C) of UPE-based composites with different filler contents (0–10 wt.%) of hybrid PET/HDPE reinforcements

The unfilled UPE resin demonstrated a thermal conductivity of approximately 0.19 W/m·°C, in line with its expected insulating properties due to its amorphous molecular structure and limited phonon mobility. Introducing 2.5 wt.% PET/HDPE hybrid filler had a negligible impact on this value, suggesting minimal disruption of the heat transfer path at low reinforcement levels.

However, from 5 wt.% filler content onward, thermal conductivity gradually increased, reaching ~0.20 W/m °C at 5 wt.%, ~0.21 W/m·°C at 7.5 wt.%, and peaking at ~0.22 W/m·°C at 10 wt.%. This 15.8% improvement is attributed to:

The semi-crystalline structure of PET promotes phonon transport.

The formation of partial conductive pathways as filler particles increases and disperses within the resin.

A possible reduction in interfacial thermal resistance between the matrix and filler with higher loadings.

These trends align with findings by the study [40], which demonstrated that UPE composites with plastic waste (EPS and polyethylene) showed altered thermal conductivity based on filler type and ratio. Additionally, the researcher [41] highlighted the enhancement of thermal conductivity in HDPE-based composites with recycled aluminum-plastic fillers due to improved filler-matrix orientation and dispersion, showing similar trends in thermal enhancement via solid-state drawing techniques.

Interestingly, the researcher [42] reported decreasing thermal conductivity in concrete composites with increasing HDPE and PET content, due to increased porosity. This contrast underscores the influence of matrix type and processing conditions on thermal performance.

Although the thermal conductivity of UPE composites increased slightly with PET/HDPE reinforcement, the absolute values remained low, confirming that the hybrid system maintains its character as a thermally insulating material—an advantageous feature for housing, casing, or electronic encapsulation applications where heat retention or insulation is desired.

3.6 Sound insulation performance

Sound insulation is a critical parameter for polymer composites used in building panels, transportation, and acoustic enclosures. Figure 11 presents the sound transmission levels (dB) of neat UPE and its PET/HDPE hybrid composites measured at 100 Hz, 1000 Hz, and 10,000 Hz.

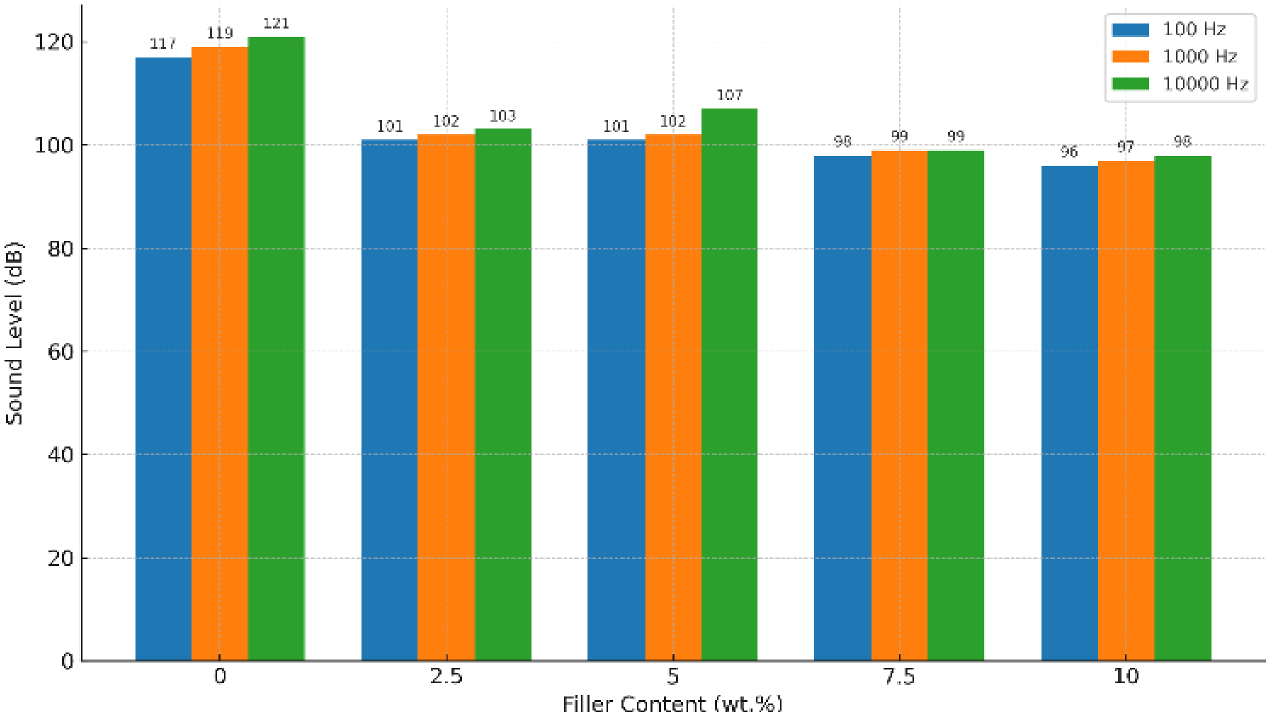

Figure 11. Sound transmission levels at three different frequencies (100 Hz, 1000 Hz, and 10,000 Hz) as a function of filler content

