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Enhancing Mechanical Properties of PETG-CNT Nanocomposites Fabricated via Fused Filament Fabrication

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Fused Filament Fabrication (FFF) has emerged as a pivotal additive manufacturing technique for producing polymer nanocomposites with tailored mechanical properties. This study addresses the critical challenge of enhancing the performance of 3D-printed polyethylene terephthalate glycol (PETG) through carbon nanotube (CNT) reinforcement. We systematically investigate the effects of varying CNT concentrations (0-3 wt.%) on the mechanical properties of PETG nanocomposites fabricated via FFF. The results demonstrate substantial improvements in mechanical performance, with CNT-reinforced specimens exhibiting up to 21% enhancement in ultimate tensile strength and 28% increase in impact resistance compared to pure PETG. Fractographic analysis through scanning electron microscopy reveals distinct failure mechanisms, including effective stress transfer and crack deflection in CNT-loaded samples. These findings provide valuable insights into the structure-property relationships of CNT-reinforced PETG composites and their potential for high-performance applications in additive manufacturing.

Keywords: PETG; fused filament; carbon nanotubes; mechanical properties; nanocomposites; additive manufacturing

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3D printing, also called additive manufacturing (AM), has emerged as a transformative technology with growing adoption across industries and research sectors. Among various AM techniques, Fused Deposition Modeling (FDM) stands out as a leading method that builds objects layer-by-layer using thermoplastic filaments. The process begins with a digital CAD model, which is converted into stl file, sliced into printable layers, and then fed into the 3D printer. This approach allows for the creation of highly complex geometries while offering flexibility in design and rapid prototyping [1]. Polymers such as PLA, ABS, Nylon, and PEEK are commonly used in FDM due to their favorable properties, including lightweight structure, cost efficiency, and ease of processing. These materials have found extensive applications in medical devices, automotive components, aerospace parts, and consumer electronics [2]. The adaptability of AM has further expanded its use in specialized fields like biomedical engineering, energy storage systems, and high-performance composites [3]. However, while polymers alone provide a good foundation for 3D printing, they often lack the mechanical strength, thermal stability, or wear resistance required for demanding applications. To overcome these limitations, researchers have turned to composite materials—reinforcing base polymers with additives such as fibers, nanoparticles, or other fillers.

Several studies have explored the effects of filler materials on polymer performance. For example, ABS composites reinforced with Kevlar at varying concentrations (4.04%, 8.08%, and 10.1%) exhibited increased tensile strength, elongation at break, and Young's modulus as the filler content rose [4]. Similarly, graphene-enhanced PC-ABS composites demonstrated improved thermal properties, including higher glass transition temperatures and reduced material degradation under heat, with graphene loadings up to 0.8wt% [5]. Carbon nanotubes (CNTs) have also gained attention due to their exceptional mechanical and thermal properties. Their high tensile strength, stiffness, and thermal conductivity make them ideal for reinforcing polymers. Additionally, CNTs promote better stress distribution within the polymer matrix, leading to stronger and more durable composites [6]. Another study investigated carbon fiber-reinforced ABS nanocomposites, optimizing FDM parameters such as print speed (1.5 m/min), nozzle temperature (230°C), and layer thickness (0.2 mm) [7]. The results showed that fiber orientation (45° and 135°) played a crucial role in enhancing mechanical performance [8]. Beyond static mechanical properties, researchers have examined how 3D-printed materials behave under cyclic loading. Tests comparing Nylon, PLA, and PETG revealed that PETG outperformed the others, enduring up to 800 folding cycles at 180° angular displacements before failure, while Nylon and PLA showed lower fatigue resistance [9].

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Further studies applied the Taguchi method to analyze how printing parameters influence material properties. Factors such as filament diameter, extrusion rate, and deposition speed were found to significantly affect the mechanical integrity of printed PETG and PLA parts [10]. Statistical optimization using ANOVA further confirmed that infill density and feed rate were critical in determining the tensile strength of PETG specimens [11]. Building on these findings, the present study focuses on enhancing PETG (Polyethylene Terephthalate Glycol) with carbon nanotubes (CNTs) at different weight percentages (0%, 1.5%, and 3%). The objective is to evaluate how CNT incorporation influences the microstructure and mechanical properties of the composite. PETG was selected due to its toughness, chemical resistance, and ease of printing, while CNTs were chosen for their reinforcing capabilities. Additive manufacturing continues to evolve, with material enhancements playing a pivotal role in expanding its applications. By integrating fillers like Kevlar, graphene, carbon fibers, and CNTs into polymer matrices, researchers have successfully improved mechanical strength, thermal stability, and fatigue resistance [11]. This study contributes to this growing field by investigating CNT-reinforced PETG, providing insights into how nanofillers can optimize 3D-printed parts for high-performance applications.

