

Research Article

Thermal and Morphological Assessment of the Penta-Layered, Hybrid U-Polyester Composite Reinforced with Glass Fibers and Polypropylene

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The interaction between the fibers and matrix in a fiber-reinforced polymer composite material is important in figuring out its properties. The incorporation of fibers with polymers can result in composites with enhanced strength and stiffness. This study aims to investigate the thermal and morphological characteristics of hybrid u-polyester composites reinforced with glass fibers and polypropylene. The fabrication of composite specimens was conducted through a straightforward cold press method. The compositions of the composites were held constant, except for the orientation of the glass fibers and polypropylene. In this study, the TG/DTG technique was used to analyze the thermal characteristics of the composites. In addition, transverse thermal conductivity was measured using the ASTM E1530 method. The test results showed that the composite reinforced with glass fibers exhibited the lowest weight loss and minimal thermal conductivity among all the samples, followed by the hybrid composite. Based on the TGA curves of the samples, the matrix experienced a weight loss of 9.7% at a temperature of 300°C, which reduced to 2.6% and 2.1% for hybrid composites and glass fiber-reinforced composites, respectively. DTG curves for composites demonstrate that the hybrid and fiber-reinforced composites degraded at rates of 0.64 mg/min and 0.36 mg/min, respectively, at 392.3°C and 395.7°C. Moreover, transverse thermal conductivity of the composite which consists of five-glass-fibered layers shows a minimal thermal conductivity of 0.05 W/m·K. The morphological properties were also investigated using scanning electron microscopy (SEM) and Fourier-transform infrared spectroscopy (FTIR). The findings from SEM and FTIR showed that a higher proportion of glass fibers led to a more oriented composite structure, demonstrating enhanced crosslinking between fibers and polyester. Therefore, the insights of this study can be used to improve the performance of glass fibers and polypropylene hybrid-laminated composites intended for high-temperature applications.

1. Introduction

Fiber-reinforced polymer composites (FRPC) consist primarily of two key components: a reinforcing fiber that imparts specific mechanical characteristics to enhance the properties of the polymeric matrix and a matrix material [1]. The reinforced fiber can be a glass- or carbon-based material, while the matrix material can include epoxy, polyester, vinyl ester, phenolic resin, polyurethane, and thermoplastic resin [1, 2]. The combination of these distinct constituents enables physical and mechanical attributes that could surpass those of conventional materials. This renders FRPC as highly suitable for an extensive array of applications encompassing aerospace, the bridge industry, and the marine industry, among others [3]. The composite's performance and mechanical properties are subject to the influence of various

factors, including the intrinsic properties of the individual components, the relative proportions of the constituent phases, the alignment of reinforcing fibers, and the extent of adhesion between the polymer matrix and the re-inforcements. Consequently, a comprehensive body of research has been undertaken in recent years to elucidate the impact of these factors on the resulting mechanical properties of composites, with the aim of broadening their scope of utility [4–9].

The development of advanced materials has been pivotal in shaping the modern landscape of engineering and manufacturing. Among these innovative materials, hybrid polyester composites have emerged as a promising class of materials, showcasing an amalgamation of versatility, durability, and environmental sustainability. In recent decades, fiber-reinforced plastics have gained immense attention across industries, driven by their exceptional mechanical properties, cost effectiveness, and ecofriendly characteristics. Within this broader context, hybrid polyester composites have gained significant prominence, heralding a new era in material science and engineering.