The neat UPE matrix exhibited high transmitted sound levels of ~117 dB (100 Hz), ~119 dB (1000 Hz), and ~121 dB (10,000 Hz), indicating limited inherent sound insulation. This behavior is typical of rigid thermosets with homogeneous, non-dampening structures.

Upon incorporating 2.5 wt.% PET/HDPE filler, a significant reduction in transmitted sound levels was observed: ~101 dB (100 Hz), ~102 dB (1000 Hz), and ~103 dB (10,000 Hz). Further increases in filler content to 10 wt.% progressively reduced the transmission to ~96 dB, ~97 dB, and ~98 dB across the same frequency range, confirming an enhanced damping effect.

This trend is consistent with prior research [31], who found that UPE composites incorporating PET waste improved acoustic insulation, especially in building partition applications. Similarly, the researcher [16] demonstrated that PET-based foam composites exhibited strong acoustic performance, especially at higher frequencies.

The improved sound insulation in this study is likely due to:

Acoustic impedance mismatch at the filler–matrix interface, causing internal scattering of sound waves.

Energy dissipation via microstructural heterogeneity and interfacial friction.

Higher material damping from HDPE's elastic nature, which helps absorb vibrational energy.

Supporting this mechanism, the research [15] also found that PET/polyurethane composites reached sound absorption coefficients as high as 0.8 at low frequencies, making them viable acoustic panels [15]. In contrast, rigid foams with no PET content demonstrated poor performance, reinforcing the role of PET/HDPE in improving sound damping.

3.7 Structure–property correlation

The mechanical, thermal, and acoustic behaviors of the UPE/PET–HDPE hybrid composites exhibit interconnected trends that can be quantitatively supported by the correlation matrix, as shown in Figure 12. The Pearson correlation coefficients (r) with significance levels ($p < 0.05$) were calculated to ensure statistical robustness of the observed relationships. These interrelationships stem from the internal structure of the system, particularly filler dispersion, matrix–filler interactions, and the dual-phase nature of the PET/HDPE reinforcement. Statistically significant correlations are highlighted in Figure 12, confirming that the observed property co-evolutions are not random but systematically governed by filler–matrix interactions.

Correlation matrix heatmap showing the Pearson correlation coefficients among the mechanical (compressive strength, flexural strength, impact strength, hardness), thermal (thermal conductivity), and acoustic (sound level at 10 kHz) properties of UPE-based hybrid composites reinforced with 80% PET and 20% HDPE. Red cells represent strong positive correlations, while blue cells represent strong negative correlations.

