



Recycled PET as Reinforcement in UPE Composites: Mechanical Integrity, Thermal Conductivity, and Acoustic Insulation Characteristics

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ABSTRACT

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This study investigates the mechanical, thermal, chemical, and acoustic properties of unsaturated polyester resin (UPE) composites reinforced with recycled polyethylene terephthalate (PET) particles. Micro-sized PET particles (~53 µm), derived from post-consumer plastic waste, were incorporated into UPE at weight fractions of 0%, 2.5%, 5%, 7.5%, and 10% using a hand lay-up technique. The resulting composites were evaluated for compressive and flexural strength, thermal conductivity, FTIR-based chemical structure, and sound insulation performance. Results showed that increasing PET content significantly enhanced compressive strength, achieving a maximum improvement of ~29% at 10 wt% PET. In contrast, flexural strength decreased sharply with PET addition due to filler-induced brittleness and weak interfacial adhesion. Thermal conductivity improved by 29.6% at 5 wt% PET before plateauing, attributed to improved phonon transport at optimal filler dispersion. FTIR analysis confirmed minor thermal degradation at higher PET contents, evidenced by the emergence of hydroxyl bands. Acoustic testing revealed broadband sound attenuation across low, mid, and high frequencies, with up to 23 dB reduction in sound transmission, peaking at 7.5 wt% PET. These findings support the use of recycled PET as a sustainable reinforcing filler for UPE composites in thermal and acoustic insulation applications. A novel approach combining mechanical, thermal and acoustic tests highlights how recycled PET can be used to enhance sustainable composite technologies in many branches of engineering.

1. INTRODUCTION

In recent decades, polymer matrix composites (PMCs) have garnered increasing attention due to their advantageous combination of light weight, high specific strength and stiffness, corrosion resistance, and multifunctionality in structural and functional applications [1-5]. Using polymer matrix composites is common for brake pedals, accelerator arms in cars [6], structural materials in buildings because of their good stiffness and corrosion resistance [7], as well as for sports and electronics equipment as they are sturdy and have useful thermal and insulation properties [8]. Top among these are the unsaturated polyester resins (UPE) that have gained wide acceptance in various industries such as automotive, construction and consumer goods, because of their low cost, good mechanical properties, chemical resistance and easy handling [9-12]. Their inherent brittleness and low impact resistance, however, limit their application in more demanding applications, thus prompting research on reinforcement strategies, which include the addition of elastomers, natural fiber, nanoclays and inorganic fillers to improve toughness and durability [13-16]. The main reason UPE is brittle and weak against impact is that its molecules are highly crosslinked, hindering movement within the material and allowing cracks to start and spread under load. As a result, it struggles to handle

high-strain or shock situations, so extra toughening is needed for these kinds of uses.

At the same time, a sharp increase in polyethylene terephthalate (PET) waste (mostly originating from disposable beverage containers) is becoming a substantial environmental problem because of its ubiquity, longevity, and strong resistance to natural decomposition processes [17-20]. In this regard, the utilization of post-consumer PET as a reinforcing filler in thermosetting polymer matrices has two advantages: it aids in sustainable waste management while similarly improving the mechanical and physical qualities of the host matrix [21-24].

Despite producing over 30 million metric tons of PET each year and supplying over 480 billion bottles, only a third of this material is recycled in various parts of the world. Much of the waste from PET is disposed of in landfills or remains in the environment as it is not easily broken down by nature. For this reason, turning this high-quality and durable waste into filling materials for composites is an excellent solution that benefits nature and improves strengths of the materials [25]. High crystallinity, stiffness, and dimensional stability are essential properties, which make PET a potential candidate for being micro-sized reinforcing filler [26, 27].

Recent research reported that the incorporation of recycled PET into unsaturated polyester matrices is capable of

enhancing flexural and compressive strength, thermal insulation, and water resistance [28, 29] once properly processed and surface treated. In addition, the utilization of recycled PET flakes in UPE composites presents a viable option towards upcycling plastic waste while lowering reliance on virgin petrochemical resources [30]. Unlike regular recycling which can make materials less useful, upcycling turns waste into useful additions for more durable products like adding PET waste to improve the performance of structural composite materials.

Despite earlier studies that studied PET in thermoplastics and in polymeric concrete using UPE matrix, little studies have been conducted for direct incorporation of micro-sized PET with emphasis on thermal conductivity and acoustic insulation into UPE. Seeds of emerging studies indicate that hybrid filler systems (e.g., combining PET with industrial wastes) can enhance thermal resistance and mechanical toughness of UPE composites [31, 32]. There is a developing trend to investigate how the surface morphology, processing temperature and interfacial adhesion of PET affect the overall performance of the composites created [33].

The current study is undertaken to find the effect of using varied weight fractions of recycled PET particles (0%, 2.5%, 5%, 7.5%, and 10%) within the UPE to enhance mechanical (bending and compression), thermal (conductivity), chemical (FTIR analysis) and acoustic insulation attributes of the resulting composites. The PET particles, processed to a uniform particle size of 53 μm , were obtained from melted and ground PET bottles, providing an environmentally sustainable reinforcement source.

In addition, Fourier Transform Infrared (FTIR) spectroscopy was employed to assess changes in the chemical bonding of the composite system before and after thermal processing, while a custom-designed acoustic box system was used to evaluate the sound insulation capabilities of the material across key frequency ranges. The study is expected to provide novel insights into the structure–property relationships of PET-reinforced UPE composites, with implications for sustainable materials engineering in thermal and acoustic insulation applications.

2. MATERIALS AND SAMPLE PREPARATION

2.1 Matrix material: Unsaturated polyester resin (UPE)

The matrix material used in this study was unsaturated polyester resin (UPE), supplied by Saudi Industrial Resins (SIR). As shown in Figure 1, the resin appears as a viscous, transparent pink liquid at room temperature. UPE is classified as a thermosetting polymer, which undergoes an irreversible chemical transformation from a liquid to a solid state upon the addition of a curing agent.