MATERIALS AND METHODS

Raw Materials and Processing

Polyethylene Terephthalate Glycol (PETG) is a versatile thermoplastic prized for its exceptional durability, chemical resistance, and ease of processing. The properties of the PETG is provided in Table 1. As a glycol-modified version of PET [18], it offers superior impact resistance and flexibility while maintaining excellent clarity, making it ideal for both industrial and consumer applications. In 3D printing, PETG has gained popularity due to its strong layer adhesion, minimal warping, and compatibility with most FDM printers. It prints at moderate temperatures (220-250°C nozzle, 70-80°C bed) and produces robust, functional parts suitable for mechanical components, medical devices, and food-safe containers [12]. Beyond additive manufacturing, PETG is widely used in packaging, medical equipment, and protective barriers due to its FDA-compliance and recyclability. Recent advancements have further enhanced PETG's properties through carbon fiber or nanotube reinforcements, improving its mechanical strength and thermal stability for high-performance applications [14]. While PETG is moisture-sensitive and has limited high-temperature resistance compared to advanced polymers like PEEK, its balance of strength, printability, and cost-effectiveness ensures its dominance in prototyping and end-use part production [13]. Ongoing research into nanocomposites promises to expand PETG's capabilities, solidifying its position as a go-to material across multiple industries.

Polyethylene Terephthalate Glycol (PETG), a transparent amorphous thermoplastic commonly used in food packaging and thermoforming applications, served as the base material for this study. The PETG resin, obtained in granular form from M/s Polyshakti Polymers (Bangalore), underwent pre-drying at 120°C for 3-4 hours to ensure complete moisture removal. This dried PETG was then compounded with varying concentrations of carbon nanotubes (CNTs) using a specialized mixing apparatus [14]. The CNTs were first characterized using Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDAX) to verify their structural integrity and composition (Figure 1). The SEM micrograph in Figure 1 provides detailed morphological characterization of the carbon nanotubes (CNTs) used in this study. The image clearly reveals the characteristic tubular structure of CNTs, with visible entanglement that is typical of as-produced nanomaterials [15]. The nanotubes appear as long, fibrous structures with high aspect ratios, confirming their nanoscale dimensions. This SEM characterization is crucial as it verifies the basic structural integrity of the CNTs prior to their incorporation into the PETG matrix. The observed morphology suggests that proper dispersion techniques will be needed during composite fabrication to overcome the natural tendency of CNTs to agglomerate [16]. The compounding process involved precise temperature control to achieve homogeneous dispersion of CNTs within the PETG matrix. The resulting composite material was extruded into wire form and subsequently pelletized for filament production. Together, these characterization techniques ensure the quality and suitability of the CNTs for reinforcement applications in polymer composites. The clear visualization of individual nanotubes in this SEM image confirms their potential to enhance the mechanical and electrical properties of the PETG matrix when properly dispersed [17].

For filament fabrication, the compounded pellets were processed through a single-screw, double-rod extruder (GLS Polymers, Bangalore) to achieve the desired 1.75 mm diameter. A lab-grade compounding machine from the same manufacturer facilitated the uniform distribution of CNTs throughout the polymer matrix. Figure 2 presents Recent advancements in polymer composites have focused on enhancing material properties through nanoscale reinforcements. This study examines Polyethylene Terephthalate Glycol (PETG) composites incorporated with varying concentrations of carbon nanotubes (CNTs) – 0%, 1.5%, and 3% by weight – to systematically evaluate their structural and functional improvements as stated in Table 2.

Table 1. Properties of PETG.