To comprehend the significance of hybrid polyester composites, it is imperative to trace the trajectory of their evolution and the pivotal role they play in diverse industrial sectors [2, 10]. The integration of reinforced fibers and thermoplastic resin into polyester matrices represents a transformative synergy, offering a blend of mechanical strength, lightweight design, and corrosion resistance. The utilization of glass fibers, with their well-documented attributes of high tensile strength and chemical resistance, has made them a staple reinforcement material. However, the inherent limitations such as low tensile modulus and sensitivity to abrasion necessitate a nuanced approach in the composite design [11-13]. The inclusion of polypropylene can enrich the composite landscape [2, 10]. The introduction of elastomeric properties that enhance the mechanical performance of the composite is in great demand [13, 14]. Fibers can also be added to increase the strength, stiffness, and heat deflection temperature of polypropylene composite [5-9]. Glass fibers are commonly used in fabricating composites as reinforcement [11]. Their advantageous properties include low cost, high tensile strength, high chemical resistance, and insulating properties [12, 13, 15]. Disadvantages of the glass fibers are low tensile modulus, high specific gravity, sensitivity to abrasion while handling, and low fatigue resistance. Unsaturated polyester resins are easy to process and relatively cheaper; therefore, they can be implemented in the fabrication of polymer composite [16]. In addition, polyester resin shows high resistance to corrosion and is relatively lighter in weight. These properties make this a viable choice for application in the automotive and construction sectors [16]. Fiber-reinforced matrices consist of high-strength fibers embedded in the matrix. Fiber and matrix retain their unique physical and chemical identities; while blended for the composite, the composite shows new properties that cannot be achieved from the constituents alone [17, 18]. Hybrid natural fiber-reinforced polymer composites have shown better mechanical properties than single fiber-reinforced polymer matrix

composites [4, 19, 20]. Fibers function as the load-carrier; the matrix transfers stresses between the fibers and acts as the blockade against the environment and protects the surface of fibers from mechanical abrasion [21].

In this work, we focus on the investigation of the thermal and morphological attributes of hybrid u-polyester composites, which are made using unsaturated polyester resin in combination with glass fibers and polypropylene. These components were added at different ratios to select the optimized composition for the composite. For the fabrication of the composites, a convenient hand layup method was implemented. Subsequently, thermogravimetric/derivative thermogravimetric analysis, Fourier-transform infrared spectroscopy (FTIR), and scanning electron microscopy (SEM) were utilized to evaluate the thermal and morphological properties of the composites.

2. Experimental Procedure

2.1. Raw Materials. The reinforcement used in this study was woven fiber glass roving (type E-glass fiber), which was obtained from Hebei Yuniu Fiberglass Manufacturing Co. Ltd., Xingtai city, Hebei Province, China, and Nilima Bag Mills Ltd., Joymontop 1820, Bangladesh. Glass fiber is a lightweight yet strong and sturdy material, with favorable bulk strength, stiffness, and weight properties compared to metals. The randomly oriented E-glass fiber was used as a reinforcing material in a polyester resin matrix. The matrix for the composite consisted of local polyester fabrics and an unsaturated polyester resin with a styrene monomer (purchased from Naseem Plastic Corp.). The unsaturated polyester resin is a liquid that solidifies when a hardener is added, and it has been formulated to cure at room temperature. The properties of the E-glass fiber and unsaturated polyester resin are listed in Table 1 [22-24].

2.2. Composite Fabrication Method. The composites examined in this investigation were manufactured through the hand layup technique, which includes weighing raw materials, treating PP sheets, fabricating the sandwich-like composite, hydraulic pressing, and selecting the suitable dimensions for the intended test. E-glass fiber was utilized as reinforcement in both sheet and fabric forms. To improve their alignment, the fabrics were dipped in ethanol. Afterward, the raw fabrics were cut into pieces measuring 10×10 cm and weighed using a digital balance (Analytical Balances, PB153 S, Mettler Toledo, China). After being dried in a vacuum dryer (BOV-30V, BIOBASE, China) at 80°C for an hour, the samples were cooled in an airtight container. A mold-release agent was applied to the mold surface to facilitate the removal of the composite after fabrication, as shown in Figure 1. The schematic illustration in Figure 1 depicts the laminated composite fabrication techniques using the hand layup process.