(a) Cutting process



(b) Fine powder of PET

Figure 1. (a) Mechanical cutting of recycled PET bottles into small fragments. (b) PET final powder obtained from melting, cooling, and grinding (average particle size of 53 μm)

Table 1. Properties of the UPE resin

Property	Value Range
Modulus of Elasticity (GPa)	2.06 – 4.41
Specific Heat (J/kg·K)	710 – 920
Thermal Conductivity (W/m·°C)	0.17
Density (g/cm ³)	1.20

The curing agent employed was methyl ethyl ketone peroxide (MEKP), also provided by the manufacturer. It was introduced at a ratio of 2 grams per 100 grams of resin, initiating the curing process at ambient laboratory temperature (~25 °C). This exothermic crosslinking reaction converts the liquid resin into a rigid, crosslinked polymer network. The primary physical and thermal properties of the UPE resin, as specified by the supplier, are presented in Table 1.

2.2 Reinforcing material: Polyethylene terephthalate (PET)

The reinforcing phase in the composite system consisted of polyethylene terephthalate (PET) particles derived from post-consumer plastic waste, specifically used bottles for drinking water and carbonated beverages (Figure 2). These plastic containers were manually cut into small fragments, followed by thermal and mechanical processing to obtain PET in fine particulate form suitable for composite reinforcement. The PET was melted, solidified, and then ground to a uniform particle size of approximately 53 μm , as detailed in Section 2.3.1.

The chemical and physical characteristics of PET—such as its high crystallinity, chemical stability, and non-hygroscopic nature—make it an appropriate reinforcement for enhancing the functional properties of polymer composites. Table 2 summarizes the key attributes of the PET material utilized in this study.

Table 2. Properties of the PET

Property	Value Range
State of Matter	Solid
Density (g/cm ³)	1.38
Water Absorption	0
Appearance	Colorless, transparent crystalline
Chemical Formula	C ₁₀ H ₈ O ₄

2.3 Sample preparation

2.3.1 Processing of reinforcing PET particles

The preparation of PET particles was carried out through a sequential process involving cutting, melting, cooling, and

grinding. Initially, discarded PET bottles were cut into small pieces using a custom-built mechanical cutter (Figure 1(a)). These pieces were then melted at 250°C in a laboratory electric furnace, followed by ambient air cooling. The solidified PET was subsequently milled using a mechanical grinder to obtain a fine powder with an average particle diameter of 53 µm, as illustrated in Figure 1(b).

2.3.2 Fabrication of composite specimens

The composite specimens were fabricated using the manual hand lay-up technique, a widely adopted method for producing thermoset-based composites. Molds made of aluminum and glass were used to shape the samples according to the required testing dimensions. PET particles were added to the UPE matrix at weight fractions of 0%, 2.5%, 5%, 7.5%, and 10%. Each formulation was prepared by gradually dispersing PET particles into the UPE resin using a glass rod until a uniform mixture was achieved. The MEKP hardener was then added in a fixed ratio of 2 g per 100 g of resin, and the mixture was poured into molds to cure under ambient conditions.

The weight percentage of reinforcement was calculated using the following relationships [34]:

$$\Psi = \left(\frac{W_f}{W_c} \right) \times 100\% \quad (1)$$

$$W_c = W_f + W_m \quad (2)$$

where,

Ψ is the weight fraction of PET (%),

w_f is the weight of PET particles,

w_m is the weight of the matrix material (UPE), and

w_c is the total composite weight.

These procedures ensured the consistent formulation and fabrication of composite samples for subsequent characterization by mechanical testing, FTIR spectroscopy, thermal conductivity measurements, and acoustic insulation evaluation.

2.4 Mechanical testing

2.4.1 Bending test

The three-point bending test was conducted to evaluate the flexural strength of the composite specimens. The test procedure adhered to the ASTM D790-17 [35] and this was done using a LARYEE Yaur Testing Solution universal testing machine for the measurements. The specimens were supported at two points and a load was applied at the middle to induce flexural stress.

The flexural strength (modulus of rupture) was determined as the maximum level of stress at which the sample was capable of sustaining before fracture. Through such tests, valuable information was gained on how the PET content affected the resistance of the composite to deformation under bending loads.

2.4.2 Compression test

Compression testing was carried out to evaluate the compressive strength of the PET-reinforced composites according to the standard of ASTM D695-15 [36]. The same LARYEE Yaur Testing Solution machine was used. Specimens are placed between two flat platens and a progressively increasing axial load is applied until substantial deformation or failure was realized.

The compressive strength, understood as the maximal stress

the material could bear before failure, was specified for each composition. This parameter was vital in assessing the impact of PET reinforcement on the composite's resistance to compressive loads and especially in static or structural bearing applications. Even though compressive modulus was not assessed in the present study, the information contained in the given strength data gave a good idea of appropriate load-carrying capacity and deformation resistance applied to PET particles in the UPE matrix.

2.4.3 Thermal conductivity test

The thermal conductivity of fabricated composites was studied using Ta Lee disk method with the help of a testing machine of Griffen & George. The setup involved the use of copper discs of standard dimensions usually 50 mm across diameter, 5 mm thick, to sandwich the test piece. A current of 0.25 A and 6V of voltage was used to facilitate consistent heat flow through the sample.

Temperatures were measured at various positions using three copper conductivity plates (TA, TB, and TC) that corresponded to the upper, middle, and lower copper discs. Following equations were used to calculate thermal conductivity (K) [37]:

$$K \left(\frac{T_B - T_A}{T_s} \right) = e \left[T_A + \frac{2}{r} \left(d_A + \frac{1}{4} d_s \right) T_A + \frac{1}{2r} d_s d_B \right] \quad (3)$$

$$H = IV = \pi r^2 e (T_A + T_B) + 2\pi r e \left[d_A T_A + d_s \cdot \frac{1}{2} (T_A + T_B) + d_B T_B + d_C T_C \right] \quad (4)$$

where,

K is the thermal conductivity (W/m·°C),

e is the thermal energy transfer rate (W/m²·°C),

H is the heat power input (W),

T_A , T_B , and T_C are the temperatures (°C) at respective copper plates,

d_A , d_B , d_C are the thicknesses (mm) of copper discs,

d_s is the sample thickness (mm),

r is the disc radius (mm).

