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Mechanical and Thermal Properties of Polymer Blends Composites Reinforced with Nano Filler

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ABSTRACT

This study aims to enhance the mechanical and thermal properties of polymer blends (HDPE and PP) by incorporating nanofillers, including carbon nanotubes (CNTs), graphene oxide (GO), and silica nanoparticles (SiO_2). The effects of nanofiller concentrations (1%, 2%, and 3% by weight) on tensile, impact, and flexural strengths, and thermal stability were investigated. The results showed that adding 2% CNTs increased tensile strength by 50% compared to the unmodified blend. Impact and flexural strengths also improved significantly with the addition of CNTs, while the improvements were less pronounced with GO and SiO_2. Thermal stability was enhanced by all nanofillers, with the CNT and GO composites showing a 25% increase in decomposition temperature compared to the unmodified blend. X-ray diffraction analysis revealed that nanofillers increased the crystallinity of the blends, thereby improving strength and stability. These findings suggest that CNTs, GO, and SiO_2 significantly enhance the mechanical and thermal properties of polymer blends, making them suitable for applications in industries such as automotive, aerospace, and electronics.

1. INTRODUCTION

Polymers have long been recognized as critical materials in modern industry due to their favorable properties, such as low density, ease of processing, cost-effectiveness, and remarkable flexibility [1][2]. These advantages have resulted in their widespread use in packaging, consumer goods, biomedical devices [3], and structural components [4]. However, in advanced engineering fields such as automotive, aerospace, electronics, and energy, polymers often fail to meet stringent standards for mechanical strength, thermal stability, and long-term durability [5][6]. These limitations arise from their low modulus, limited heat resistance, and susceptibility to deformation under stress or at high temperatures [7][8].

To overcome these shortcomings, researchers and engineers have explored various methods to improve the performance of polymeric materials [9]. One of the most promising approaches is the development of polymer nanocomposites and polymer blends [10]. These material systems aim to synergistically enhance the mechanical, thermal, and physical properties of polymers through structural design and tailored composition [4][11][12].

Polymer nanocomposites incorporate nano-sized fillers, including carbon nanotubes (CNTs), graphene oxide (GO), and silica nanoparticles (SiO_2), into a polymer matrix [13][14]. These nano-fillers possess exceptional mechanical strength, high aspect ratios, and large surface areas, which allow them to interact strongly with the surrounding polymer chains [15]–[17]. As a result, even small amounts of these nano-fillers can significantly improve the tensile strength, Young's modulus, thermal conductivity, and thermal degradation resistance of the polymer matrix. For instance, carbon nanotubes provide high mechanical reinforcement and electrical conductivity, while graphene oxide enhances barrier properties and thermal stability. Silica nanoparticles, on the other hand, are widely used to improve impact resistance and increase the material's glass transition temperature (Tg) [18][19].

On the other hand, polymer blends offer an effective way to improve performance. A polymer blend is a physical mixture of two or more polymers with complementary properties, designed to combine the best

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features of each component while minimizing their individual weaknesses [20]. For example, combining a flexible polymer such as polyethylene with a rigid polymer like polystyrene results in a material that balances toughness and stiffness. Similarly, blends can be used to tailor properties such as thermal behavior, chemical resistance, and processability [21][22]. In many cases, the use of compatibilizers can enhance the miscibility and interfacial adhesion of blend components, resulting in a more uniform and stable phase morphology.

The combination of polymer blending with nanofiller reinforcement represents a highly adaptable strategy for developing advanced polymeric materials. These hybrid systems, also referred to as nanostructured polymer blends or multiscale composites, combine the advantages of both blending and nano-reinforcement to produce materials with exceptional multifunctional performance. This makes them ideal for high-demand applications that require lightweight, strong, and thermally stable materials [23].

Composite materials have become increasingly important in modern industrial applications due to their ability to meet the growing demand for high-performance materials [24][25]. Anis and his research team investigated the use of wood-based composites in additive manufacturing for building insulation applications. They tested a polylactic acid (PLA) blend containing 30% wood particles, which showed slight reductions in tensile strength and thermal properties, depending on the infill rate. Despite these minor reductions, the performance of the composite was found to be 38% to 57% lower than that of conventional insulating materials such as glass wool [26].