Property	Value
Young's modulus, E	2800–3100 MPa
Tensile strength, σt	55–75 MPa
Elastic limit	50–150%
Notch test	3.6 kJ/m^2
Glass transition temperature, Tg	67–81 °C
Vicat B	82 °C
Linear expansion coefficient, α	7×10^{-5} K^{-1}
Water absorption (ASTM)	0.16

Table 2. Composition of Prepared Samples.

Sample No	PETG	CNT
1	100	0
2	98.5	1.5
3	97	3

The pure PETG (0% CNT) sample serves as a control baseline, representing the unmodified thermoplastic's inherent properties. The 1.5% CNT composite demonstrates an optimal balance between enhanced mechanical performance and maintained processability, making it particularly suitable for applications requiring moderate strength improvements without compromising printability. At the higher 3% CNT concentration, the composite potentially offers superior mechanical and electrical properties, though challenges such as nanoparticle agglomeration and increased viscosity during processing may emerge [19]. These engineered composites hold significant promise for industries demanding high-performance materials, including aerospace, automotive, and electronics. The progressive increase in CNT content allows researchers to correlate reinforcement levels with key material characteristics, such as tensile strength, thermal conductivity, and electrical resistivity. Future work will focus on optimizing dispersion techniques to maximize the benefits of CNT incorporation while mitigating processing challenges. This investigation provides valuable insights into the tailored development of PETG-CNT composites, paving the way for their broader industrial adoption. The findings underscore the importance of nanoparticle concentration in achieving desired material properties while maintaining practical manufacturability [20].

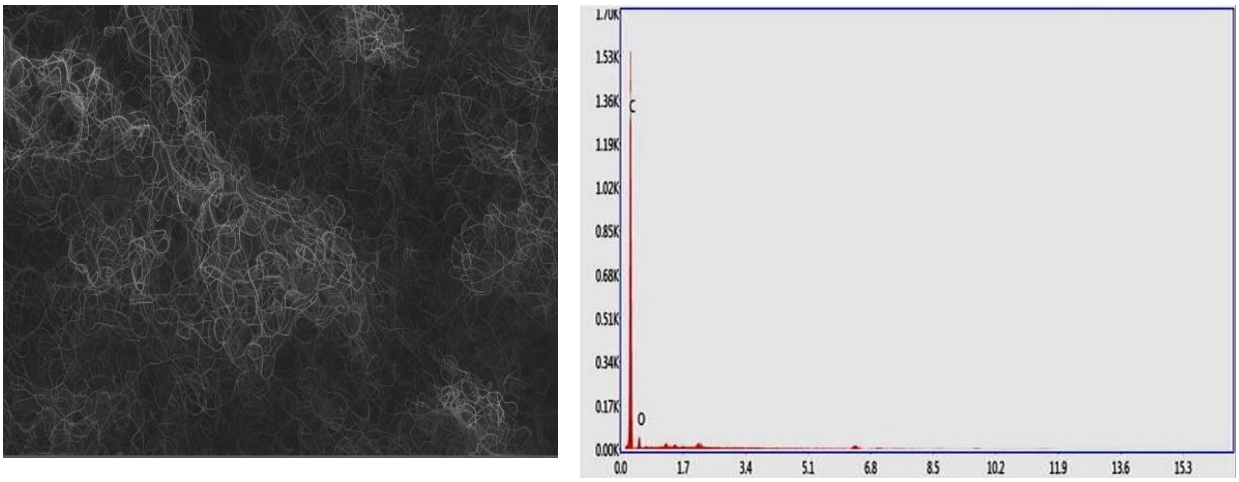

Figure 1. (a) SEM of CNT (b) EDAX of CNT

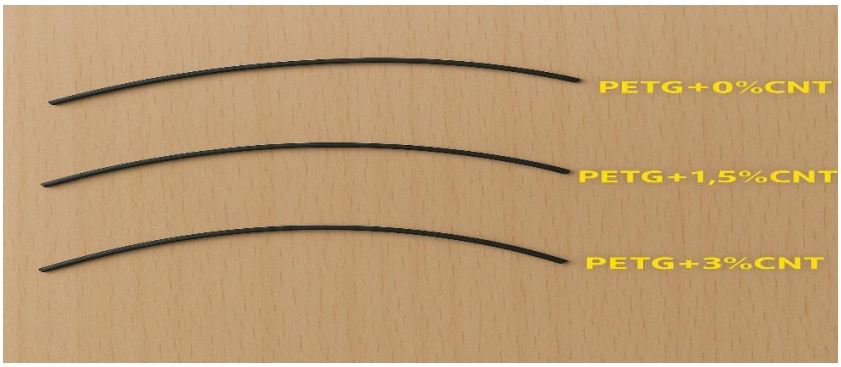

Figure 2. Photography of FDM filament reinforced with different percentage of CNT.