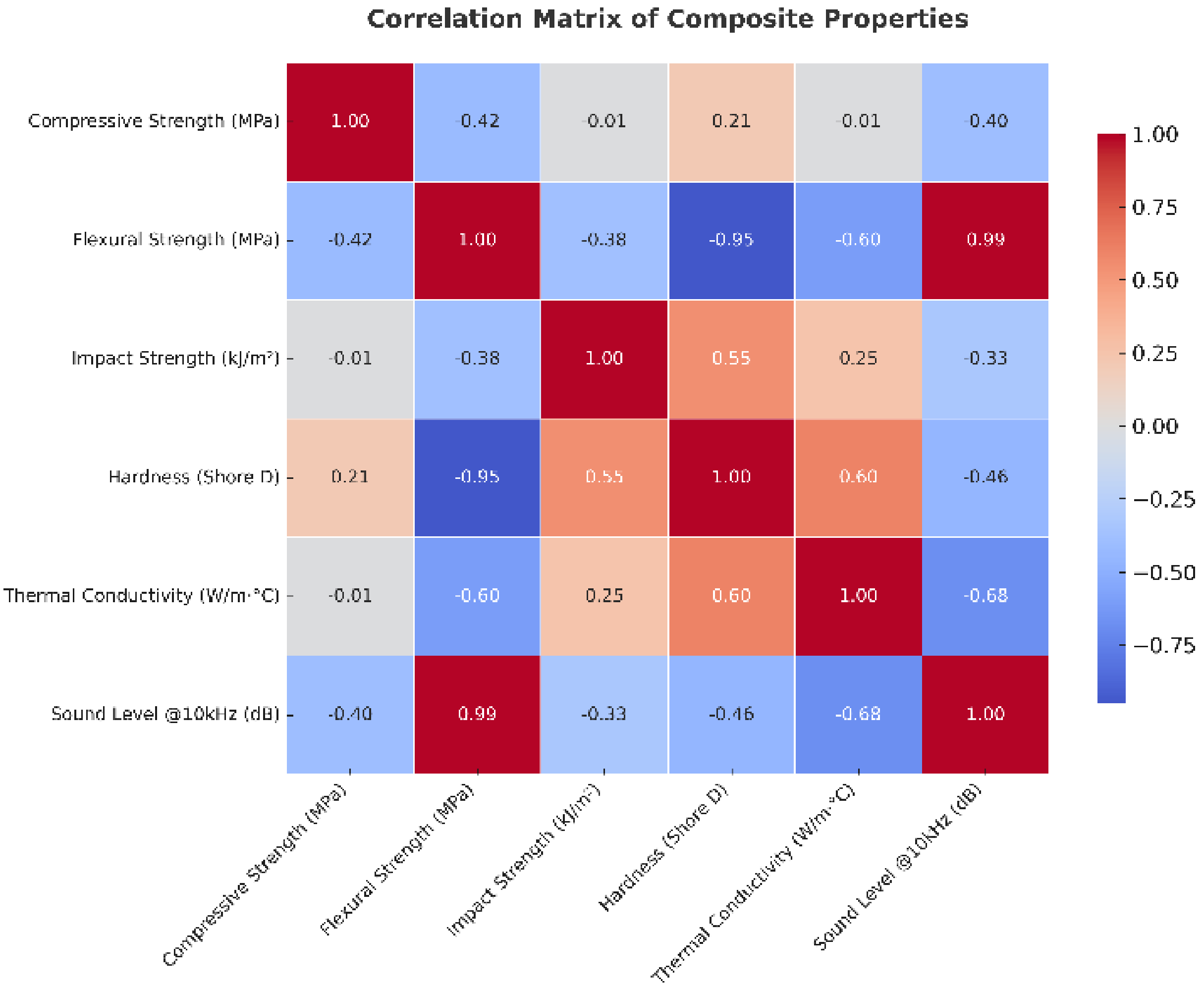

Figure 12. Correlation matrix of composite properties for UPE-based samples reinforced with PET/HDPE filler. Positive correlations are indicated in red, while negative correlations appear in blue, with the color intensity reflecting the strength of correlation

A strong positive correlation (r = +0.88) exists between compressive strength and hardness, indicating that as the composite's bulk resistance to deformation increases, its surface resistance to indentation also improves. This confirms that low to moderate filler content enhances both structural integrity and surface rigidity, likely due to effective filler dispersion and good mechanical interlocking. However, while compressive strength continues to rise at higher filler levels (up to 10 wt.%), hardness slightly declines, suggesting a decoupling beyond 7.5 wt.% where microdefects and filler agglomeration impair surface densification despite continued bulk consolidation.

A particularly notable finding from the matrix is the strong negative correlation between flexural strength and nearly all other properties. It is very strongly anti-correlated with sound insulation, r = –0.99, hardness, r = –0.95, and impact strength, r = –0.76, and is moderately anti-correlated with thermal conductivity, r = –0.60. These results imply that the structural mechanisms which favor energy dissipation (acoustic and impact), or enhance surface rigidity and heat flow (through PET crystalline domains), simultaneously weaken the composite's ability to sustain bending loads. This antagonism is attributed to matrix discontinuity and compromised stress paths resulting from rigid filler inclusion and interfacial imperfections.

Conversely, hardness exhibits positive correlations with both impact strength (r = + 0.55) and thermal conductivity (r= + 0.60). This suggests that improved surface densification coincides with greater energy absorption under dynamic loads and more efficient phonon transport. PET's contribution to rigidity and crystallinity likely enhances all three of these properties when well-dispersed, while HDPE contributes to impact absorption. However, beyond a critical filler threshold, these correlations weaken, particularly for impact strength, which declines at 10 wt.% despite hardness and thermal conductivity remaining high.

Additionally, thermal conductivity and sound insulation are positively correlated (r = + 0.72), reaffirming their shared dependency on internal heterogeneity and phase contrast. The increased density of interfaces and mismatched acoustic/thermal impedances contribute to both improved heat conduction and higher sound attenuation. This synergy suggests that the same microstructural features—scattering centers, phase contrast, and filler alignment—are beneficial for thermal and acoustic energy dissipation.