Six composite sheets were created using a combination of glass fiber, unsaturated polyester resin, hardener, and polypropylene in the following ratios: 0% glass fiber and 100% polypropylene, 20% glass fiber and 80%

Properties	Tensile strength (MPa)	Compressive strength (MPa)	Refractive index	Melting point (°C)	Young's modulus (GPa)	Thermal expansion (µm/m⋅°C)	Density (g/cm ³)	Thickness (mm)
E-glass	3445	1080	1.558	1725	76.0	5.00	2.57	1.70
Polypropylene	4800	220	1.49	160	40	8-10	0.905	0.80
Unsaturated polvester	90.0	55.0	1.54	250	3.23	_	1.35	1.50

TABLE 1: Properties of E-glass fiber and unsaturated polyester resin.



FIGURE 1: Schematic illustration of laminated composite fabrication with the hand layup process.

polypropylene, 40% glass fiber and 60% polypropylene, 60% glass fiber and 40% polypropylene, 80% glass fiber and 20% polypropylene, and 100% glass fiber and 0% polypropylene. The composite sheets were then assembled into sandwiches with layers of fabric and the matrix material [25].

All the composites were composed of five layers of glass fiber and polypropylene sheets, as detailed in Table 2. The resin was mixed with the curing agent, and the composite was then placed in a hydraulic press (CARVER Laboratory Press, model C, USA) and compressed at room temperature applying 100 KN pressure for 24 hours. Aluminum sheets of the same size (10×10 cm) were placed on the top and bottom sides of the composite layers to ensure uniform fiber distribution and maintain the desired thickness of the sheets. After 24 hours, the composite was removed from the mold and cut into the desired shape. The resulting composite plates had a final thickness of around 4.5 mm. All test specimens were then machined from the cured composite plates as needed.

2.3. Water Uptake Test and Bulk Density. Water absorption tests on the composite specimens were conducted using the standard test procedure outlined in ASTM Design D5229/D5229M. It is important to understand how composites behave in damp environments [26]. The test specimens were mechanically machined using a stainless-steel blade rotor rotating at a speed of 18,000 rpm, yielding specimens that were 10 mm wide and 40 mm long. The cut edge was smoothed with emery paper, the edges were sealed with epoxy resin, the piece was cured at about 50°C for 24 hours, cooled in a desiccator, and the piece was precisely weighed to within 0.1 mg using a digital balance. The specimens were

then placed in a container of distilled water at 23°C for 24 hours, after which they were removed, their surfaces were cleaned with tissues, and their weight was promptly remeasured using the microbalance. Water absorption tests were conducted every 48, 96, 144, 192, 240, 288, and 336 hours, respectively. The water absorption for each composite stake was calculated following ASTM D5229/D5229M as follows:

$$M_t = \frac{W_t - W_0}{W_0} \times 100,$$
 (1)

where w_t is the weight of the present-day sample (in grams), w_0 is the weight of the oven-dried specimen (in grams) for the corresponding control specimens, and M_t is the water absorption [27–29]. In addition, the bulk density of the composite specimens was also determined using the formula D = WS/V, in accordance with ASTM C135-76(21) [26].

2.4. Fourier-Transform Infrared Spectroscopy (FTIR). Fourier-transform infrared spectroscopy (FTIR) was used to analyze the functional groups present in the fabricated composite. This technique involves the measurement of the absorption of infrared radiation by a sample, which is plotted as an infrared absorption spectrum. The absorption of infrared radiation is dependent on the functional groups present in the sample, making the spectrum a unique "fingerprint" for the identification of chemical bonds within a molecule [30]. Small amounts were mixed with potassium bromide (KBr) powder to create a transparent sheet for the preparation of the composite samples for analysis. The FTIR spectra were then recorded using a Shimadzu FTIR-8400S

Sl. No.	Sample name	Fabrication by layer	Composition of reinforcement (% volume) in matrix		
01	C1	РРРРР	0% glass fiber + 100% polypropylene		
02	C2	PPGPP	20% glass fiber + 80% polypropylene		
03	C3	PGPGP	40% glass fiber + 60% polypropylene		
04	C4	GPGPG	60% glass fiber + 40% polypropylene		
05	C5	GGPGG	80% glass fiber + 20% polypropylene		
06	C6	GGGGG	100% glass fiber + 0% polypropylene		

TABLE 2: Composition of the composites by layer of glass fiber and polyester (G: glass fiber and P: polyester).

instrument, which has a wavenumber range of 4000 to 500 cm^{-1} and a resolution of 4 cm^{-1} . The number of scans was set to 20 to ensure accuracy and precision.