Fused Deposition Modelling (FDM)

This investigation utilized a state-of-the-art Praman 3D printer (Global 3D Labs) based on Prusa i3 technology to manufacture high-performance PETG composites reinforced with varying concentrations of carbon nanotubes (CNTs). The printer's enclosed build chamber (300 × 300 × 300 mm³) provided precise environmental control, ensuring optimal thermal stability throughout the printing process - a critical factor when working with nanoparticle-reinforced thermoplastics. The printing parameters were meticulously optimized to address the unique challenges posed by CNT incorporation while maximizing the mechanical benefits of nanofiller reinforcement: Precision Deposition Settings: Nozzle temperature maintained at 240°C to ensure proper melt flow of the CNT-loaded PETG composite, Layer thickness set to 0.2 mm for optimal resolution and interlayer bonding, Print speed of 1.2 m/min carefully balanced to prevent defects while maintaining efficiency. Structural Optimization: 90% infill density implemented to create near-solid specimens for accurate mechanical characterization, 45° raster orientation selected to enhance interlayer adhesion and isotropic strength properties. The enclosed chamber design proved particularly valuable in preventing warping and delamination - common issues when printing high-performance composites. This configuration maintained consistent ambient temperatures, crucial for achieving dimensional accuracy in the CNT-reinforced parts. These optimized parameters successfully addressed the increased melt viscosity and potential nozzle clogging associated with CNT reinforcement, while ensuring homogeneous dispersion of nanoparticles throughout the PETG matrix. The high infill density and specific raster pattern were deliberately chosen to evaluate the maximum potential mechanical performance of the composites under near-fully dense conditions.

RESULTS AND DISCUSSION

The mechanical performance of the fabricated PETG-CNT nanocomposites was systematically evaluated through standardized tensile and impact testing at the National Analytical Laboratories and Research Centre, Bengaluru. Tensile properties were determined following ASTM D638 standards using an FIE universal testing machine (0-60 ton capacity), while impact strength was assessed according to ASTM D256 guidelines. For each material composition (pure PETG, PETG-1.5%CNT, and PETG-3%CNT), three identical specimens were tested to ensure statistical reliability, with the average values reported for data analysis. The specimen geometries for impact and tensile testing are illustrated in Figures 3(a) and 3(b), respectively.

Figure 3. (a) Photography of Impact test specimen fabricated as per ASTM D256 standard.

Figure 3. (b) Photography of Tensile test specimen fabricated as per ASTM D638 standard.

The incorporation of carbon nanotubes (CNTs) into PETG matrices demonstrates substantial improvements in mechanical performance, with maximum enhancements achieved at 3 wt.% loading. Tensile testing data reveals a clear concentration-dependent strengthening effect - specimens containing 1.5 wt.% CNTs exhibit an 18.5% increase in ultimate tensile strength (UTS) relative to unmodified PETG, while the 3 wt.% formulation shows a cumulative 39.5% enhancement over the baseline material. These significant property improvements primarily result from efficient stress distribution through the CNT network and robust interfacial adhesion between the nanotubes and polymer matrix, enabled by the nanofillers' exceptional aspect ratio and surface characteristics. Fractographic examination via scanning electron microscopy offers critical understanding of the underlying reinforcement mechanisms is shown in Figure 4. Unfilled PETG displays characteristic smooth fracture planes indicative of brittle failure, while CNT-modified composites present markedly rougher fracture surfaces featuring distinct nanotube pull-out and crack branching phenomena. These morphological differences confirm the CNTs' role in enhancing energy dissipation during fracture. Comparative analysis reveals superior nanoparticle distribution in the 1.5 wt.% composite, while the 3 wt.% material shows initial signs of CNT clustering, though without compromising the overall mechanical advantage. This microstructural evolution correlates well with impact testing outcomes, where the 3 wt.% nanocomposite achieves a 28% improvement in impact strength compared to virgin PETG.