This method enabled a precise evaluation of heat transport through the composite, providing critical insight into its suitability for thermal management applications. Variation in PET content was linked to reported change in thermal conductivity, which is elaborated further in Section 3.3.

2.5 Fourier transform infrared (FTIR) spectroscopy

In order to study the chemical composition and molecular interactions and possible structural modifications in the case of polyethylene terephthalate (PET) particles, Fourier Transform Method Infrared (FTIR) spectroscopy was utilized. Analysis was done both pre- and post-thermal processing to identify for variation in chemical bondings or degradation effects that may have impact on mechanical and thermal behavior of composite.

FTIR spectra were obtained using a PerkinElmer Spectrum Two FT-IR Spectrometer with high sensitivity detector and integrated signal processing system. Spectral measurements were performed within mid-infrared range (400-4000cm⁻¹) with a resolution 4cm⁻¹ and 16 scans averaged per sample, in order to guarantee high spectral clarity and favorable signal-noise ratio.

Composite specimens were studied in transmission mode,

for which thin homogeneous films of cured PET were prepared. The use of FTIR spectroscopy also acted as a diagnostic method to monitor the chemical integrity of the PET mechanism, with regard to the thermal and mechanical toughness of the material system under processing conditions of particular relevance to industrial applications.

2.6 Acoustic testing

Acoustic testing over a wide range of frequencies was used to assess sound insulation performance of the fabricated UPE–PET composites to determine the effectiveness of the material in suppressing airborne sound transmission through the structures. This test is critical in establishing whether polymer composites are appropriate for use in acoustic insulation application such as building panels, enclosures or transportation components.

The acoustic measurements were conducted from a fixed standardized reverberation chamber setup (see Figure 2) in which each composite sample was placed as a barrier between a controlled sound source and a receiving sensor array. The test protocol was directed at three characterizing frequencies – namely, 100 Hz; 1000 Hz; and 10,000 Hz corresponding to the low-, mid- and high-frequency propagation sound accordingly. These frequencies were chosen to represent the usual noises in a natural and industrial environment.

The sound pressure level (SPL) was recorded using a high-sensitivity decibel meter for each PET content level (0%, 2.5%, 5%, 7.5%, and 10%). Three readings were performed at a given frequency to guarantee measurement reliability, and the mean sound level (in dB) was computed together with its standard deviation to check the consistency of data.

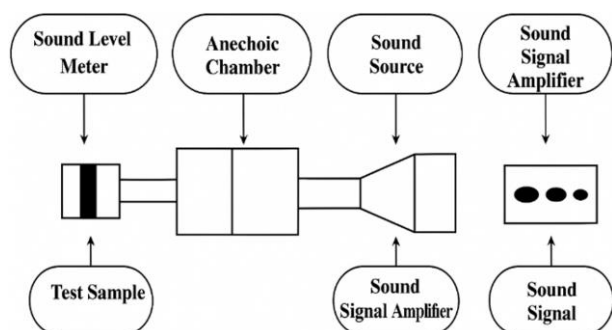


Figure 2. Schematic diagram of the acoustic insulation testing setup illustrating the path of sound from source to the amplified system and test sample to anechoic chamber where the sound levels are measured

The experimental arrangement was chosen that ensured the minimal background noise and echo interference and all the tests were performed in controlled ambient environment. The acoustic response was addressed by comparing the transmitted sound levels of the reinforced composites to the unfilled UPE matrix. An observed reduction in SPL with increased PET content could be explained as an improved sound absorption and reflection due to internal scattering, viscoelastic damping, and acoustic impedance mismatch provided by the PET filler.

Fundamentally, this acoustic testing methodology offered invaluable insight on the multi-frequency noise-damping properties of the PET-reinforced composites, thus posing them as an interesting option for use in instances where sustainable sound insulation needs are expressed.

3. RESULTS AND DISCUSSION

3.1 Compressive strength results

Experimental testing results of the compressive strength of unsaturated polyester resin (UPE) reinforced composites with micro-sized particles of polyethylene terephthalate (PET) were analyzed where varying weight percentages (0%, 2.5%, 5%, 7.5%, and 10%) were used. The results demonstrate continued improvement of the compressive performance with increasing PET content (see Figure 3). In particular, the neat UPE matrix had a mean compressive strength of 55.2 MPa. Upon the incorporation of 2.5 wt% PET, the strength increased to 59.0 MPa, and further rose to 60.8 MPa and 65.1 MPa at 5 wt% and 7.5 wt%, respectively. The highest strength value of 71.2 MPa was recorded at 10 wt% PET, reflecting an overall improvement of approximately 29% relative to the unreinforced matrix, consistent with trends observed in other studies involving recycled PET in thermoset composites [38].

