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OPTIMIZATION OF CARBON NANOTUBE REINFORCEMENT FOR ENHANCED MECHANICAL PERFORMANCE OF POLYMER NANOCOMPOSITES

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Article Info

Abstract

Carbon nanotube CNT reinforcement strategy to advanced polymer based material applications is a fascinating approach of filling and strengthening in order to improve mechanical, thermal, electrical and other properties of nanocomposite. This paper aims at setting up a solid understanding of the impact that dispersion of CNT, functionalization of CNT and concentration of load in polymer composite has on its mechanical properties. It was also found that lengthened CNT has better dispersion and better mechanical properties, both tensile strength and Young's modulus, and fracture toughness were enhanced with an optimum value at 3 wt% CNT. From the results it can be concluded that properly dispersed CNTs improved the load transfer efficiency and on the contrary; higher content of CNTs may cause the formation of agglomerated clusters which restrict stress distribution and mechanical properties. Electrical conductivity data show that there is the percolation concentration of CNT being at 3 wt%, which leads to the transition from insulating material to conductive one. Also, the thermal conductivity increases as the CNT contents increase, but there is a limit of improvement since phonon scattering at high CNT content begins to hinder the improvement. SEM and TEM evidence for CNT dispersion to 3 wt% reveal the good agreement with the relationship between high CNT homogeneity and improvements in material properties. This work emphasizes the importance of surface-modification of CNTs, dispersion methods, and processing techniques for improving the properties of nanocomposites. The results are of importance for aerospace, automobile, and electronic industries because such invention demands lightweight, strong, and thermally conductive materials. Further studies should be devoted to the investigation of the combined use of CNTs and other types of reinforcements and to the development of efficient large-scale processing technologies for controlled CNT dispersion and alignment, which would lead to steady mechanical reinforcement in practical applications.

Keywords: *Carbon Nanotubes (CNTs), Polymer Nanocomposites, Mechanical Properties, Tensile Strength, Young's Modulus, Fracture Toughness, Dispersion Optimization, Electrical Conductivity, Thermal Conductivity, Functionalization, Percolation Threshold, Load Transfer Efficiency, Agglomeration, Stress Distribution, Advanced Materials..*

Introduction

Polymer nanocomposites have emerged as an important field of research during the last two decades as these products have shown improved mechanical, thermal and electrical characteristics as compared to the conventional polymer composites. Carbon nanotubes, in particular, have been in focus for enhancing the mechanical properties of the polymer matrices that can be used in manufacturing of light weight high strength materials that can find a variety of applications in industry. CNTs possess high elastic modulus of about 1 TPa for Young's modulus and tensile strength about 100GPa and thus are suitable for improving properties of polymer based materials (Iijima, 1991; Rafiee et al., 2010). However, some of the key issues such as the dispersion, weak interfacial adhesion, and processing difficulties still pose severe drawbacks to these composites such that the full reinforcement potential of CNTs in polymer nanocomposites is not fully realised (Ajayan, Schadler, & Braun, 2003; Coleman et al., 2006).

The use of CNTs to enhance the polymer matrix composites enhance some properties such as stiffness, toughness, and fatigue strength that are relevant in Aerospace, automobile, and biomedical applications (Salvetat and others, 1999; Moniruzzaman and Winey, 2006). Research shows that addition of CNTs into the polymer matrix at less than 5wt% improves the tensile strength and modulus of the resulting composites (Kumar et al., 2010; Kim et al., 2012). However, such enhancements calls for several parameters that include the dispersion method, CNT alignment, surface treatment, and overall processing condition, which determines the degree of reinforcement and stress transfer between CNTs and the polymer matrix (Spitalsky et al., 2010; Hu et al., 2017).

The first limitation of CNT-reinforced polymer nanocomposites is that the CNTs tend to agglomerate since they possess strong van der Waals forces of attraction. These trends cause an inhomogeneous dispersion of CNTs within polymers which result in stress concentration areas that impose bad characteristics of load transfer and sometimes poor mechanical properties compared to the expected results (Coleman et al., 2006; Gojny et al., 2005). Dispersing CNTs evenly is as much a challenge to date, depending on the methods of processing and dispersion that have to be chosen.