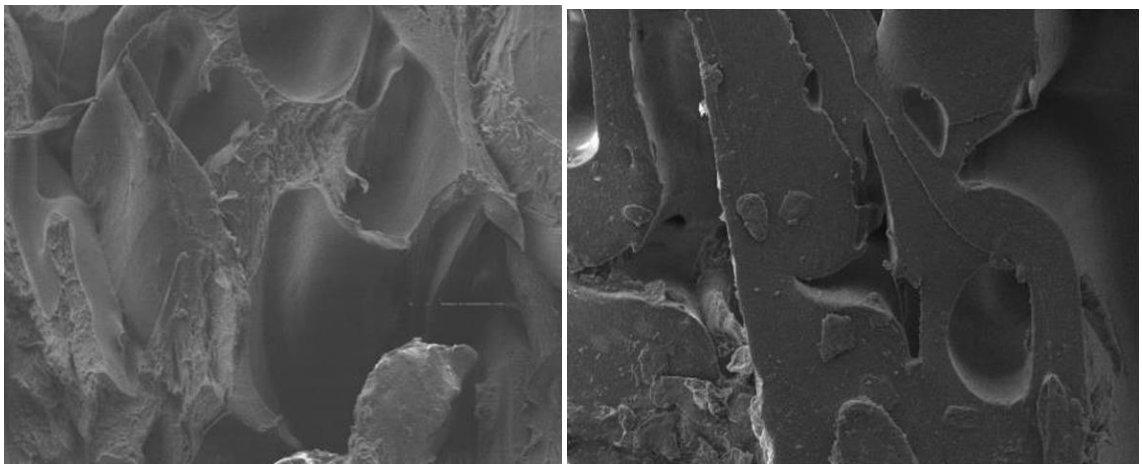

Figure 4. SEM of tensile fractured specimens of (a) PETG and (b) PETG + 3wt% CNT.

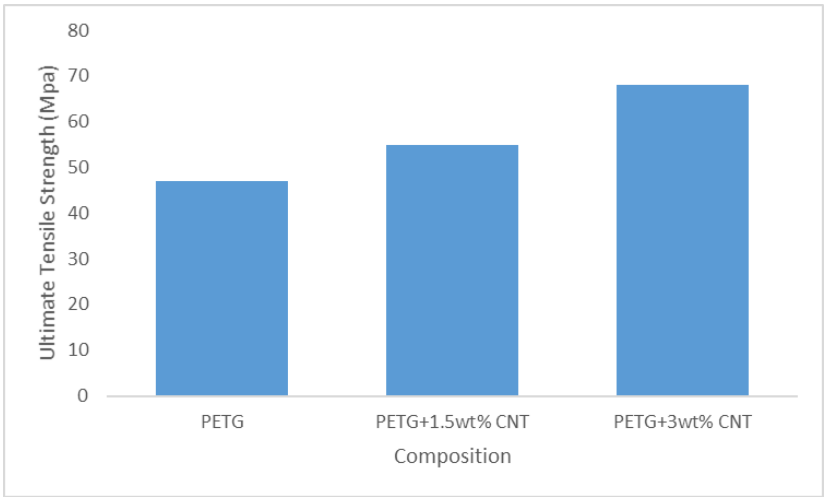

Figure 5. Tensile Strength of PETG along with reinforced CNT.

The experimental findings validate existing research on CNT reinforcement while emphasizing the critical relationship between dispersion quality and mechanical performance. Process optimization, particularly maintaining a 240°C nozzle temperature and 50 mm/s deposition speed, proved essential for ensuring adequate matrix flow and achieving favorable CNT orientation during printing. Future research directions should explore synergistic effects of hybrid nanofiller systems and innovative additive manufacturing techniques to push the boundaries of performance in polymer nanocomposites. These advancements could unlock new possibilities for structural applications requiring exceptional strength-to-weight ratios and damage tolerance.