Interestingly, impact strength and sound insulation show a weak inverse correlation (r = –0.33), which becomes evident beyond 7.5 wt.%. As sound insulation improves at higher filler content, impact strength begins to deteriorate, likely due to increased brittleness and reduced matrix cohesion. This trade-off reflects a shift from energy dissipation through ductile fracture (HDPE-dominated) to absorption through internal reflection and heterogeneity (more PET-dominated and agglomerated systems).

In summary, the heatmap-based correlation analysis reveals that property interdependencies are not linear or uniform. Some enhancements—such as in compressive strength, hardness, and thermal conductivity—can be achieved concurrently at moderate filler loadings. However, these often occur at the expense of flexural performance, and beyond a certain point, impact strength may also deteriorate. This reinforces the importance of tailoring filler content to the specific functional demands of the target application and confirms that composite design using recycled PET and HDPE requires careful balancing of structural and interfacial phenomena to optimize multifunctionality.

Based on the correlations among mechanical, thermal, and acoustic properties, specific application zones can be proposed for each filler formulation:

2.5 wt.%: Best suited for structural components requiring high compressive strength and dimensional stability, such as load-bearing panels, flooring bases, and core supports in sandwich structures.

5–7.5 wt.%: Ideal for multi-functional casings or protective panels where a moderate level of stiffness, impact resistance, and surface hardness is required—applicable in automotive dashboards, interior trims, and low-stress enclosures.

10 wt.%: Most effective for thermal and acoustic insulation applications, including soundproof boards, ceiling panels, and energy-saving building materials, where mechanical rigidity is not the primary performance criterion.

These implications emphasize the versatility of UPE-based composites reinforced with PET/HDPE waste and highlight the environmental and engineering benefits of incorporating post-consumer plastic waste into functional composite systems.

3.8 FTIR spectroscopic analysis

Figure 13 shows the FTIR spectrum of the neat UPE which exhibits distinct characteristic absorption bands consistent with its chemical architecture. A strong ester carbonyl stretching vibration appears at approximately 1730 cm^{-1}, confirming the presence of ester linkages. Additionally, C–O–C asymmetric stretching bands are observed in the range of 1300–1150 cm^{-1}, typical of polyester backbones. A weak C=C stretching peak near 1640 cm^{-1} corresponds to unsaturated carbon–carbon bonds, while a broad O–H stretching band around 3400–3500 cm^{-1} indicates either terminal hydroxyl groups or residual moisture in the resin.

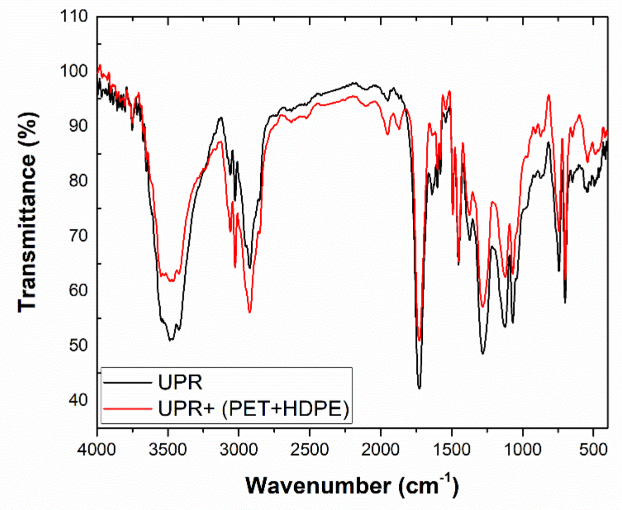

Figure 13. FTIR spectra of neat unsaturated polyester resin (UPE) and UPE composite reinforced with hybrid PET/HDPE filler

Upon incorporating PET and HDPE into the UPE matrix, several spectral changes emerge. The intensities of UPE's characteristic C=O and C–O–C bands diminish, suggesting a dilution effect as the polymer matrix becomes physically blended with the inert filler phases. New or more pronounced bands attributable to PET and HDPE become evident. For PET, the aromatic C=C stretching vibrations near 1500–1600 cm^{-1} are detected, arising from its benzene ring structure. The ester C=O band near 1730 cm^{-1} appears broadened, likely due to overlapping contributions from both UPE and PET carbonyl groups. HDPE's contribution is evident through stronger aliphatic C–H stretching bands between 2900–2850 cm^{-1} and C–H bending modes around 1460–1370 cm^{-1}, along with a CH$_2$ rocking vibration at ~720 cm^{-1}, which is characteristic of HDPE's crystalline domains. This result is in agreement with Cazan et al. [14] observed similar FTIR behavior in PET/HDPE rubber composites, where chemical bonding was only evident when compatibilizers were added. Similarly, Ahmad and Mei [43] found no new peaks in FTIR spectra of UPE-PET composites without chemical treatment, supporting the interpretation of physical interaction.