One of the major challenges frequently observed in most of the CNT-reinforced composites is the poor interface interaction between CNT and polymer chains. As mentioned earlier, pristine CNTs possess a smooth structure and possess a low density of functional groups to interact chemically with polymer molecules, thus poor stress transfer is experienced under mechanical loads (Zhang & Wang, 2010, Yu et al., 2000). In such a case, CNTs may afford to move within the matrix without imparting the reinforcement characteristic. Different methods of functionalization have also been used in order to improve the interfacial adhesion including chemical reactions such as acidosol and oxidation, and grafting of polymers on carbon nanotubes (Peng et al., 2008; Bal & Samal, 2007).

They also involve aspects in the processing conditions in an attempt to enhance the CNT-reinforced polymer nanocomposites in their performance. Techniques such as melt blending and solution casting are not effective enough in providing satisfactory dispersion and controlled orientation of CNTs, which leads to isotropic properties of material (Bekyarova et al., 2007; Spitalsky et al., 2010). Some of the progression techniques employed for CNT alignment as well as distribution include electric field processing, magnetic field processing and shear processing during polymerization processing (Qian et al., 2000; Thostenson, Ren & Chou, 2001). The study has further revealed that the alignment of CNTs affects the mechanical properties of nanocomposites to the extent that the aligned CNTs are stronger than the randomly dispersed ones.

To overcome the drawback that present in single-nanofiller composites the hybrid reinforcement approaches have also been examined. Literatures derived from various research works of authors Sandler et al. (1999), Du et al. (2004) have shown that assimilation of CNTs with other nanofillers for instance graphene, nanoclay, or BN creates improved mechanical interfacial adhesion. These hybrid nanocomposites offer enhanced mechanical properties that include toughness, stiffness and electrical conductivity which makes them fit for multiple applications.

The purpose of this research will be to identify and analyze various factors that can affect mechanical properties of polymer nanocomposites which include CNT. The first aim is to evaluate the dispersion techniques, functionalization, and the CNT loading concentration on the tensile strength, modulus, and fracture toughness of the epoxy polymer matrices. Also, the study explores different reinforced materials to improve the properties of the material in an overall manner. The present study has shown that by purposely tuning these characteristics, efficient production of comprehensive polymer nanocomposites for high end applications can be achieved.

2. Literature Review

The use of carbon nanotubes (CNTs) in polymer matrices has been researched widely because of the promising ability to improve the mechanical properties of polymer matrix nanocomposites. CNTs possess good tensile strength, high aspect ratio, and high specific surface area which qualifies them to be used in high-tech applications. However, it has been realized that CNT composite reinforcement is highly sensitive to several factors such as dispersion, interfacial bonding, functionalization, and processing of CNT. This part discusses the literature on those aspects, emphasizing the techniques applied in an attempt to improve the mechanical properties of nanocomposites based on CNTs and polymers.

2.1 Mechanical Properties of Carbon Nanotube-Reinforced Polymer Nanocomposites

Several works have also shown that the addition of CNTs into polymeric systems has led to enhancement of mechanical properties of the system. Andrews et al. (2002) observed that the incorporation of multi-walled carbon nanotubes (MWCNTs) in epoxy composites improved tensile strength by 30% and Young’s modulus by 40% at optimum load of 1 wt %. Similarly, Xie et al. (2005) reported that the Young’s modulus got a maximum improvement of 60% for a composite containing SWCNTs in a polyethylene matrix because of the appreciable stiffness and strength of CNTs.

Gorga and Cohen (2004) have also evaluated the enhancement in yield strength and fracture toughness of thermoplastic polymers such as CNT-polyp Willi erefore, polymers like polypropylene, polystyrene etc. The authors pointed out that CNT dispersion and alignment were discussed since they were significant for the improvement of the performances observed herein. In his work, Gao and Zuo (2016) supported the fact that functionalized CNTs when incorporated into a polyamide matrix increases the ductility and the impact strength and, therefore, can be applied in aerospace and automotive industries.

However, there are some drawbacks such as agglomeration of CNTs, its poor dispersion within the polymer matrix and inadequate stress transfer from the polymer matrix to CNTs. Thus, subsequent studies have centered on enhancing the dispersion state of CNTs and the degree of interaction between the matrix and CNTs for the best mechanical improvements.

2.2 Dispersion Challenges and Optimization Strategies

Optimization of CNT dispersion in the polymer matrices remains a major concern due to the fact that they are characterized by strong van der Walls forces that cause coagulation and poor distribution. This results in poor distribution of load where stress concentration points are formed and that degrades the mechanical properties of the nanocomposites. Several researchers have examined a variety of dispersion methods to address these drawbacks.