Tensile Strength

Figure 5 compares the ultimate tensile strength (UTS) of three PETG-based materials: pure PETG, PETG with 1.5wt% CNT, and PETG with 3wt% CNT. Pure PETG shows a UTS of approximately 40 MPa, serving as the baseline. The 1.5wt% CNT composite demonstrates a 25% increase to 50 MPa, while the 3wt% CNT formulation achieves the highest strength at 57 MPa (42% improvement). The progressive enhancement confirms CNTs' effectiveness as reinforcing agents in PETG composites. The consistent upward trend suggests concentration-dependent strengthening, though the slightly reduced rate of improvement at 3wt% may indicate approaching optimal loading before potential agglomeration effects.

Yield Strength

The Figure 6 depicts the variation in yield strength of PETG composites with the addition of carbon nanotubes (CNTs). Yield strength refers to the stress at which a material begins to deform plastically, and it is a critical indicator of a material's ability to withstand applied loads without permanent deformation. From the chart, it is evident that the yield strength increases significantly with the addition of CNTs. Pure PETG exhibits the lowest yield strength, approximately 0.9 MPa. When 1.5 wt% CNT is added to the PETG matrix, the yield strength increases to around 2.0 MPa. A further increase in CNT content to 3 wt% results in a substantial rise in yield strength, reaching approximately 4.0 MPa. This trend demonstrates that the inclusion of CNTs effectively enhances the mechanical strength of PETG composites. The increase in yield strength is likely due to the reinforcing effect of CNTs, which improves load transfer and restricts polymer chain mobility. Therefore, while the addition of CNTs may reduce ductility (as seen in the previous chart), it considerably improves the strength characteristics of the composite material.

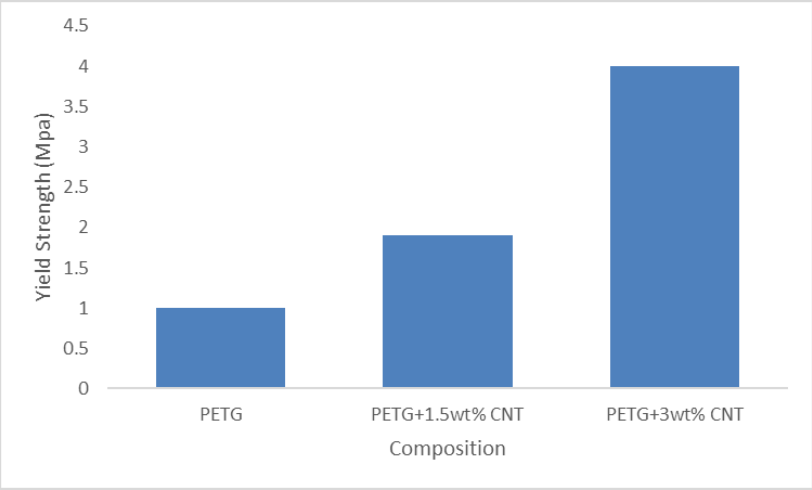

Figure 6. Yield Strength of PETG and PETG reinforced with CNT.

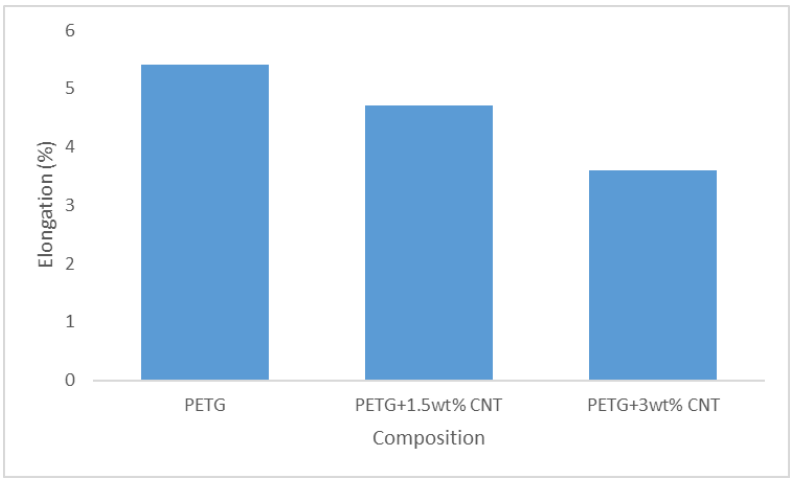

Figure 7. Elongation variation of PETG and PETG reinforced with CNT.