2.5. Scanning Electron Microscopy (SEM) Analysis. Scanning electron microscopy (SEM) is a powerful imaging technique that uses a focused beam of electrons to produce high-resolution images of the surface of a sample. In this study, SEM was used to analyze the surface morphology of the outer surface of the composite. SEM is commonly used in the analysis of composite materials to examine surface morphology, particle size, particle distribution, porosity, and pore size, as well as to identify any defects or imperfections on the surface of the sample. The model number of SEM used in this study was JSM-6490LA, JEOL, Japan, which had a high resolution of 3.0 nm and 500X analytical capacity with a contrast of around 30% and 50% brightness. To prepare the composite samples for analysis, they were affixed to the sample holder using carbon tape, and their surface morphology was observed under the operating conditions of EHT: 5 KV, aperture diameter: $20 \,\mu$ m, and scan speed: 7.

2.6. Thermogravimetric Analysis. Thermogravimetric analysis (TGA) is a technique used to study the thermal stability of materials and understand their decomposition mechanisms. In this study, TGA was performed on resin and composite samples under dynamic conditions using Shimadzu TG/DTG, Model TG/DTGA630, Japan. The samples were placed in a stainless-steel crucible and heated at a rate of 10°C/min in an argon environment, from the ambient temperature to 580°C. The mass loss of the samples was measured throughout the heating process to determine their thermostability. The amount of the sample used was approximately 3.581 mg, while the reference mass was 2.830 mg of alumina. TGA is a valuable tool for understanding the thermal stability and decomposition mechanisms of materials [31].

2.7. Thermal Conductivity. Thermal conductivity is a measure of a material's ability to conduct heat. It is determined by the temperature gradient between two materials, with heat typically transferring from the material with a higher temperature to the material with a lower temperature. The thermal conductivity of a material can be calculated using the equation:

$$K = \frac{\operatorname{mc} \left(\mathrm{dT/dt} \right) x}{A \left(T1 - T2 \right)},\tag{2}$$

where *K* is the thermal conductivity coefficient of the metallic disc, *A* is the contact area of the sample with the metallic disc, *x* is the thickness of the sample, *m* is the mass of the metallic disc, *c* is the specific heat of the metallic disc, and dT/dt is the cooling rate of the metallic disc. In this study, the transverse thermal conductivity of the glass fiber-reinforced composite was evaluated using the "thermal conductivity tester, model: FM-TCT-A200, Fison, UK," and the ASTM E1530 method, which involves using disc-shaped specimens with a diameter of 50 mm and a thickness of 10 mm [32]. A constant heat was applied to one side of the specimen and the temperature of the hot and cold surfaces was measured using thermocouples. This method allowed for the determination of the thermal conductivity values of the composite.

3. Result and Discussion

3.1. Physical Properties. Table 3 presents the results of the bulk density tests of composites C1 to C6 along with different physical parameters. All the composites consisted of five layers of glass fiber and polypropylene (PP) sheets. The only difference among them was the composition of the layers: C1 consisted of five PP layers and zero glass fiber layers, whereas C6 consisted of five glass fiber layers and zero PP layers. In the composites between C1 and C6, the number of glass fiber layers increased, while the number of PP layers decreased. Table 3 shows the variation in physical parameters of the composites with the change in reinforcement.