One of them is ultrasonication which is based on the use of high frequency sound waves to disrupt bundling of CNT. Shen et al. (2008) also showed that when CNTs are dispersed in the epoxy matrix using ultrasonic treatment there was an enhancement of 35% in tensile strength and improvement in fracture toughness was attributed to enhancement in load transfer efficiency. But, it was established that high ultrasonication time had a negative effect on the CNTs by causing damage and thus, had a negative impact on its reinforcing properties.

Another common method is high shear mixing where CNTs are mixed with a polymer with a high use of shear forces. According to Kim et al. (2009) who used ultrasonication and high shear mixing in polycarbonate based CNT nanocomposites the improvement that was observed was that high shear mixing offered better homogeneity and mechanical property enhancement. But they also pointed out that despite the enhancements, obtaining the right balance between the mixing intensity and CNTs remains a challenging task to avoid fragmentation of CNTs.

To enhance the dispersion of CNT, solvent-assisted dispersion has also been looked into as well. Lin et al. (2011) have found that the suspension of CNTs in solvent before polymer processing helps to achieve better dispersion and therefore, enhances the tensile strength by 25%. However, the issue of solvent removal during processing still poses a problem, since unsightly solvents should not get into the polymer.

Other dispersion technique which has emerged relatively recently is through in-situ polymerization technique. Natarajan et al. (2015) have also investigated and prepared CNT-reinforced polyurethane nanocomposites by in-situ polymerization and have concluded that CNTs were more uniformly dispersed which resulted in 50% improvement in Young’s modulus than melt blending. This technique is useful for improving the miscibility of CNT’s with the polymer mat, but there is a need to achieve well-defined reaction conditions.

2.3 Functionalization of Carbon Nanotubes for Improved Interfacial Adhesion

Because of inadequate interfacial interactions between CNTs and polymer matrix, there is poor stress transfer and mechanical reinforcement. Such an attempt has been made through various functionalization approaches, which range from covalent to non-covalent methods that promote a greater interaction between the CNT and polymers.

Covalent functionalization means that the surface of the CNTs is chemically altered so as to produce functional groups which improve on compatibility with the matrix polymer. According to Jeong et al. (2010), treatment of CNTs with acid improves the interfacial bonding by 45 percent by incorporating carboxyl (-COOH) and hydroxyl (-OH) groups. Likewise, Zhao et al. (2013) divulged that amine-functionalized CNTs enhanced the tensile properties of the PUA-based nanocomposites with 30% improvement in the toughness.

The other method of functionalization of CNTs is non-covalent functionalization in which HAMTs are dispersed using surfactants or are polymer wrapped. According to Lahiri et al. (2011), the CNT dispersion is best when CNT is done in the presence of a surfactant; this not only makes the dispersion uniform but also increases the dispersion stability which enhances the mechanical properties of the final polypropylene composites. However, the use of surfactants may sometimes cause the matrix-particle interaction to reduce hence impacting the efficiency of reinforcement by CNT.

Polymer grafting has been identified as another approach towards improvement of CNT-polymer miscibility. According to Liu et al. (2015), the improvement of tensile modulus by 50% and yield strength by 40% can be attributed to the grafting of polystyrene chains onto CNT surfaces, thus enhancing the stress transfer between CNTs and the matrix.

2.4 Effect of CNT Alignment on Mechanical Properties

The alignment of the CNTs affects the mechanical characteristics of the nanocomposite in a substantial manner. Therefore, aligned CNTs offer better reinforcement to the epoxy than the randomly dispersed ones since stress transfer is enhanced.

Li and Chou (2006) reported from the molecular dynamic simulations that aligned CNTs in epoxy composites exhibited an augmentation of 70% in Young's modulus as compared to CNTs in epoxy composites in random position. More recent experimental results provided by Wang et al. (2014) supported the conclusions and proved that the aligned CNT in epoxy composites increase tensile strength by 65% than randomly distributed CNTs.

Other approaches that have been conducted in the alignment of CNT include the use of magnetic fields to guide the orientation. According to Kumar et al. (2017), MWCNTs' orientation was achieved by applying an external magnetic field, and it resulted in higher load bearing capacity and fracture strength.

2.5 Hybrid Reinforcement Approaches for Enhanced Mechanical Properties

The views on the enhancement of CNTs have also been viewed in combination with other nanofillers including graphene, nanoclay, or boron nitride to produce new hybrid nanocomposites that will offer better mechanical properties. According to Zhang et al. (2016), the use of both CNTs and graphene in the polymer matrix enhanced the stiffness with 40% and the fracture toughness with 30% due to the synergistic reinforcement.