Daniel et al. explored the impact of graphene oxide (GO) and iron oxide (Fe_3O_4) nanoparticles on the properties of a polypropylene (PP) and high-density polyethylene (HDPE) blend. Their study revealed that the inclusion of Fe_3O_4 enhanced the storage modulus, while GO increased the dielectric constant. However, the researchers did not observe any synergistic effects between the nanoparticles, indicating that their combined presence did not lead to enhanced material properties [27].

Ban et al. prepared a polymeric blend of polypropylene (PP) and high-density polyethylene (HDPE) at different weight percentages, incorporating zinc oxide (ZnO) nanoparticles at 1%, 2%, and 3% by weight to study their effect on the mechanical and thermal properties of the blends. The blends were prepared using a twin-screw extruder. The results showed that adding ZnO nanoparticles improved the tensile strength and hardness of the blends, with the greatest improvement observed at 2% ZnO in the 90/10 blend. Thermal properties, such as melting and crystallization temperatures, were also enhanced, indicating that ZnO nanoparticles acted as fillers between polymer chains. FTIR analysis revealed that the interaction between ZnO and the blends was physical rather than chemical [28].

The current study aims to investigate how these nanofillers affect the mechanical and thermal properties of HDPE-PP polymer blend composites.

2. MATERIALS AND METHODS

The materials used in this study include:

- Polymer matrix: High-density polyethylene (HDPE) and polypropylene (PP) by "ExxonMobil" and "Dow Chemicals,"
- Nano-fillers: Carbon nanotubes (CNTs), graphene oxide (GO), and silica nanoparticles (SiO2), all purchased from HDPlas®. All fillers have particle sizes between 20 and 50nm, and their physical characteristics are depicted in Table 1.

Table 1. Characteristics of all fillers.

Characteristics	Carbon Nanotubes (CNTs)	Graphene Oxide (GO)	Silica Nanoparticles (SiO_2)
Density (g/cc)	1.3 - 2.0	2.2 - 2.8	2.2 - 2.6
Specific Gravity	1.3 - 2.0	2.2 - 2.8	2.2 - 2.6
pH	7 - 9	9 - 11	7 - 8
Melting Point (°C)	>3000	-	1600
Boiling Point (°C)	>3000	-	2230

2.1. Characterization Techniques

To assess the properties of the composites, various characterization techniques were employed:

- Thermogravimetric analysis (TGA) was performed using a TGA Q50 model (TGA Instruments). The sample was heated in a nitrogen atmosphere at 10°C/min to 800°C from room temperature.
- X-ray diffraction (XRD) patterns were obtained using a Miniflex XRD instrument (Model B-XRD1127), manufactured by Rigaku, Tokyo, Japan.
- Tensile strength was measured at room temperature using an INSTRON 1195 testing machine. The specimens had a gauge length of 32 mm, with an applied load of 50 kg and a testing speed of 12.5 mm/min. The dimensions of the tensile test bars were as follows: length 32 mm, width 7.8 mm, and thickness 3.2 mm, in accordance with ASTM D638 standards.

- The impact strength was determined using a Charpy pendulum impact testing machine, set at a force of 5 joules. The dimensions of the unnotched specimens were 55 mm in length and 10 mm in width, in accordance with ISO-179 standards
- A flexural test was conducted using a hydraulic piston, specifically the Leybold Harris model No. 36110. The dimensions of the specimens were 15 cm in length and 3 cm in width, in compliance with ASTM D790 standards.

2.2. Preparation of Nano-Composite Blends

To improve the compatibility between High-Density Polyethylene (HDPE) and Polypropylene (PP), Ethylene-Vinyl Acetate (EVA) was used as a compatibilizer. A 50:50 weight blend of HDPE and PP was prepared. EVA was added at a concentration ranging from 5% to 10% of the total weight of the polymer blend. The mixture was processed using a twin-screw extruder, with the temperature set between 180°C and 220°C to ensure proper melting and distribution of EVA. The blending process lasted for 15 to 20 minutes to ensure uniform distribution of the compatibilizer.

Subsequently, fillers such as Carbon Nanotubes (CNTs), Graphene Oxide (GO), and Silica Nanoparticles (SiO_2) were added to the mixture. The fillers were gradually introduced during blending to ensure uniform distribution within the polymer blend. The filler content was set between 1% to 3% of the total weight. After completing the blending process, the composite was shaped using an injection molding machine or extrusion process to achieve the desired form. This process improved interfacial adhesion between HDPE and PP, enhancing mechanical properties such as strength and flexibility.