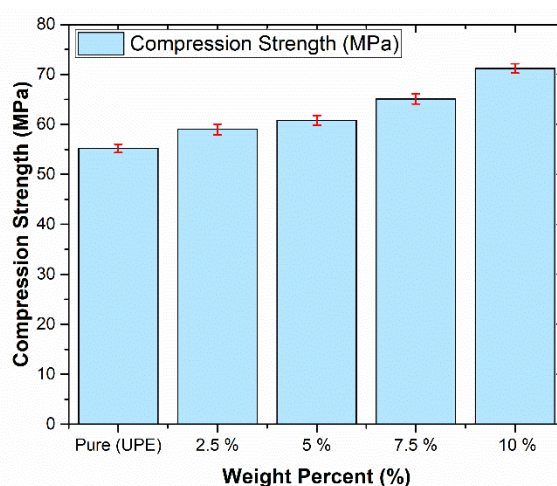


Figure 3. Compressive strength of PET-reinforced UPE composites at various weight percentages

This progressive enhancement in compressive strength is primarily attributed to the inherent mechanical rigidity of the PET particles, which possess a high modulus and excellent load-bearing capacity due to their semi-crystalline nature. When dispersed within the polymer matrix, these particles act as micro-reinforcements that hinder local deformation under compressive loading. The fine particle size (~53 μm) ensures a relatively large surface area for interaction, promoting effective stress transfer across the matrix–filler interface. Furthermore, the stiff PET inclusions constrain the mobility of the polymer chains under compressive stress, thereby increasing the overall stiffness and deformation resistance of the composite structure.

Additionally, the low standard deviation values observed across all samples (ranging from 0.85 to 1.05 MPa) indicate a high level of experimental consistency and homogeneity in the fabricated composites. This suggests that the hand lay-up technique, when combined with appropriate PET dispersion, can yield structurally uniform specimens with reproducible mechanical performance. Notably, no saturation or decline in compressive strength was observed within the studied PET concentration range, implying that further enhancement might be achievable beyond 10 wt%, pending optimization of filler dispersion and interfacial bonding.

3.2 Flexural strength results

The flexural (bending) behavior of the unsaturated polyester resin (UPE) composites reinforced with varying weight percentages of polyethylene terephthalate (PET) particles was assessed using a three-point bending test. As shown in Figure 4, the results indicate a pronounced decline in flexural strength with increasing PET content. The unreinforced UPE matrix exhibited a mean flexural strength of 162.9 MPa, representing the highest value in the test series. Upon the addition of 2.5 wt% PET, the strength decreased sharply to 32.2 MPa, followed by further reductions to 24.1 MPa, 22.8 MPa, and 22.2 MPa for 5 wt%, 7.5 wt%, and 10 wt%, respectively. Standard deviation values remained low (0.89–1.01 MPa), indicating good reproducibility of the experimental procedure despite the large variance in mean strength values.

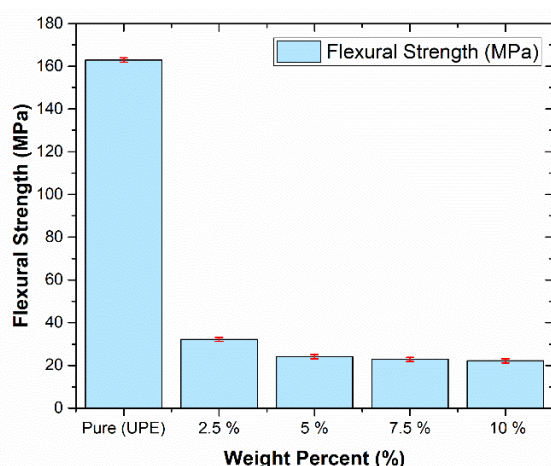


Figure 4. Flexural strength of PET-reinforced UPE composites at various weight percentages

The significant deterioration in flexural performance can be attributed to several interrelated factors. Flexural strength in polymer composites is highly sensitive to the nature of the filler, the interface quality between the matrix and reinforcement, and the filler dispersion. Unlike tensile or compressive loading, flexural loading induces combined tensile and compressive stresses across the cross-section of the sample. In such conditions, discontinuities or stress concentrators, such as poorly bonded or agglomerated filler particles, become critical failure initiators. The sharp drop from 162.9 MPa to 32.2 MPa at only 2.5 wt% PET suggests that the added particles may have introduced stress-raising sites or micro-voids, resulting from inadequate wetting or weak interfacial adhesion between the PET particles and the polyester matrix—similar to what has been reported in recent studies examining flexural behavior of recycled PET composites without compatibilizers [39].

Moreover, PET, despite its rigidity, is inherently brittle and lacks the deformability required to accommodate strain gradients during bending. This brittleness, combined with possible filler-matrix mismatch in mechanical modulus, likely led to early crack initiation and propagation under flexural stress. Additionally, the low particle size (53 μm) and increasing volume fraction could have resulted in localized particle-particle interactions, impeding matrix continuity and promoting microstructural heterogeneity.

The plateau observed between 7.5% and 10% PET suggests that the detrimental effect stabilizes at higher filler loadings,

possibly due to a balance between particle interference and partial stress redistribution. Nonetheless, the reduction in flexural strength points to a trade-off between compressive reinforcement and flexural ductility, emphasizing that PET reinforcement in UPE composites, while beneficial under compressive loads, is not advantageous under bending conditions without further surface treatment or compatibilization strategies.

3.3 Thermal conductivity

The thermal conductivity of unsaturated polyester resin (UPE) composites reinforced with recycled polyethylene terephthalate (PET) particles was evaluated to investigate the influence of filler content on heat transfer characteristics. As revealed in Figure 5, the measured values demonstrate a clear increase in thermal conductivity with the introduction of PET particles up to a certain threshold. Specifically, the pure UPE matrix exhibited a mean thermal conductivity of 0.1898 $\text{W/m}\cdot^\circ\text{C}$. Upon the incorporation of 2.5 wt% PET, the value increased substantially to 0.2266 $\text{W/m}\cdot^\circ\text{C}$, and reached a peak of 0.2459 $\text{W/m}\cdot^\circ\text{C}$ at 5 wt% PET. Slight decreases were observed at higher filler contents—0.2395 $\text{W/m}\cdot^\circ\text{C}$ and 0.2409 $\text{W/m}\cdot^\circ\text{C}$ for 7.5 wt% and 10 wt% PET, respectively. The associated standard deviations across all measurements were low ($\leq 0.0051 \text{ W/m}\cdot^\circ\text{C}$), indicating high experimental precision.