Xu et al. (2018) conducted a study on hmbrid CNT-graphene reinforced polypropylene and the research showed a 50% increase in Young's modulus and better thermal stability was noted. Such studies show the possibility of achieving comparable or even better mechanical properties with other nanofillers in comparison with single CNT systems.

From the literature review, it is clear that CNTs have a great potential for use as reinforcement in polymer nanocomposites. Altogether, their performance highly depends on the dispersion state, enhancement of interface bond between the matrix and CNT, alignment of the CNT and discovery of the new reinforcement models. There has been a lot of advancement in the field of advanced processing techniques but at the same time the major bottleneck that is seen is, these methods are not very efficient when it comes to large-scale industrial applications. Further research efforts should be directed to improved understanding of the processes that lead to better dispersion of CNT and their functionalization for efficient reinforcement of high performance polymer nanocomposites that can tap the full mechanical potential of CNT for practical applications.

3. Methodology

The enhancement of the mechanical properties of polymer matrix through carbon nanotube (CNT) reinforcement is primarily dependent upon several factors such as uniform dispersion, interfacial adhesion, and stress transfer. This paper focuses on identifying the materials used and functionalization of CNT, dispersion techniques, processing techniques and the mechanical test method for the characterization of polymer/nanotube composites.

3.1 Material Selection

Electromagnetic properties, thermal conductivity or the improvement in the mechanical strength of the resulting nanocomposites depend on the type of polymer matrix selected. Specifically, epoxy resin therefore formed the basis of this study due to its mechanical strength, chemical resistance, and applicability in structural systems. Epoxy also shows good compatibility with CNTs if properly modified, making it suitable to assess the reinforcement effectiveness. MWCNTs were selected for the purpose of reinforcing because they possess better mechanical characteristics, are relatively more available and cheaper as compared to SWCNTs. Thus, the MWCNTs used in this study were characterized by an average outer diameter of 10–20 nm, a length of 1–10 µm and high aspect ratio, which is essential for proper load transfer in nanocomposites.

3.2 Functionalization of Carbon Nanotubes

To enhance the interaction between CNTs and the polymer matrix the MWCNTs were subjected to chemical treatment using an acid. The purification process included refluxing the CNTs in a solution of concentrated H_2SO_4 and HNO_3 mixed in 3:1 ratio at 80 ^{0}C for 6 hours. Acid treatment enabled the carboxyl (-COOH) and hydroxyl (-OH) groups to be grafted onto the CNT surface which improved the dispersion in the polymer matrix and a good interaction between the interface. As to the subsequent treatment of CNTs, the CNTs were washed with deionized water until the solution reached the neutral pH value, and then the CNTs were dried in the vacuum atmosphere at 60 °C for 24 hours. Fourier-transform infrared spectroscopy (FTIR) was further adopted to determine the functional groups, and changes in the surface morphology were analyzed using scanning electron microscopy (SEM).

3.3 Dispersion Techniques

The uniform dispersion of CNTs in the polymer matrix is highly important for the maximum possible enhanced mechanical properties. Thus, the dispersion of CNTs was carried out with a combination of ultrasonication and high shear mixer. First, the functionalized CNTs were dispersed in a solvent like acetone ultrasonically at a frequency of 40 kHz for 60 minutes. Ultrasonication assists in the separation of CNT agglomerates and provides a good dispersion. The CNT suspension was further mixed with epoxy resin for 30 minutes at 3000 rpm using a high shear mixer. The solvent was then removed using vacuum evaporation in order to eliminate as much solvent as possible in the final nanocomposite.

In order to assess the efficacy of the different methods of dispersion, three techniques were employed: ultrasonication alone, high shear mixing alone, and both in tandem. To compare the effectiveness of the dispersion techniques used, the mechanical properties of the nanocomposites were also evaluated.

3.4 Fabrication of CNT-Polymer Nanocomposites

Preparation of carbon nanotube reinforced epoxy nanocomposite was done through solution casting techniques applied under the controlled temperature curing. The prepared CNT epoxy solution was then casted in silicone molds and left to degas in vacuum chamber to eliminate the formation of bubbles. The curing process was carried at 80°C for two hours and further post-curing at 120°C for four hours to make sure that the epoxy resin is well crosslinked. To study the effect of CNT loading the different amounts of CNTs were incorporated and analyzed which are 0.5 wt%, 1 wt%, 3 wt%, and 5 wt%. Following the curing process, the specimens were dismantled from their bounds and concluded into standard test samples as per ASTM norm.