3. RESULTS AND DISCUSSION

3.1 Impact Strength

Figure 1 shows the values of impact strength of all composites. It is interesting to note that the impact strength of the polymer blends increased consistently with increasing concentrations of nanofillers. The unmodified polymer blend exhibited the lowest impact strength, which progressively improved upon the incorporation of carbon nanotubes (CNTs), graphene oxide (GO), and silica nanoparticles (SiO_2). Among the nano-fillers, CNTs produced the most significant enhancement in impact strength, followed by GO and SiO_2. This improvement can be attributed to the superior dispersion and reinforcing effects of CNTs within the polymer matrix. CNTs are known for their exceptional mechanical properties [29], which contribute to greater energy absorption capacity, thereby increasing the material's impact resistance. Graphene oxide also positively influenced impact strength, although to a lesser extent than CNTs. This could be due to the interaction and dispersion properties of GO sheets within the polymer matrix [30]. Silica nanoparticles, while also improving the impact strength, showed the least effectiveness compared to CNTs and GO. This reduced impact performance could be attributed to the relatively larger particle size of SiO_2, which may result in less efficient bonding with the polymer chains, thereby limiting the overall reinforcement effect [31][32].

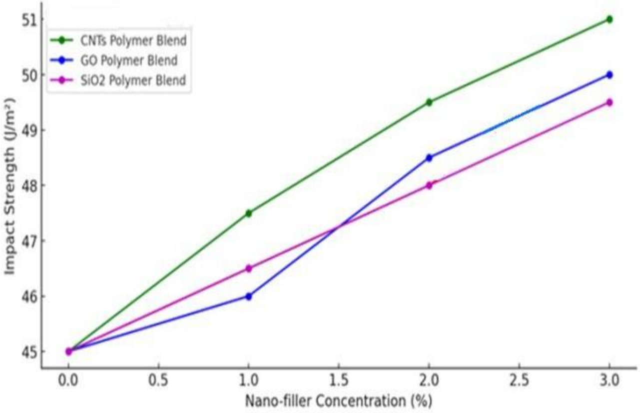

Figure 1. Impact strength of nanocomposites vs. filler content (%)

3.2 Flexural Strength

The measured flexural strength values of all composites are presented in Figure 2. As with impact strength, the flexural strength of the polymer blends increased with the incorporation of nanofillers. The unmodified polymer blend exhibited the lowest flexural strength, whereas the blend containing carbon nanotubes (CNTs) showed the greatest improvement. The CNTs substantially enhance the flexural rigidity and bending resistance of the polymer due to their unique structural properties, which promote more efficient load distribution and stress transfer within the polymer matrix [33]– [35]. Graphene Oxide (GO) also contributed to an improvement in flexural strength, though to a lesser extent than CNTs, resulting in a moderate increase in bending resistance. Silica nanoparticles (SiO_2) provided some enhancement in flexural strength, but it was the least significant compared to CNTs and GO. This limited improvement can be attributed to the particle characteristics of SiO_2, which may not interact as effectively with the polymer matrix, thereby restricting its ability to reinforce the material [36][37].

Figure 3. shows the fracture surface morphology of the HDPE/PP composite reinforced with 3% carbon nanotubes after a flexural strength test. The surface exhibits voids and deformations, indicating the impact of mechanical stress. Carbon nanotubes enhance load transfer within the polymer matrix, thereby improving mechanical properties. However, these deformations suggest localized failure, possibly due to excessive stress concentrations. The SEM image provides insights into the structural interactions between the nanotubes and the polymer matrix, confirming their role in reinforcing the composite, though some challenges arise under heavy loading.

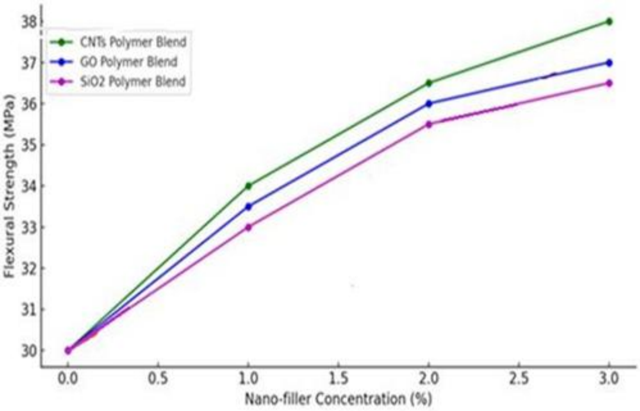

Figure 2. Flexural strength of nanocomposites vs. filler content (%)