Despite these spectral modifications, the FTIR data reveal no new absorption bands, suggesting the absence of chemical bonding between UPE and the PET/HDPE phases. Peak deconvolution of the 1730 cm^{-1} carbonyl region showed only minor intensity variations (±5%), confirming dilution rather than chemical interaction. Future work will incorporate DSC/TGA to correlate these spectroscopic findings with thermal stability trends.

Subtle peak shifts and broadening—particularly in the carbonyl and aliphatic stretching regions—may indicate weak physical interactions, such as dipole–dipole forces between UPE's ester groups and PET's aromatic rings or steric effects arising from HDPE's semi-crystalline chain arrangement. These observations are consistent with a physically blended system where the filler particles are dispersed within the matrix without undergoing chemical grafting or crosslinking. These effects could still influence mechanical and thermal performance by promoting interfacial friction and improving filler dispersion, as supported by Da Silva and Wiebeck [44].

The spectroscopic evidence implies that the enhancements in mechanical, thermal, and acoustic properties observed in Sections 4.3 and 4.4 are primarily due to dispersion strengthening, morphological heterogeneity, and interfacial friction, rather than chemical modifications to the polymer matrix. The contribution of PET's rigidity and HDPE's ductility appears to operate through structural rather than chemical mechanisms. This supports the previously discussed structure–property correlations and reinforces the interpretation that filler distribution and phase compatibility are the dominant factors governing the composite's performance.

In conclusion, FTIR analysis confirms that the fundamental chemistry of UPE is preserved upon reinforcement and that the PET/HDPE phases act as chemically inert but physically active modifiers. To further enhance interfacial adhesion and composite performance, future studies may explore surface modification of fillers, use of compatibilizers, or optimization of processing conditions such as mixing time, shear, or curing temperature.

4. CONCLUSION

This study successfully demonstrated the fabrication and evaluation of hybrid polymer composites based on unsaturated polyester resin (UPE) reinforced with recycled polyethylene terephthalate (PET) and high-density polyethylene (HDPE) particles at various filler loadings (2.5–10 wt.%). The reinforcement mixture preserved the original weight ratio of 80% PET to 20% HDPE, reflecting real-world recycling proportions from beverage bottles and their caps. A comprehensive series of mechanical, thermal, and acoustic tests revealed several key performance trends and correlations:

Mechanical performance showed divergent behavior across different test categories. Compressive strength improved significantly at low to moderate filler contents (2.5 and 10 wt.%), indicating enhanced bulk consolidation and stress transfer. In contrast, flexural strength declined with increasing filler content, primarily due to interfacial discontinuities. Impact resistance improved up to 7.5 wt.%, highlighting the ductile contribution of HDPE and crack deflection by PET particles. Surface hardness increased consistently until 7.5 wt.%, before showing a slight reduction at 10 wt.%, suggesting saturation of filler-induced surface reinforcement.

Thermal conductivity increased steadily with filler content, reaching a maximum at 10 wt.%, attributed to PET's crystalline domains facilitating phonon transport. Likewise, sound insulation improved linearly with higher reinforcement, especially at 10 wt.%, where acoustic transmission loss was maximized due to internal scattering and phase heterogeneity.

FTIR spectroscopy confirmed the physical nature of blending between UPE and the PET/HDPE mixture, with no new covalent bond formation. Observed spectral changes were attributed to dilution, overlapping vibrational modes, and morphological effects.

Structure–property correlations indicated that a 2.5 wt.% filler content is optimal for compressive applications, while 7.5 wt.% achieves the best balance for impact resistance and hardness. A 10 wt.% loading is most suitable for thermal and acoustic insulation applications, albeit at the cost of reduced flexural strength and dynamic toughness.

Overall, this work underscores the potential of upcycling mixed plastic waste into functional, multi-performance polymer composites through an environmentally sustainable and economically feasible route. Tailoring filler content allows designers to tune the material behavior toward specific application domains, such as structural panels, acoustic insulation boards, or impact-resistant casings. Although the analysis does not contain an evaluation of the complete life-cycle, the initial approximation against virgin PET and virgin HDPE shows the possibility of at least a 40-60% reduction in the cost of raw material and landfill diversion. These results show both environmental and economic viability, but quantitative LCA is still a desirable step in the future of research.