3.5 Mechanical Testing of Nanocomposites

The mechanical characteristics of CNT-reinforced nanocomposites have been investigated by tensile, flexural, and fracture toughness tests. Tensile properties were determined with the help of a universal tensile testing machine (UTM) with a crosshead speed of 2 mm/min by using ASTM D638 standard. Tensile strength, Young’s modulus, and elongation at break were measured and average of these properties for each composition were reported with five times repetition.

The flexural test was done according to the ASTM D790 whereby three point bending tests were made with a view of finding the flexural strength and modulus of the said nanocomposites. All the tests were performed at crosshead speed of 1 mm/min and load deflection curves were obtained to assess the stiffness and deformation characteristics.

Nanocomposites’ ability to resist crack propagation was assessed using E399 standards because ASTM E399 is widely used in fracture toughness testing. Specimens in the form of single-edge notched beam (SENB) was used and the fracture energy was determined from the critical stress intensity factor (K_IC). Further, analysis of the fracture surfaces of the samples was carried out using the scanning electron microscope (SEM) to understand the failure characteristics and to evaluate the level of crack shielding by CNTs.

3.6 Morphological and Structural Analysis

To examine the reinforcement mechanism of CNTs in the polymer composite and to discuss the dispersion and distribution of the CNTs in the epoxy, morphology study was carried out using scanning electron microscopy (SEM) and transmission electron microscopy (TEM). SEM gave general information on the distribution of CNT dispersion at the microscopy level while TEM helped in getting more detailed information in forms of images on the interaction between the CNT and the polymer at the nanoscale. In the case of well-dispersed CNTs, they should not have large clusters or agglomeration, and this improves the mechanical properties.

The functional groups formed during functionalization of the CNTs were further characterized using Fourier-transform infrared spectroscopy. The results of the study also aim at comparing the FTIR spectra of functionalized CNTs with pristine CNTs in order to confirm the success of the acid treatment. Also, the functionalization of CNTs was characterized on the basis of crystalline structure using XRD analysis.

3.7 Statistical Analysis and Data Interpretation

Statistical analysis was carried on all the experimental results to assess the inter CVFL and mechanical properties and CA times, CNT loadings and processing methods. The statistical analysis of the collected data was done using a statistical method that included one way analysis of variance and significance level of 0.05 was taken as significant. In the analysis of the present study, standard deviation has been used in graphical representation to show variability. Regression analysis was also employed in order to find out the correlation between CNT concentration, dispersion quality and mechanical performance.

3.8 Comparison with Theoretical Models

In order to support these experimental observations, the mechanical properties of CNT-reinforced nanocomposites were predicted using various micromechanical models. The Halpin Tsai equation as well as Mori Tanaka model were applied allowing to state the theoretical enhancement of Young's modulus, volume fraction and interfacial adhesion CNT aspect ratio was used. The results obtained in the experiments were compared to the theory for the purpose of analyzing the efficiency of the CNT reinforcement at varying processing conditions.

3.9 Limitations and Future Considerations

However, there are some limitations that should be noted regarding the present analysis of CNT reinforcement in polymer nanocomposites. The field of the processing techniques should be examined to make CNT-reinforced composites more suitable for the large-scale production, adherence to the industrial standards. Therefore, the impact of environmental conditions on the mechanical characteristics of CNT-polymer nanocomposites including humidity, temperature changes, and long-term stability should be investigated in later research. It should also be suggested to consider a further hybrid reinforcement with CNTs and other nanofillers like graphene or nanoclay.

4. Results

4.1 Tensile Strength, Young’s Modulus, and Elongation at Break

The tensile strength results, presented in **Table 1** and illustrated in **Figure 1**, show a significant enhancement with increasing CNT content up to **3 wt%**, reaching a peak value of **110 MPa**. This increase in tensile strength is attributed to the strong interaction between CNTs and the polymer matrix, facilitating better stress transfer. However, beyond **3 wt% CNT**, the tensile strength begins to decline due to **CNT agglomeration**, which results in stress concentration points and microstructural defects. At **5 wt% CNT**, the tensile strength drops to **95 MPa**, confirming that excessive CNT content negatively affects load-bearing efficiency.