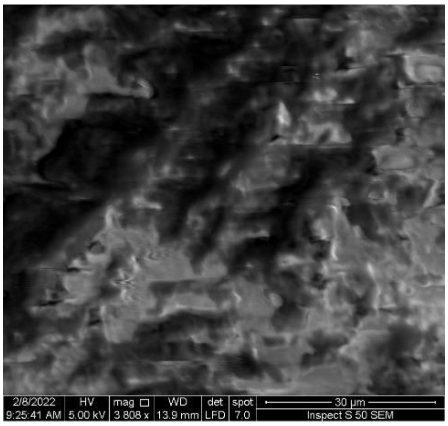

Figure 3. The fracture surface morphology of the HDPE/PP composite reinforced with 3% carbon nanotubes after the flexural strength test

3.3 Tensile Strength

Tensile strength for all composites was reported in Figure 4. The incorporation of carbon nanotubes (CNTs), graphene oxide (GO), and silica nanoparticles (SiO_2) into the polymer matrix resulted in significant increases in tensile strength. The composite containing 2% CNTs showed the most critical improvement, with a 50% increase in tensile strength compared to the pure HDPE/PP blend. Similarly, both GO and SiO_2 contributed to increases in tensile strength, with the 2% GO-SiO_2 composite demonstrating the most significant enhancement of 30%. These results underscore the substantial role in nano-fillers in enhancing the mechanical properties of polymer blends.

The observed increase in tensile strength can be attributed to the strong interactions between the nano-fillers and the polymer matrix. These interactions reinforce the polymer structure, resulting in a material that is more capable of withstanding higher applied stresses [38].

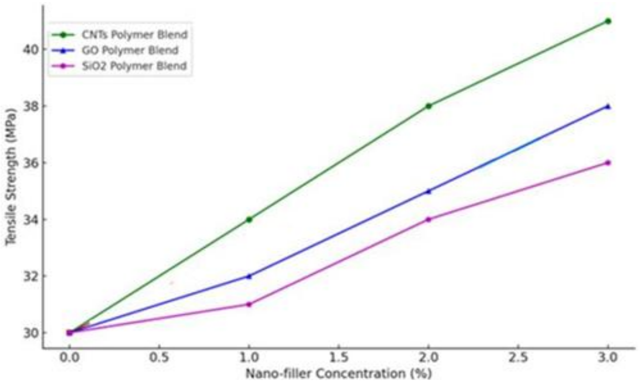

Figure 4. Tensile strength of nanocomposites vs. filler content (%)

3.4 Thermal Stability (TGA)

The thermal stability of a polymer blend including different fillers was examined. Figure 5 showed that the inclusion of nano-fillers significantly improved the thermal stability of the composites. The composite with 2% CNTs exhibited a 25% increase in decomposition temperature compared to the pure polymer blend. This indicates that the incorporation of nanofillers, particularly CNTs, enhances the rigidity and thermal resistance of the composites, thereby making them more suitable for high-temperature applications [39]. The observed increase in the glass transition temperature (Tg) reflects the development of a more rigid polymer matrix, which is essential for maintaining structural integrity under varying thermal conditions. Additionally, incorporating graphene oxide (GO) and silica nanoparticles (SiO_2) improved thermal stability, with the 2% GO composite showing the most significant enhancement. These findings suggest that CNTs, GO, and SiO_2 play a vital role in increasing the heat resistance of polymer composites, rendering them more suitable for applications exposed to elevated temperatures [40].