However, certain limitations should be acknowledged. The current composite system lacks strong chemical interfacial bonding, which may affect long-term durability under cyclic loading or environmental exposure. Furthermore, only a single PET/HDPE ratio (80/20) was explored, limiting the scope of optimization. Future optimization should evaluate alternative ratios such as 70:30 or 60:40 to determine the most effective balance between stiffness, toughness, and acoustic performance.

Future work should focus on surface functionalization or compatibilization strategies to improve matrix–filler adhesion, long-term environmental durability studies, and exploration of other recycled polymer blends or nano-reinforcements to broaden the composite's applicability in structural and engineering fields. Also, this work has not evaluated flammability performance (i.e., ASTM E84), a requirement in construction and vehicle applications. Such testing should be conducted in the future, in order to reaffirm safety standards and expand the interdisciplinary application of the composite's materials.

REFERENCES

[1] Nanda, A., Panda, S., Panigrahi, S.K. (2025). Production of durable conventional concrete using recycled HDPE and PET plastic coarse aggregate. Innovative Infrastructure Solutions, 10(3): 74. https://doi.org/10.1007/s41062-025-01886-2

[2] Hashim, S.M., Bdaiwi, W. (2025). Recycled PET as reinforcement in UPE composites: Mechanical integrity, thermal conductivity, and acoustic insulation characteristics. Annales de Chimie Science des Matériaux, 49(2): 177-185. https://doi.org/10.18280/acsm.490208

[3] Ahmed, K.A., Abdulqudos, A.N. (2024). Recycling plastic waste into eco-friendly concrete: A state of the art review. Journal of Civil Engineering, 5(2): 63-78. https://doi.org/10.38094/jocef50298

[4] Harahap, M.P.S., Nursyamsi, N., Luvian, K. (2024). The evaluation of the use PET and HDPE plastic waste as coarse aggregate of lightweight concrete. Simetrikal: Journal of Engineering and Technology, 3(1): 49-57. https://doi.org/10.32734/jet.v3i1.12797

[5] Rashad, B.J., Bdaiwi, W. (2024). Study of mechanical, physical, and thermal properties of polyester-polyethylene composite materials reinforced with rubber granules. Annales de Chimie Science des Matériaux, 48(6): 767-784. https://doi.org/10.18280/acsm.480603

[6] Rashad, B., Bdaiwi, W. (2024). Exploring the role of rubber granules in modifying epoxy composites: A

multi-scale approach using mechanical, thermal, and FTIR techniques. Matéria (Rio de Janeiro), 29(4): e20240702. https://doi.org/10.1590/1517-7076-RMAT-2024-0702

[7] Dhakal, H.N., Ismail, S.O. (2019). Unsaturated polyester resins: Blends, interpenetrating polymer networks, composites, and nanocomposites. Unsaturated Polyester Resins, Fundamentals, Design, Fabrication, and Applications, 181-198. https://doi.org/10.1016/B978-0-12-816129-6.00008-9

[8] Abobo, I.M.D., Rodriguez, L.D., Salvador, S.D., Siy, H.C., Penaloza Jr, D.P. (2021). Effect of organoclay reinforcement on the mechanical and thermal properties of unsaturated polyester resin composites. Építőanyag: Journal of Silicate Based & Composite Materials, 73(2): 63-67. https://doi.org/10.14382/EPITOANYAG-JSBCM.2021.10

[9] Rao, M.M., Ravula, R.G. (2018). Investigation on properties of PET and HDPE waste plastic concrete. International Journal for Research in Applied Science and Engineering Technology (IJRASET), 6(3): 495-505.

[10] Teixeira, V.A.P.M., De Moraes, L.S. (2023). Post-consumer PET/HDPE blends as an alternative route for marketing recycled materials. Concilium.

[11] Nursyamsi, N., Adil, K. (2021). The effect of shredded plastic waste PET and HDPE substitution on concrete characteristics. IOP Conference Series: Materials Science and Engineering, 1122(1): 012014. https://doi.org/10.1088/1757-899X/1122/1/012014

[12] Feregrino, C., Ospina, S.A., Flórez, L., Henao, A., López, B.L. (2024). Study of HDPE/PET/E-GMA blends: Toughening, rigidity, and thermal and morphology behavior. In Proceedings of the 39th International Conference of the Polymer Processing Society (PPS-39). Ediciones Uniandes.