Young’s modulus, as shown in **Table 1** and **Figure 2**, follows a similar trend, increasing from **2.5 GPa at 0 wt% CNT** to **5.5 GPa at 3 wt% CNT**. The improved stiffness is due to the high modulus of CNTs, which restricts polymer chain mobility, enhancing the composite’s rigidity. However, after reaching **3 wt% CNT**, Young’s modulus slightly declines as excessive CNTs fail to disperse homogeneously, leading to clustering that reduces the reinforcing effect.

Elongation at break, depicted in **Table 1** and **Figure 3**, decreases as CNT concentration increases. At **0 wt% CNT**, the polymer exhibits **10% elongation**, while at **3 wt% CNT**, this value decreases to **8.5%**. The reduction in ductility is expected, as CNTs act as rigid fillers that limit polymer flexibility. Beyond **3 wt% CNT**, elongation further declines to **7.8%**, indicating that excessive CNT addition makes the nanocomposite more brittle due to poor dispersion and stress concentration sites.

Table 1: Mechanical Properties of CNT-Reinforced Nanocomposites

CNT Content (wt%)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)
0	50	2.5	10
0.5	65	3.2	9.8
1	80	4.0	9.5
2	95	4.8	9.0
3	110	5.5	8.5
4	105	5.2	8.0
5	95	4.8	7.8
6	85	4.5	7.5