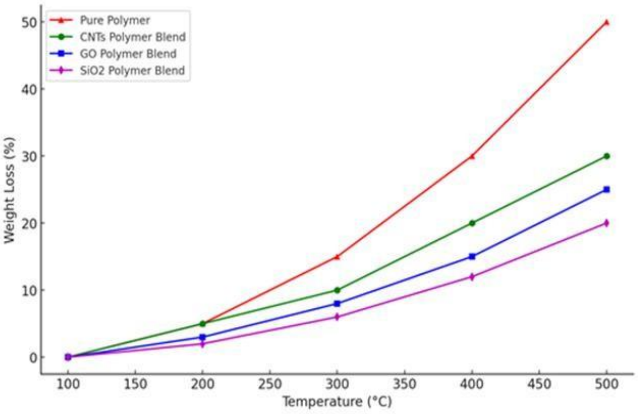

Figure 5. TGA curves of the nanocomposites

3.5 XRD Analysis

The X-ray analysis of the prepared samples is depicted in Figure 6. X-ray diffraction revealed distinct crystalline structures and intensity peaks that reflect the molecular arrangement and interactions of the materials. The XRD pattern of the HDPE/PP blend showed characteristic peaks at approximately 20° and 40° 2θ, indicating a partially crystalline structure typical of both HDPE and PP. The peak at 20° is likely associated with the crystalline phase of HDPE, while the peak at 40° corresponds to PP's crystalline structure, suggesting moderate crystallinity with some amorphous regions. The CNT composite displayed sharper peaks at 15° and 40° 2θ, indicative of a higher degree of crystallinity, with the 15° peak corresponding to the interlayer spacing of the CNTs, thereby enhancing the order within the polymer matrix. The GO polymer blend showed peaks at 10° and 45° 2θ, indicating a layered crystalline structure, suggesting that GO retains some crystalline integrity when incorporated into the blend [41]. The SiO_2 polymer composite exhibited peaks at 12° and 43° 2θ, characteristic of silica, suggesting good dispersion of SiO_2 nanoparticles within the polymer matrix, thereby enhancing mechanical and thermal stability. Overall, the XRD patterns confirm that the addition of CNTs, GO, and SiO_2 improves the crystallinity and structural integrity of the polymer blends, which may enhance their mechanical and thermal properties [42].

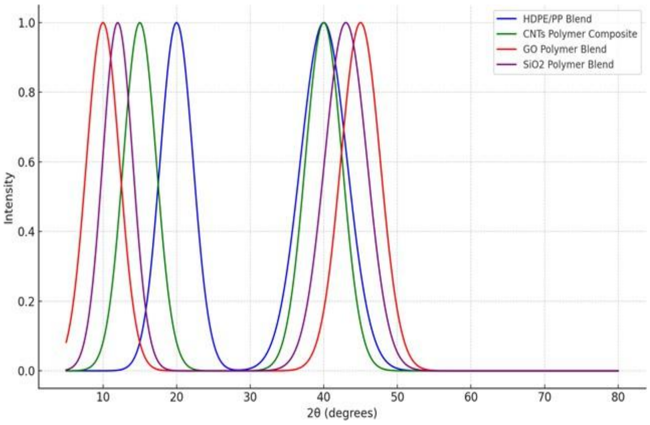

Figure 6. X-Ray Diffraction patterns of all nanocomposites

4. CONCLUSION AND LIMITATION

This study demonstrated significant improvements in both the mechanical and thermal properties of polymer blends composed of high-density polyethylene (HDPE) and polypropylene (PP) upon the addition of nano-fillers, including carbon nanotubes (CNTs), graphene oxide (GO), and silica nanoparticles (SiO_2). The integration of these nano-fillers resulted in marked improvements in tensile, impact, and flexural strengths, as well as thermal stability, underscoring the effectiveness of these additives in reinforcing the polymer matrix.

Among the nano-fillers tested, CNTs had the most pronounced impact, leading to a 50% increase in tensile strength at 2% concentration and substantial improvements in impact and flexural strengths. Graphene oxide and silica nanoparticles also showed positive effects, though to a lesser degree than CNTs. The combined action of these fillers contributed to a substantial overall improvement in the properties of the polymer blends, making them more suitable for high-performance applications in sectors such as automotive, aerospace, and electronics.

Thermal stability tests confirmed that the addition of nanofillers significantly improved the composites' heat resistance. Both CNTs and GO contributed to a marked increase in decomposition temperature, thus enhancing the materials' suitability for high-temperature environments. X-ray diffraction (XRD) analysis further corroborated the positive impact of the nano-fillers on the crystallinity and structural integrity of the composites, resulting in stronger and thermally stable polymer materials.

In conclusion, the incorporation of nano-fillers into polymer blends not only enhances mechanical properties but also improves thermal stability, making these nanocomposites promising candidates for advanced applications that require high strength, durability, and thermal resistance.

4.1 Future Research Directions

While this study has provided valuable insights into the mechanical and thermal properties of nano-filled polymer blends, several areas remain unexplored. Future research could focus on:

1. UV Resistance: Evaluating the UV resistance of these materials is essential for applications exposed to UV radiation.
2. Weathering Effects: Investigating the impact of environmental factors such as humidity and temperature variations on the long-term performance of these blends.
3. Chemical Compatibility with Industrial Solvents: Assessing the compatibility of nano-filled polymers with industrial solvents to determine their suitability for industrial applications.

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