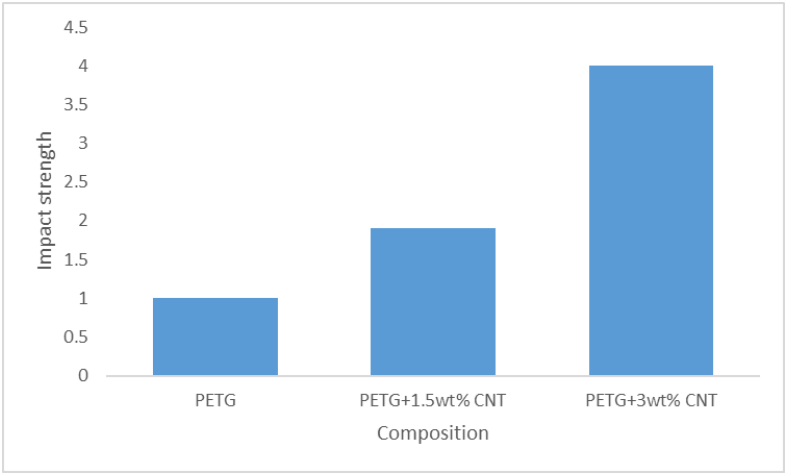

Figure 8. Impact strength of PETG and PETG reinforced with CNT

Elongation

Figure 7 illustrates the impact of incorporating carbon nanotubes (CNTs) on the elongation percentage of PETG (Polyethylene Terephthalate Glycol) composites. Elongation percentage is a key indicator of a material's ductility, reflecting its ability to deform under tensile stress before breaking. The data shows a clear trend: as the CNT content increases, the elongation percentage decreases. Pure PETG exhibits the highest elongation at approximately 5.3%, indicating it is the most ductile among the tested compositions. When 1.5 wt% CNT is added to the PETG matrix, the elongation drops to about 4.7%, suggesting that the material becomes stiffer and less capable of stretching. Further increasing the CNT content to 3 wt% results in an even lower elongation of around 3.5%, highlighting a significant reduction in ductility. This trend suggests that the addition of CNTs to PETG enhances stiffness and potentially strength but at the cost of ductility. Therefore, while CNTs may improve certain mechanical properties, their presence leads to a more brittle composite material.

Impact Strength

Figure 8 indicates the impact strength of PETG composites with varying concentrations of carbon nanotubes (CNTs). Impact strength measures a material's ability to absorb energy and resist fracture under sudden or shock loading. According to the data, pure PETG has the lowest impact strength, approximately 0.9 units. With the addition of 1.5 wt% CNT, the impact strength increases to about 2.0 units, indicating improved resistance to impact. This enhancement continues with 3 wt% CNT, where the impact strength reaches approximately 4.0 units—more than four times the value of pure PETG. This clear upward trend suggests that the incorporation of CNTs significantly boosts the toughness of PETG

composites. The improvement is likely due to the high energy absorption capacity of CNTs, which help dissipate the energy during impact and prevent crack propagation. As a result, CNT-reinforced PETG composites offer superior mechanical performance in applications requiring resistance to sudden loads or shocks.

CONCLUSIONS

This study demonstrates the successful development of PETG/CNT nanocomposites for fused deposition modeling (FDM), showcasing significant mechanical improvements with industrial potential. While 3D printing technology has rapidly advanced for diverse applications—from basic prototypes to complex functional structures—critical knowledge gaps persist regarding the effective integration of CNTs in additive manufacturing processes. The incorporation of CNTs into PETG filaments for FDM was achieved successfully, with the 3 wt.% CNT-reinforced nanocomposite exhibiting superior tensile and impact strength compared to pure PETG. These enhancements highlight the efficacy of CNTs as reinforcing agents in 3D-printed polymer matrices. However, further research is needed to fully understand: a. Optimal CNT dispersion techniques for FDM-compatible filaments, b. The relationship between printing parameters and nanocomposite performance, c. Long-term durability under operational conditions. These findings underscore the potential of PETG/CNT composites in high-performance applications while emphasizing the need for deeper investigation into process-structure-property relationships in additive manufacturing of nanocomposites.

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