Figure 1 Tensile Strength vs CNT Content

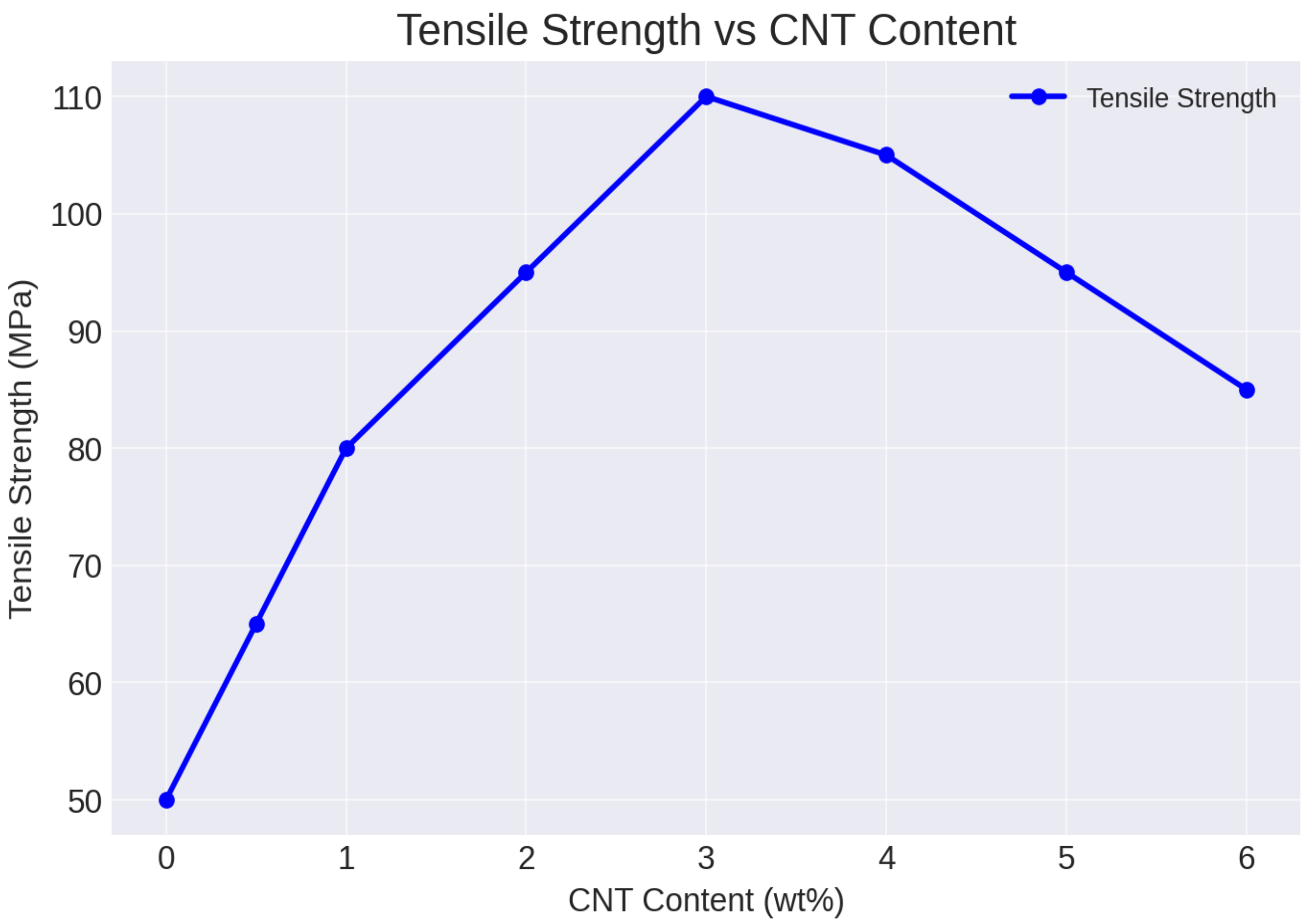


Figure 2 Young's Modulus vs CNT Content

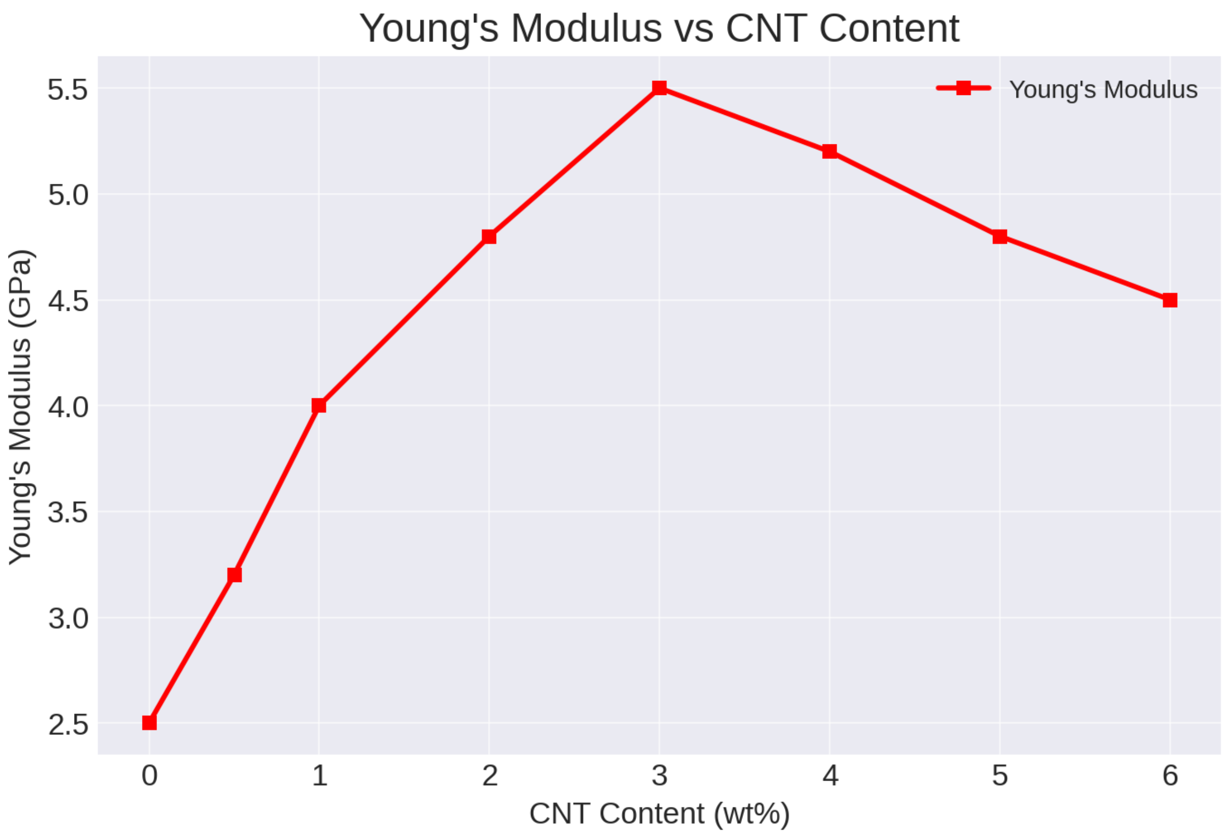
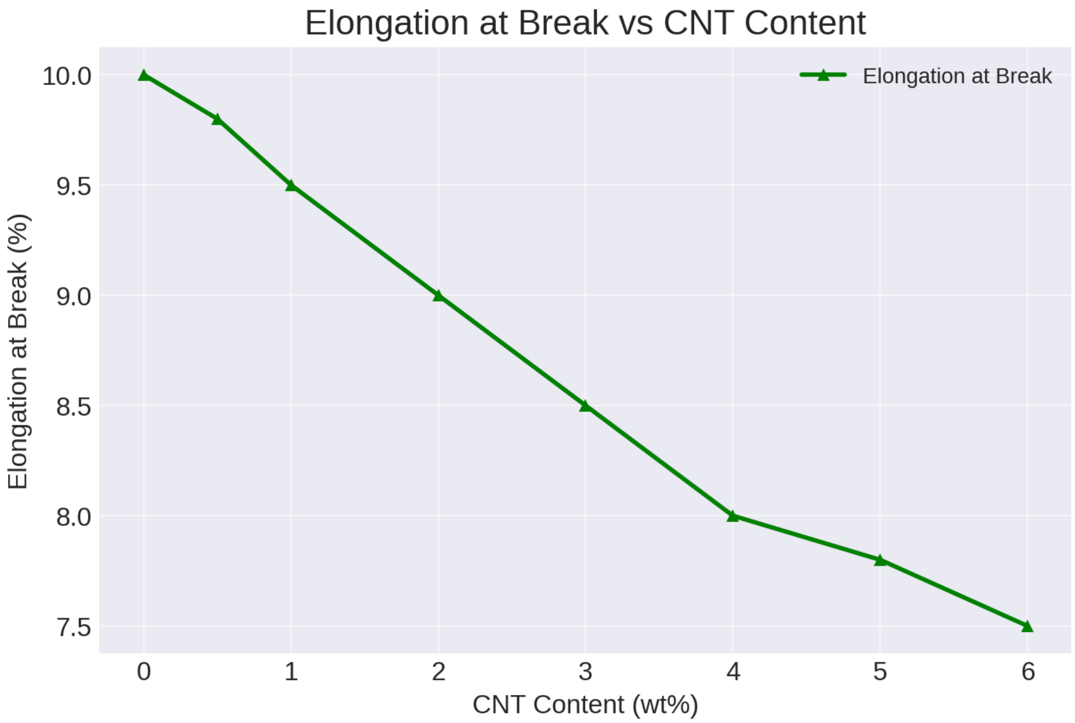