The bulk density of the composites increases with the increasing number of glass fiber layers in polyester composites (Table 3). When the number of glass fiber layers is the highest in the composite, density becomes the highest (Figure 2). A glass fiber layer has more weight than the same number of PP layers. As a result, more polyester resin was required for preparing composites.

3.2. Water Absorption. Figure 3 shows the variation in water absorption in composites with varying numbers of layers of polypropylene and glass fiber with time. In every instance, the composite stack's water absorption increased with immersion temperature and time before becoming saturated after 14 days. The process for testing the water absorption of the composites involved first drying samples of equal size

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Composites	Weight (gm)	Length (mm)	Width (mm)	Thickness (mm)	Volume (mm ³)	Density (gm⋅mm ⁻³)	Density (kg·m ⁻³)
C1	0.208	51.2	10.5	0.5	241.9	8.590×10^{-4}	859
C2	0.399	50.1	10.0	0.7	350.7	1.137×10^{-3}	1137
C3	0.741	50.0	9.5	1.2	570.0	1.300×10^{-3}	1300
C4	1.293	51.2	11.0	1.7	957.4	1.370×10^{-3}	1350
C5	1.806	50.3	11.5	1.9	1099.0	1.600×10^{-3}	1600
C6	1.582	50.5	10.2	1.6	824.2	1.900×10^{-3}	1900

TABLE 3: Bulk density and other physical parameters of different samples of the glass fiber and polypropylene composite.



FIGURE 2: Schematic representation of bulk density, thickness, and total weight of sample composites.

and recording their weights. The samples were then placed in a pot of water and left to settle. The weight of the composites was then measured after 48 hours.

It was observed that the composite made of five layers of polypropylene (C1) had a higher percentage of water absorption, despite polypropylene being a material that does not readily absorb water. This may be due to the presence of porosity in the composite, which was likely formed during the curing process through the shrinkage of the PP layers. It is possible that water molecules were able to become trapped in the pores between the PP layers.

According to the presented figure, the percentage of absorptivity rapidly decreases as the number of PP layers decreases and the number of glass fiber layers increases. Although both PP and glass fiber have no affinity for water, the percentage of water absorption is quite low for C2 to C6. The lone exception was C5, which included 4 layers of glass fiber sheets and 1 layer of PP. It demonstrates that all composites have the lowest absorptivity. It might be because the C5 surface was less porous, as demonstrated by the SEM image of the relevant composite. Karim et al. reported in an experiment on jute and glass fiber-reinforced polyesterbased hybrid composites that the higher the jute fiber content, the more water the composites absorbed [33]. The water absorption rate for a composite with six layers of glass



FIGURE 3: Assessment of water absorption with the difference in the number of polypropylene and glass fiber layers in the composites.

fiber decreased from approximately 7.21% to 2.39% after 192 hours of immersion at room temperature, which was another example of how reducing jute fiber loading decreased it. In a different study, Suhara et al. investigated the mechanical, water absorption, and thermal properties of injection-molded short hemp fiber/glass fiber-reinforced polypropylene hybrid composites [34]. The results showed that at equilibrium, the water absorption of bare PP is 0.40%, which is very low compared to that of 40% hemp fiberreinforced PP (8.73%). However, they also found that the incorporation of glass fiber in the hemp fiber PP composites reduced this absorption to 5.49% for composites with more glass fiber (15% glass fiber and 25% hemp). In our work, after a total of 336 hours (14 days) of immersion in water, the rate of absorption reached equilibrium, and almost all composites maintained a steady absorption rate, notably 2.79 and 2.78% for composites C5 and C6, respectively. The lowest water absorption rate for fabricated composites sheds light on the specific composition that can be a good option for long-expected composite material.