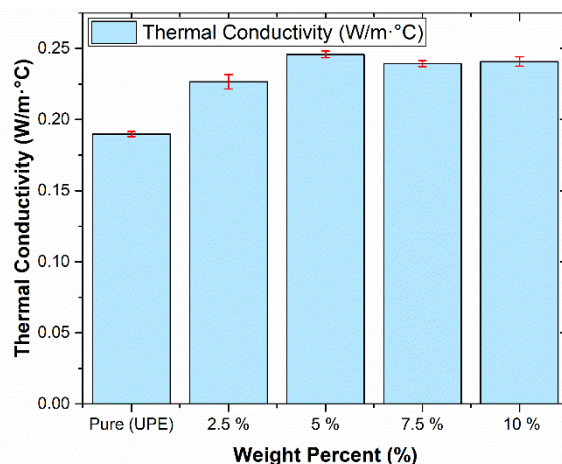


Figure 5. Thermal conductivity of PET-reinforced UPE composites at various weight percentages

The initial rise in thermal conductivity can be attributed to the intrinsic thermal properties of PET, which possesses a relatively higher thermal conductivity than the amorphous UPE matrix. As PET particles are introduced, they create additional conductive pathways within the composite, facilitating more efficient phonon or molecular vibration transmission across the matrix. This is especially effective at lower loadings (2.5–5 wt%), where the particles are well dispersed and interfacial thermal resistance remains moderate. In recent studies on PET-based composites, a similar trend of enhanced thermal conductivity as a consequence of PET dispersion and interfacial interactions has been evidenced [40].

However, beyond 5 wt%, a slight decline or saturation effect is noted. This plateau in conductivity may result from particle agglomeration or increased interfacial phonon scattering, where the mismatch in thermal vibrational modes between the PET filler and the UPE matrix becomes more

pronounced. In these cases, instead of creating a continuous conductive network, excess filler creates extra interfacial boundaries instead of connecting them, hence hindering rather than aiding heat transfer. Moreover, at fuller filler fractions, poor interfacial adhesion or void formation may develop thermal insulation zones, working against the possible benefits from the PET inclusions.

3.4 FTIR spectroscopy

Fourier Transform Infrared spectra were obtained to study the chemical constitution and functional groups variation in the polyethylene terephthalate (PET) particles, pre and post the melting step. This analysis offered insight into the chemical stability of the matrix–filler system, especially when subjected to thermal conditions, and enabled the interpretation of any degradation mechanisms, or structural changes that could affect the mechanical and thermal performance.

The FTIR of polyethylene terephthalate (PET) before melting (see Figure 6) showed characteristic absorption bands which indicated its semicrystalline polyester structure. A prominent peak was observed around 1719 cm^{-1} attributed to C=O stretching vibrations of the ester function, characteristic of PET backbone fingerprint. Furthermore, distinct peaks in $2924\text{--}2854\text{ cm}^{-1}$ region were attributed to aliphatic C–H stretching while those in the range of $1260\text{--}1015\text{ cm}^{-1}$ were assigned to C–O–C stretching vibrations that were characteristic of the ester linkage and aryl ether functionalities inherent to the PET molecular framework. These spectral signatures authenticate the completely preserved chemical integrity of virginal PET before exposure to thermal energy.

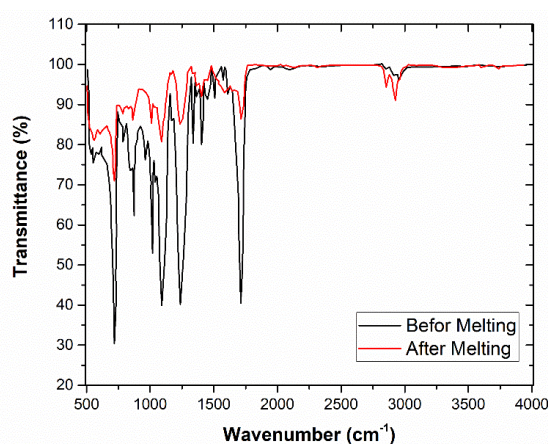


Figure 6. FTIR spectra of PET samples before and after melting

After the melting process, the FTIR spectrum showed slight but important changes indicating thermal degradation phenomena. A weaker absorption band emerged in $3750\text{--}3710\text{ cm}^{-1}$ region for the free hydroxyl (–OH) stretching vibrations. The presence of this band suggests the potential development of hydroxyl-containing degradation products, which may be caused by thermal hydrolysis or the scission of an ester bond at an elevated temperature. While the C=O band at 1719 cm^{-1} stayed relatively station and intensive (conveying that most of ester-groups were still formed), C–O–C zone had some new broadening and attenuation (assumed that some degradation or molecular-reorganization had arisen within PET chains). These observations are in line with recent reports, where thermally degraded PET had enhanced hydroxyl signals and

modified ester group absorbance in FTIR spectra, suggesting partial chain degradation and decreased crystallinity [41].

These molecular changes are consistent with the macroscopic thermal and mechanical response that the thermally treated PET usually exhibits. The decrease in spectral intensity and increase in band width in particular in the ester associated regions acts as indicators of chain scission events and a propensity to reduce crystallinity, which may reduce structural coherence. Such modifications are reported to lower flexural stiffness and thermal conductivity especially as the polymer changes from semi-crystalline to more amorphous state as the result of local bond cleavage.

3.5 Acoustic insulation properties

The acoustic insulation behavior of unsaturated polyester resin (UPE) composites reinforced with polyethylene terephthalate (PET) particles derived from recycled plastic waste was investigated by measuring the transmitted sound levels at three frequencies: 100 Hz, 1000 Hz, and 10,000 Hz. The aim was to evaluate the potential of the PET/UPE composites for noise control applications across low, mid, and high-frequency ranges. As shown in Figure 7, the results clearly demonstrate that the inclusion of PET particles leads to a significant and systematic reduction in transmitted sound levels, confirming enhanced acoustic damping performance of the composites.