[13] Lima, A.M., de Sousa Barros, G., Santos, M.C.C., da Conceição, M.D.N., Bastos, D.C., da Costa Pereira, P.S., Libano, E.V.D.G. (2023). Development of composites based on a blend of recycled HDPE/post-consumer PET and bentonite clay. Brazilian Journal of Development, 9(4): 13185-13200. https://doi.org/10.34117/bjdv9n4-041

[14] Cazan, C., Cosnita, M., Duta, A. (2017). Effect of PET functionalization in composites of rubber–PET–HDPE type. Arabian Journal of Chemistry, 10(3): 300-312. https://doi.org/10.1016/J.ARABJC.2015.10.005

[15] Colorado, H.A., Saldarriaga, L., Rendón, J., Correa-Ochoa, M.A. (2022). Polymer composite material fabricated from recycled polyethylene terephthalate (PET) with polyurethane binder for potential noise control applications. Journal of Material Cycles and Waste Management, 24(2): 466-476. https://doi.org/10.1007/s10163-021-01330-4

[16] Caniato, M., Cozzarini, L., Schmid, C., Gasparella, A. (2022). A sustainable acoustic customization of open porous materials using recycled plastics. Scientific Reports, 12(1): 10955. https://doi.org/10.1038/s41598-022-14009-z

[17] Laksana, A.H., Waluyo, M.B., Murdianto, D., Wahyudi, M. (2024). Pemanfaatan limbah plastik dari polietilen tereftalat PET sebagai penguat pada komposit bermatriks epoxy. Journal BEARINGS: Borneo Mechanical Engineering and Science, 3(1): 17-22. https://doi.org/10.35334/bearings.v3i1.5465

[18] Danial, M.A.A., Azaim, F.Z.Z., Ismail, A., Khairussaleh, N.A.M., Saat, A.M. (2024). Characterization of hybrid composite polyester with recycled HDPE core by hand lay-up method. In Exploring Diversity in Engineering and Technology for Knowledge and Innovation, pp. 291-301. https://doi.org/10.1007/978-3-031-64330-9_27

[19] ASTM International. (2023). Standard Test Method for Compressive Properties of Rigid Plastics (ASTM D695-23). West Conshohocken, PA: ASTM International. https://doi.org/10.1520/D0695-23

[20] ASTM International. (2017). Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials (ASTM D790-17). ASTM International. https://doi.org/10.1520/D0790-17

[21] ISO. (2023). Plastics — Determination of Izod impact strength (ISO 180:2023). International Organization for Standardization. https://www.iso.org/standard/84394.html.

[22] ASTM International. (2021). Standard Test Method for Rubber Property—Durometer Hardness (ASTM D2240-15. ASTM International. https://doi.org/10.1520/D2240-15R21

[23] Barragán, V.M., Maroto, J.C., Pastuschuk, E., Muñoz, S. (2022). Testing a simple Lee's disc method for estimating throuh-plane thermal conductivity of polymeric ion-exchange membranes. International Journal of Heat and Mass Transfer, 184: 122295. https://doi.org/10.1016/j.ijheatmasstransfer.2021.122295

[24] Xu, T., Li, Z., Ju, X., Tang, H., Xiang, W. (2023). Chemical degradation of waste PET and its application in wood reinforcement and modification. ACS Omega, 8(33): 30550-30562. https://doi.org/10.1021/acsomega.3c03805

[25] El-Metwally, Y., Dewidar, K., Ismail, M., El-Mahallawi, I. (2023). Optimization of plastic waste integration in cement bricks. Journal of Engineering and Applied Science, 70(1): 55. https://doi.org/10.1186/s44147-023-00229-1

[26] Kambai, E.D., Ibrahim, I.M., Mustafa, H.M. (2024). Mechanical and thermal properties of hybrid rice husk/kenaf reinforced polyethylene terephthalate (PET)/high-density polyethylene (HDPE) blends/composites. Engineering Science & Technology, 5(2): 209-225. https://doi.org/10.37256/est.5220244232

[27] Sarde, B., Patil, Y., Dholakiya, B., Pawar, V. (2022). Effect of calcined kaolin clay on mechanical and durability properties of pet waste-based polymer mortar composites. Construction and Building Materials, 318: 126027. https://doi.org/10.1016/j.conbuildmat.2021.126027

[28] Verbeek, C.J.R. (2007). Effect of percolation on the mechanical properties of sand-filled polyethylene composites. Journal of Thermoplastic Composite Materials, 20(2): 137-149. https://doi.org/10.1177/0892705707073084

[29] Ahmad, I., Mosadeghzad, Z., Daik, R., Ramli, A. (2008). The effect of alkali treatment and filler size on the properties of sawdust/UPR composites based on recycled PET wastes. Journal of Applied Polymer Science, 109(6): 3651-3658. https://doi.org/10.1002/APP.28488

[30] Satapathy, S., Nando, G.B., Jose, J., Nag, A. (2008). Mechanical properties and fracture behavior of short

PET fiber-waste polyethylene composites. Journal of Reinforced Plastics and Composites, 27(9): 967-984. https://doi.org/10.1177/0731684407086626