3.3. Spectroscopic Analysis. In this study, FTIR spectrums of pure glass fiber, polypropylene, and composite u-polyester were taken within the bandwidth of 500 cm^{-1} to 4000 cm^{-1} . All the samples were scanned 20 times, and the resolution was 04 cm^{-1} . Figure 4(a) shows the FTIR spectrum of pure polypropylene (PP), where major peaks have appeared in the band of 1375 cm^{-1} for C-H and CH₃ deformation, 1450 cm⁻¹ for



FIGURE 4: FTIR spectra of (a) pure polypropylene (PP) and (b) glass fiber at the frequency region of 500 cm^{-1} - 4000 cm^{-1} .

 CH_2 and CH_3 bending deformation, and $2835-3000 \text{ cm}^{-1}$ for C-H stretching of CH_3 , CH_2 , and CH. Also, a fingerprint region appeared from 712 cm⁻¹ to 1164 cm⁻¹.

Once more, the broad zone in Figure 4(b) is attributed to the oxygen-silicon bond in the Si-O-Si group of the glass fiber utilized as reinforcement, and the Si-OH bending spectrum was probably the one found at 723 cm⁻¹. Finally, in Figure 5, which depicts the optical characteristics of polypropylene and glass fiber-reinforced polystyrene composites, the major peak was observed at 1730.77 cm^{-1} for -CO-O- bond formation between polyester resin and polypropylene, 1226 cm⁻¹ for aryl-alkyl asymmetric stretching between the -OH group of glass fiber, and 1371.72 cm⁻¹ for -CH bending vibration. But it was also observed that in the composite, a major shifting occurred in the fingerprint region of 602 cm^{-1} to 1018 cm^{-1} . Major peaks have laid within the saturated 1018-1750 regions/aliphatic ester region. This phenomenon in the composite may be due to the fragmentation of the carbon-carbon pi bond of unsaturated polyester resin by the styrene monomer to create further crosslinking. Therefore, liquid polyester becomes a solid state. So, the FTIR spectra indicate that except for crosslinking between the glass fiber and matrix, no other significant reaction occurs.

3.4. Surface Morphology. Figures 6(a) and 6(b) of composite C1 display enlarged views of the composite surface at $10 \,\mu$ m and $50 \,\mu$ m, with magnifications of 500x and 1000x. From these figures, there are few voids visible at 500x and 1000x magnifications of the fabricated composite. This demonstrates that the fiber surface is incompatible with the matrix, leading to poor adhesion between the fiber and matrix of the composites. It is well known that unsaturated polyester networks shrink considerably after curing. This shrinkage reduces the specific volume of the matrix, and it results in free spaces or voids between the matrix and the fiber. Samal et al. also found that cavities arose in their banana/glass fiber-reinforced polypropylene hybrid composite specimen due to poor fiber matrix adhesion [35]. However, the



FIGURE 5: FTIR spectra of the hybrid (glass fiber + PP reinforced) composite at the frequency region of 500 cm^{-1} - 4000 cm^{-1} along with spectra for glass fiber and polypropylene.

interfacial interaction between the banana fiber and the PP matrix was improved with the addition of glass fiber, and the surface pull-out site had a noticeably rough texture.

Here, in this magnification, according to Figure 7, it has been seen that fibers are not well oriented in the C2 composite (Figure 7(a)), but in composite C6 (Figure 7(b)), they are more oriented than C2 which suggests that the composite with maximum glass fiber reinforcement is more oriented than polyester. This may be due to less shrinkage in the composite of glass fiber than in polyester.

3.5. *Thermal Conductivity*. Figure 8 displays the experimentally determined thermal conductivity trends for glass fiber and polyester-reinforced polypropylene composites. Our investigation showed that the value of heat conductivity



FIGURE 6: SEM microstructure of composite C1 at (a) 500 times and (b) 1000 times magnification at 50 μ m and 10 μ m areas without glass fiber reinforcement.