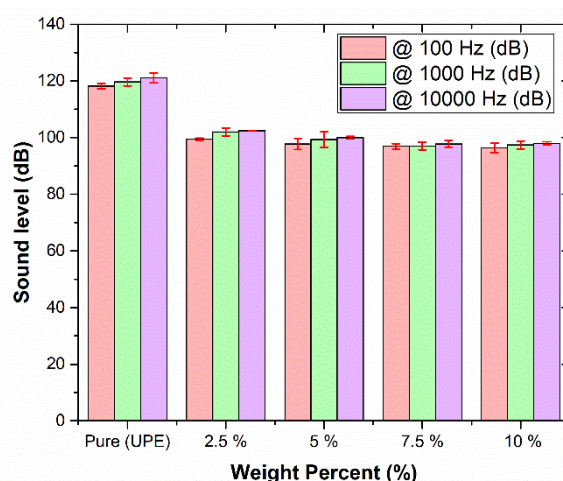


Figure 7. Sound level measurements at 100, 1000, and 10,000 Hz for PET-reinforced UPE composites

At 100 Hz, the unreinforced UPE sample exhibited a mean transmitted sound level of 118.14 dB, indicating poor low-frequency attenuation. With the addition of 2.5 wt% PET, a substantial reduction to 99.41 dB was observed, corresponding to a decrease of approximately 18.73 dB. Further increases in PET content led to additional attenuation, with the transmitted sound levels measured at 97.72 dB (5 wt%), 96.91 dB (7.5 wt%), and 96.30 dB (10 wt%). This represents a total reduction of 21.84 dB, clearly illustrating the effectiveness of PET reinforcement in dampening low-frequency acoustic energy.

At the mid-frequency range (1000 Hz), the same declining trend in sound transmission was observed. The neat UPE matrix transmitted 119.64 dB, while the composites reinforced with 2.5, 5, 7.5, and 10 wt% PET transmitted 101.98 dB, 99.30 dB, 96.99 dB, and 97.39 dB, respectively. The maximum attenuation of 22.65 dB was achieved at 7.5 wt%, suggesting

that a balance between particle dispersion and matrix flexibility can result in enhanced mid-frequency noise suppression. The slight increase observed at 10 wt% may be due to increased rigidity or potential filler agglomeration, which limits energy dissipation.

At the high-frequency range (10,000 Hz), the baseline UPE recorded the highest transmitted sound level of 121.00 dB. However, the addition of PET particles led to significant reductions: 102.40 dB (2.5 wt%), 99.94 dB (5 wt%), 97.76 dB (7.5 wt%), and 97.97 dB (10 wt%). The net reduction of 23.03 dB indicates that the PET/UPE composite system is highly effective in attenuating high-frequency acoustic waves, likely due to increased scattering and interface-based reflection mechanisms. Other PET-based polymer composites that have been designed for noise control have demonstrated analogous acoustic insulation advantages, including PET-polyurethane systems with high sound absorption over 125 Hz to 4 kHz frequency ranges [42].

The observed improvements in acoustic insulation across all frequencies can be explained through several physical mechanisms. Firstly, PET particles introduce heterogeneity within the matrix, resulting in a complex internal structure that scatters incident sound waves, thereby elongating the path and increasing energy dissipation. This scattering effect is especially pronounced at frequencies with wavelengths on the order of or smaller than the PET particle size (~53 µm), which include both the mid- and high-frequency ranges. Secondly, interfacial damping arises from the frictional motion between the relatively stiff PET particles and the surrounding viscoelastic matrix during sound-induced vibrations. This friction converts acoustic energy into heat, contributing to the material's overall sound absorption capacity. Thirdly, the acoustic impedance mismatch between PET and UPE causes partial reflection of acoustic waves at internal interfaces, further limiting wave transmission.

Additionally, increasing the PET content enhances the number of these impedance mismatched regions, but excessive filler may lead to particle agglomeration or increased matrix stiffness, which could diminish damping efficiency. This effect explains the trend of diminishing returns in sound level reduction observed between 7.5 wt% and 10 wt%, particularly at 1000 Hz and 10,000 Hz.

Overall, the results confirm that PET-filled UPE composites offer substantial broadband acoustic attenuation, achieving reductions exceeding 20 dB across all tested frequencies. The enhancement is most prominent in the range of 2.5–7.5 wt% PET, beyond which the performance tends to plateau. The low standard deviation values across all measurements (ranging from ~0.37 to 1.74 dB) reflect high reproducibility, indicating uniform dispersion and consistency in sample fabrication. These findings suggest that PET/UPE composites are promising candidates for eco-friendly acoustic insulation materials suitable for construction panels, transportation interiors, and equipment enclosures where sustainable soundproofing solutions are required.

4. CONCLUSION

This study has shown that incorporating micro-sized recycled polyethylene terephthalate (PET) particles into unsaturated polyester resin (UPE) composites significantly enhances compressive strength, thermal conductivity, and acoustic insulation performance. Compressive strength

improved by nearly 29% at 10 wt% PET, and thermal conductivity peaked at 5 wt%, indicating effective heat transfer enhancement. Acoustic testing confirmed substantial reductions in transmitted sound levels across all tested frequencies, with attenuation exceeding 23 dB. FTIR analysis revealed that the essential chemical structure of the PET remained largely intact after processing, though minor signs of thermal degradation were observed.

Despite the positive outcomes, this study has several limitations. Flexural strength declined with increasing PET content, likely due to weak interfacial bonding and PET's inherent brittleness. No surface treatment or compatibilization strategies were employed to improve matrix–filler adhesion. The PET content was limited to 10 wt%, and acoustic testing was performed at only three fixed frequencies. Long-term durability factors such as aging and recyclability were not investigated.

Future work should explore surface modification of PET to enhance bonding, extend PET loading beyond 10 wt%, and include broader acoustic and durability testing to assess performance under real-world conditions.