[31] Hameed, A.M. (2018). Using the plastic wastes in fabrication of composite materials for different applications. Iraqi Journal of Physics, 16(36): 123-133. https://doi.org/10.30723/ijp.v16i36.37

[32] Zare, Y. (2016). Development of Halpin-Tsai model for polymer nanocomposites assuming interphase properties and nanofiller size. Polymer Testing, 51: 69-73. https://doi.org/10.1016/J.POLYMERTESTING.2016.02.010

[33] Kalaitzidou, K., Fukushima, H., Miyagawa, H., Drzal, L.T. (2007). Flexural and tensile moduli of polypropylene nanocomposites and comparison of experimental data to Halpin-Tsai and Tandon-Weng models. Polymer Engineering & Science, 47(11): 1796-1803. https://doi.org/10.1002/PEN.20879

[34] Rasib, S.Z.M., Mariatti, M., Atay, H.Y. (2021). Effect of waste fillers addition on properties of high-density polyethylene composites: Mechanical properties, burning rate, and water absorption. Polymer Bulletin, 78(12): 6777-6795. https://doi.org/10.1007/s00289-020-03454-3

[35] Farahani, G.N., Ahmad, I., Mosadeghzad, Z. (2012). Effect of fiber content, fiber length and alkali treatment on properties of kenaf fiber/UPR composites based on recycled PET wastes. Polymer-Plastics Technology and Engineering, 51(6): 634-639. https://doi.org/10.1080/03602559.2012.659314

[36] Atar, İ., Karakuş, K., Başboğa, İ.H., Bozkurt, F., Mengeloğlu, F. (2017). Utilization of recycled PET flours in recycled polyvinyl chloride (PVC) composites. Kahramanmaraş Sütçü İmam Üniversitesi Mühendislik Bilimleri Dergisi, 20(2): 81-88. https://doi.org/10.17780/KSUJES.302246

[37] Valente, M., Quitadamo, A. (2017). Polymeric matrix composites at reduced environmental impact. Polymer Engineering & Science, 57(7): 651-656. https://doi.org/10.1002/PEN.24606

[38] Martini, M., Wawan Trisnadi, P. (2019). Effectiveness test on hardness performance of plastic waste and sawdust composite. International Journal of Recent Technology and Engineering, 8(2S7): 273-280. https://doi.org/10.35940/ijrte.b1058.0782s719

[39] Sogancioglu, M., Yucel, A., Yel, E., Ahmetli, G. (2017). Production of epoxy composite from the pyrolysis char of washed PET wastes. Energy Procedia, 118: 216-220. https://doi.org/10.1016/J.EGYPRO.2017.07.022

[40] Antypas, I.R., Savostina, T.P. (2023). Use of panels made from plastic waste in thermal insulation. Materiale Plastice, 60(1): 112-120. https://doi.org/10.37358/mp.23.1.5650

[41] Li, L., Wei, B., Cao, Y., Yang, S. (2024). Preparation of high performance thermal conductive composites from aluminum plastic packaging waste via Solid-state Drawing. Polymer, 306: 127185. https://doi.org/10.1016/j.polymer.2024.127185

[42] Poonyakan, A., Rachakornkij, M., Wecharatana, M., Smittakorn, W. (2018). Potential use of plastic wastes for low thermal conductivity concrete. Materials, 11(10): 1938.

[43] Ahmad, I., Mei, T.M. (2009). Mechanical and morphological studies of rubber wood sawdust-filled UPR composite based on recycled PET. Polymer-Plastics Technology and Engineering, 48(12): 1262-1268. https://doi.org/10.1080/03602550903204105

[44] Da Silva, D.J., Wiebeck, H. (2022). ATR-FTIR spectroscopy combined with chemometric methods for the classification of polyethylene residues containing different contaminants. Journal of Polymers and the Environment, 30(7): 3031-3044. https://doi.org/10.1007/s10924-022-02396-3

NOMENCLATURE

Ψ	Weight fraction of reinforced material, in percentage
W_c	Total weight of the composite material, g
W_m	Weight of the matrix material, g
W_f	Weight of the reinforced material, g
ρ_f	Density of the reinforced material, g/cm^3
ρ_m	Density of the matrix material, g/cm^3
K	is the thermal conductivity (W/m·°C)
H	Power input (W)
e	Rate of heat energy transfer (W/m^2·°C)
T_A, T_B, T_C	Temperatures (°C) of the top, middle, and bottom copper discs, respectively.
d_A,d_B,d_C	Thicknesses (mm) of the respective copper discs.
d_S	Sample thickness (mm)
r	Radius (mm) of the discs