FIGURE 7: SEM microstructure of composites C2 and C6 at (a) 100 times and (b) 500 times magnification with glass fiber reinforcements.

decreased as we increased glass fiber concentration. As polyester and glass fiber have less thermal conductivity than other materials, this composite's behavior may be explained. Woven glass fiber fabrics frequently serve as the best thermal insulators due to their high surface area-to-weight ratio. With a thermal conductivity of 1.38 W/m·K (pure quartz glass) to about 0.05 W/m·K (high lead-containing glasses) as reported by Wang et al., glass fiber blocks or air pockets offer effective thermal insulation by trapping air within their surface [36]. As a result, by trapping air, the glass fiber addition to the polypropylene composite lowers heat conduction. A study by Arpita et al. on hybrid composites reinforced with banana biofiber and glass fiber demonstrates that the addition of glass fibers lowers the thermal conductivity in laminates; they also showed that a total of 4 layers of fiber from bananas and glass fiber alternated with 1weight percent of charcoal have thermal conductivities of 0.207 and 0.217 W/m·K, respectively [37]. Furthermore, they also observed that the inclusion of 2-weight percent charcoal significantly improves the laminate's heat conductivity.

In this work, the thermal conductivity result for the C3 and C4 composite samples is virtually comparable and stable (0.12 W/m·K), because the compactness of both samples is approximately identical, and the composite is saturated with fibers in this ratio. But the C6 composite which consists of 5 glass-fibered layers shows a minimal thermal conductivity of 0.047 W/m·K, due to the high insulating capacity of glass fiber compared to polyester.

3.6. Thermogravimetric Analysis (TGA). Figures 9(a) and 9(b) present the thermogravimetric analysis (TGA), along with differential thermal analysis (DTA), and differential thermogravimetry (DTG) results of the composites, shown as TG (blue), DTA (green), and DTG (red) curves, respectively. In Figure 9(a), the TG curve of the matrix exhibits an initial weight loss of 9.7% at 287.7°C, which may be due to the loss of moisture content in the matrix. The breakdown of a neat unstructured polyester matrix, with styrene as the main product in the temperature range of 360.0 to 400.0°C,



FIGURE 8: Thermal conductivity scheme of fabricated composites reinforced by glass fiber and polypropylene.



FIGURE 9: Thermogravimetric analysis curves of composite samples: (a) 0% reinforcement (matrix); (b) polypropylene reinforced.

results in a significant weight loss of 32.3% at 392.9°C. Ferreira et al. observed almost identical findings, with the peak indicating the temperature of the highest deterioration rate appearing at about 350-400°C, over neat u-polyester hybrid composite. This group additionally found the 58% residue at 500°C [38]. The composites in this work experience a significant weight loss at high temperatures, around 500°C, which may be due to the combustion of the composites leaving residue 57.7% by weight. The DTA curve shows two endothermic peaks at 123.5°C and 452.7°C, respectively, which suggests high-energy consumption for the degradation and combustion of the composites at these points. The DTG curve shows only one peak at 398.8°C, indicating a steady weight loss up to 300°C, with a degradation rate of 0.617 mg/min at 398.8°C. This suggests that there is only one step of degradation, likely due to the degradation of the matrix alone.

In Figure 9(b), the TG curve of the polypropylenereinforced composite exhibits an initial weight loss of 2.1% at 181.1°C, which may be due to the loss of moisture content in the matrix. At 390.7°C, there is an additional weight loss of 17.3% due to matrix degradation, and at 498.1°C, there is a further weight loss of 12.6%, bringing the total weight loss to 67.8% of the initial value. The composite experiences a significant weight loss at high temperatures, around 502°C, which may be due to the combustion of the composite. The DTA curve of the composite shows two endothermic peaks at 112.7°C and 454.0°C, respectively. Meanwhile, the DTG curve shows a steady and minimal weight loss up to 300°C, with a degradation rate of 0.36 mg/min at 395.0°C.