REFERENCES

- [1] Kessler, M.R. (2012). Polymer matrix composites: A perspective for a special issue of polymer reviews. *Polymer Reviews*, 52(3): 229-233. <https://doi.org/10.1080/15583724.2012.708004>
- [2] Chung, D.D.L. (2019). A review of multifunctional polymer-matrix structural composites. *Composites Part B: Engineering*, 160: 644-660. <https://doi.org/10.1016/j.compositesb.2018.12.117>
- [3] Zindani, D., Kumar, K. (2018). Industrial applications of polymer composite materials. *Composites and Advanced Materials for Industrial Applications*, pp. 1-15. <https://doi.org/10.4018/978-1-5225-5216-1.ch001>
- [4] Mishra, S., Dubey, A., Bhaskey, H.B., Soni, A., Dixit, A., Eswara Prasad, N. (2019). Functional polymer matrix composites for structural and stealth applications. *Transactions of the Indian Institute of Metals*, 72(6): 1659-1662. <https://doi.org/10.1007/s12666-019-01634-y>
- [5] Dubey, K.A., Bhardwaj, Y.K. (2021). High-performance polymer-matrix composites: novel routes of synthesis and interface-structure-property correlations. In *Handbook on Synthesis Strategies for Advanced Materials: Volume-III: Materials Specific Synthesis Strategies*, Singapore: Springer Singapore, pp. 1-25. https://doi.org/10.1007/978-981-16-1892-5_1
- [6] Karthik, K., Ganesh, R. (2015). Mechanical characterization of polymer matrix composite for foot rest in automotive brake pedals. *Journal Of Applied Sciences Research*, 11(14): 93-104. <http://www.aensiweb.com/JASR>.
- [7] Eluwa, S., Kilanko, O. (2024). Biofuel as an alternative for Sub-Saharan Africa's transition to cleaner energy. *Academia Green Energy*, 1(1). <https://www.doi.org/10.20935/AcadEnergy6227>
- [8] Dhanasekar, S., Stella, T.J., Thenmozhi, A., Bharathi, N.D., Thiagarajan, K., Singh, P., Jayakumar, M. (2022). Study of polymer matrix composites for electronics applications. *Journal of Nanomaterials*, 2022(1): 8605099. <https://doi.org/10.1155/2022/8605099>
- [9] Devaraju, S., Alagar, M. (2019). Unsaturated polyester—