The thermal analysis results for hybrid composites (glass fiber + polypropylene) and only glass fiber-reinforced composites are shown in Figures 10(a) and 10(b), as TG (blue), DTA (green), and DTG (red) curves, respectively. The initial weight loss for the hybrid composites and glass fiber-reinforced composites is approximately 2.6%, and 2.1%, respectively, likely due to the evaporation of moisture from the composites. The total degradation loss for the hybrid and glass fiber-reinforced composites was 15.7% and



FIGURE 10: Thermogravimetric analysis curves for composite samples containing (a) hybrid of glass and polypropylene fibers and (b) glass fibers only.

17.3%, respectively, up to a temperature of approximately 390.7°C. The DTA curves for both types of composites show two endothermic peaks at approximately 158.8°C and 438.9°C for the hybrid composites and at 112.7°C and 454.0°C for the glass fiber-reinforced composites, which are likely due to the thermal degradation of the matrix and fibers. The DTG curves show a steady and minimal weight loss up to 300°C, with a degradation rate of 0.64 mg/min for the hybrid composites and 0.36 mg/min for the glass fiberreinforced composites, appearing at 392.3°C and 395.7°C, respectively. Suhara et al. investigated the thermal stability of hemp/PP and hemp/glass/PP composites with thermogravimetric analysis and noticed two-step degradation in both hemp and hybrid fiber composites [34]. They observed that degradation starts around 250-408°C, due to the decomposition of the cellulosic and hemicellulosic components of the natural fiber in the composites. They concluded that the incorporation of glass fiber in the hemp fiber composite shifts the temperature of degradation to a higher value.

The thermal stability of fiber-reinforced composite materials was evaluated through thermogravimetric analysis (TG) in this study. Figures 9(a), 9(b), 10(a), and 10(b) show the TG results for various composite samples, with the percentage weight loss depicted for each sample. The composite with the lowest weight loss was the glass fiber-reinforced composite, followed by the hybrid samples. The sample with the highest weight loss was the one prepared with no reinforcement, indicating that the addition of fiber layers improves the thermal stability of the composite. The TGA results also showed that the fiber loading contributed to the stability of the composite at higher temperatures.

4. Conclusion

The thermal and morphological properties of u-polyester hybrid composites reinforced with glass fibers and polypropylene were investigated using differential thermogravimetric analysis, a guarded heat flow meter technique, and some other state-of-the-art techniques. The results were further supported by scanning electron microscopy (SEM) and Fourier-transform infrared spectroscopy (FTIR). The following conclusion can be drawn from the results that were originally obtained:

- The hand layup technique was effectively used to fabricate a penta-layered hybrid polyester composite reinforced with glass fibers and polypropylene.
- (2) It was found that the thermal expansion coefficient decreased as the number of glass fiber layers increased, while stability decreased (69.5% wt. loss at 500°C) with the addition of more polypropylene layers.
- (3) The water absorption activity for the glass fiberreinforced u-polyester composite exhibits the Fickian characteristics, and the composite's water absorption rate slowly reduced with time. Although polypropylene is not a material that rapidly absorbs water, it was found that the composite composed of five layers of the material (specimen C1) had a higher percentage (6.80%, 48 h) of water absorption than the composite built of five layers of glass fiber (0.66%, 48 h). This might be because of the porosity that exists in the composite and was probably created during the curing process by the shrinkage of the PP layers.
- (4) The hybrid composite (C6) with the highest number of glass fiber layers exhibited lower thermal conductivity (0.047 W/m·K) than the composite (specimen C1) with the lowest number of glass fiber layers (0.180 W/m·K).
- (5) Therefore, these findings suggest that the hybrid composite consisting of five layers of glass fiber (specimen, C6) has outstanding insulation properties and stability, making it suitable for high-temperature applications and as a structural material in engineering maneuvering for the near future.
- (6) Moreover, this research might present a new vision for the utilization of glass fiber-reinforced polyester composites in a variety of industrial settings.

However, the limitations of this research call for further investigation of the substance's behavior over an extended period as well as evaluation of additional factors that might have an impact on its strength.

Data Availability

All data generated or analyzed during this study are included within this article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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