- macrocomposites. In *Unsaturated Polyester Resins*, Elsevier, pp. 43-66. <https://doi.org/10.1016/B978-0-12-816129-6.00002-8>
- [10] Dhakal, H.N., Ismail, S.O. (2019). Unsaturated polyester resins: Blends, interpenetrating polymer networks, composites, and nanocomposites. In *Unsaturated Polyester Resins*, Elsevier, pp. 181-198. <https://doi.org/10.1016/B978-0-12-816129-6.00008-9>
- [11] Kandelbauer, A., Tondi, G., Zaske, O.C., Goodman, S.H. (2022). Unsaturated polyesters and vinyl esters. In *Handbook of Thermoset Plastics*, William Andrew Publishing, pp. 97-158. <https://doi.org/10.1016/B978-0-12-821632-3.00015-4>
- [12] Abu-Jdayil, B. (2019). Unsaturated polyester microcomposites. In *Unsaturated Polyester Resins*, Elsevier, pp. 67-100. <https://doi.org/10.1016/B978-0-12-816129-6.00003-X>
- [13] Benny, C.A., Thachil, E.T. (2004). Modification of isophthalic unsaturated polyester resin using elastomers bearing reactive functional groups. *Progress in Rubber Plastics and Recycling Technology*, 20(4): 247-266. <https://doi.org/10.1177/147776060402000401>
- [14] Esfahani, J.M., Sabet, A.R., Esfandeh, M. (2012). Assessment of nanocomposites based on unsaturated polyester resin/nanoclay under impact loading. *Polymers for Advanced Technologies*, 23(4): 817-824. <https://doi.org/10.1002/pat.1977>
- [15] Dhakal, H.N., Zhang, Z.Y., Richardson, M.O.W., Errajhi, O.A.Z. (2007). The low velocity impact response of non-woven hemp fibre reinforced unsaturated polyester composites. *Composite Structures*, 81(4): 559-567. <https://doi.org/10.1016/j.compstruct.2006.10.003>
- [16] Baskaran, R., Sarojadevi, M., Vijayakumar, C. (2011). Mechanical and thermal properties of unsaturated polyester/calcium carbonate nanocomposites. *Journal of Reinforced Plastics and Composites*, 30(17), 1549-1556. <https://doi.org/10.1177/0731684411424630>
- [17] Kim, N.K., Lee, S.H., Park, H.D. (2022). Current biotechnologies on depolymerization of polyethylene terephthalate (PET) and repolymerization of reclaimed monomers from PET for bio-upcycling: A critical review. *Bioresource Technology*, 363: 127931. <https://doi.org/10.1016/j.biortech.2022.127931>
- [18] Salam, M.D., Varma, A., Prashar, R., Choudhary, D. (2021). Review on efficacy of microbial degradation of polyethylene terephthalate and bio-upcycling as a part of plastic waste management. *Applied Ecology and Environmental Sciences*, 9: 695-703. <https://doi.org/10.12691/aees-9-7-8>
- [19] Soong, Y.H.V., Sobkowicz, M.J., Xie, D. (2022). Recent advances in biological recycling of polyethylene terephthalate (PET) plastic wastes. *Bioengineering*, 9(3): 98. <https://doi.org/10.3390/bioengineering9030098>
- [20] Das, P., Tiwari, P. (2019). Thermal degradation study of waste polyethylene terephthalate (PET) under inert and oxidative environments. *Thermochimica Acta*, 679: 178340. <https://doi.org/10.1016/j.tca.2019.178340>
- [21] Kovačević, T., Brzić, S., Kalagasidis Krušić, M., Nešić, J., Radović, L., Dojčinović, M., Rusmirović, J. (2021). Reuse potential of functionalized thermoplastic waste as reinforcement for thermoset polymers: Mechanical properties and erosion resistance. *Journal of Composite Materials*, 55(28): 4207-4220. <https://doi.org/10.1177/00219983211037045>
- [22] Yadav, Y.K., Dixit, G., Dixit, S. (2023). Natural fiber reinforced rPET/polyester composites: A review on development, mechanical performance, and sustainable management. *Polymer-Plastics Technology and Materials*, 62(14): 1823-1843.
- [23] Singh, A.K., Bedi, R., Kaith, B.S. (2021). Composite materials based on recycled polyethylene terephthalate and their properties—A comprehensive review. *Composites Part B: Engineering*, 219: 108928. <https://doi.org/10.1016/j.compositesb.2021.108928>
- [24] Teixeira, V.A.P.M., de Moraes, L.S. (2024). Post-consumer PET/HDPE blends as an alternative route for marketing recycled materials.
- [25] Jovanović, A., Bugarčić, M., Simić, M., Pejić, J., Dimitrijević, J. (2025). The global market of PET production: from origins to recycling. *Metallurgical and Materials Data*, 2(4): 113-118. <http://dx.doi.org/10.30544/MMD46>
- [26] Rebeiz, K.S. (1996). Strength and durability properties of polyester concrete using PET and fly ash wastes. *Advanced Performance Materials*, 3: 205-214. <https://doi.org/10.1007/BF00136746>
- [27] Nair, V.K., Kulkarni, D. (2022). Synthesis of Unsaturated polyester resin based on PET waste. *International Journal for Research in Applied Science and Engineering Technology*, 10: VIII. <https://doi.org/10.22214/ijraset.2022.46459>
- [28] Abdullah, N.M., Ahmad, I. (2013). Potential of using polyester reinforced coconut fiber composites derived from recycling polyethylene terephthalate (PET) waste. *Fibers and Polymers*, 14: 584-590. <https://doi.org/10.1007/s12221-013-0584-7>
- [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] Kim, J., Jeong, D., Son, C., Lee, Y., Kim, E., Moon, I. (2007). Synthesis and applications of unsaturated polyester resins based on PET waste. *Korean Journal of Chemical Engineering*, 24: 1076-1083. <https://doi.org/10.1007/s11814-007-0124-5>
- [31] Tasnim, S., Shaikh, F.U.A., Sarker, P.K. (2021). Mechanical properties and microstructure of lightweight polymer composites containing mono and hybrid fillers sourced from recycled solid wastes. *Construction and Building Materials*, 277: 122369. <https://doi.org/10.1016/j.conbuildmat.2021.122369>
- [32] Jamdar, V., Kathalewar, M., Sane, D., Sabnis, A. (2025). Chemical recycling of PET waste and utilization of recycled product for synthesis of hybrid unsaturated polyester-urethane coatings. *Polymer Bulletin*, 82(5): 1625-1642. <https://doi.org/10.1007/s00289-024-05587-1>
- [33] Rubeš, D., Vinklár, J., Podzimek, Š., Honzicek, J. (2024). Bio-based unsaturated polyester resin from post-consumer PET. *RSC Advances*, 14(12): 8536-8547. <https://doi.org/10.1039/D3RA08500G>
- [34] Peters, S.T. (2013). *Handbook of Composites*. 2nd ed., Springer, New York, NY.
- [35] ASTM International. (2017). ASTM D790-17: Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials. <https://store.astm.org/d0790-17.html>

- [36] ASTM International. (2015). ASTM D695-15: Standard test method for compressive properties of rigid plastics. <https://store.astm.org/d0695-15.html>.
- [37] Barragán, V.M., Maroto, J.C., Pastuschuk, E., Muñoz, S. (2022). Testing a simple Lee's disc method for estimating through-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>
- [38] Dehas, O., Babouri, L., Biskri, Y., Bardeau, J.F. (2024). Mechanical and morphological properties of unsaturated polyester resin composites reinforced with recycled PET fibers of varying lengths. *World Journal of Engineering*, 21(6): 1142-1153. <https://doi.org/10.1108/WJE-07-2023-0246>
- [39] Shaikh, F.U.A. (2021). Mechanical properties of recycled polyethylene terephthalate (PET) fiber-reinforced fly ash geopolymer and fly ash-slag-blended geopolymer composites. In *Composite Materials*, Elsevier, pp. 265-284. <https://doi.org/10.1016/B978-0-12-820512-9.00003-4>
- [40] Rajeshkannan, S., Sivakumar, A., Mariappan, M., Gunasekaran, J. (2025). Performance evaluation of PET foam and areca fruit fibre reinforced modified cellulose-vinyl ester composite on thermal and water ageing conditions. *Waste and Biomass Valorization*, 16(4): 1911-1925. <https://doi.org/10.1007/s12649-024-02753-4>
- [41] Gong, L., Pan, Y., Cui, L., Zhang, X. (2024). Atomic insights into the thermal degradation of polyethylene terephthalate combining STA-FTIR and DFT methods. *Fuel*, 364: 131067. <https://doi.org/10.1016/j.fuel.2024.131067>
- [42] 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*, pp. 1-11. <https://doi.org/10.1007/s10163-021-01330-4>

NOMENCLATURE

V_f	volumetric fraction of reinforced material
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	the thermal conductivity (W/m·°C)
H	the power input (W)
e	the rate of heat energy transfer (W/m ² ·°C)
T_A, T_B, T_C	the temperatures (°C) of the top, middle, and bottom copper discs, respectively.
d_A, d_B, d_C	the thicknesses (mm) of the respective copper discs.
d_s	the sample thickness (mm)
r	the radius (mm) of the discs