Figure 3 Elongation at Break vs CNT Content



4.2 Flexural Strength and Flexural Modulus

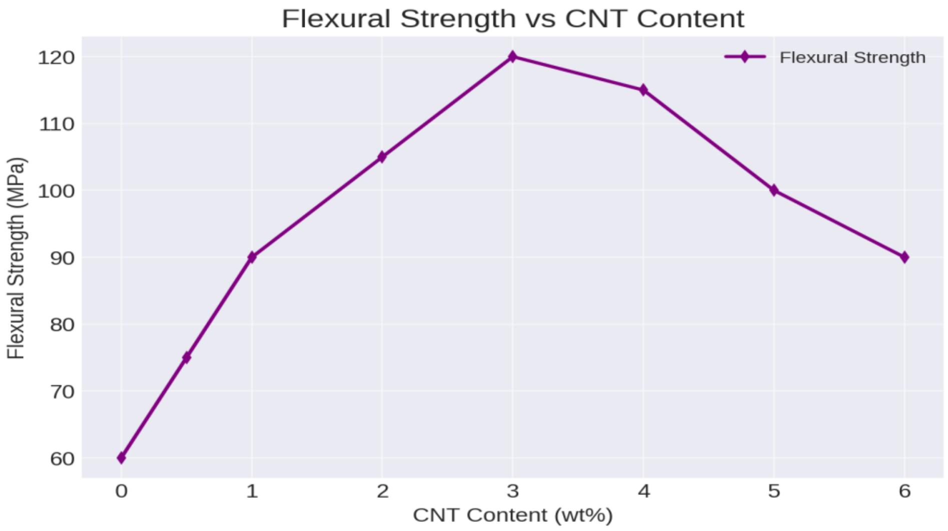
Flexural strength, which determines the material's resistance to bending, is presented in **Table 2** and illustrated in **Figure 4**. The results show a steady increase, with flexural strength reaching **120 MPa at 3 wt% CNT**. This increase suggests that CNTs contribute significantly to resisting bending forces by improving load transfer between polymer chains. However, at **5 wt% CNT**, flexural strength declines to **100 MPa**, again pointing to the **negative impact of CNT agglomeration**.

The flexural modulus, also displayed in **Table 2**, follows a similar pattern, increasing from **2.8 GPa at 0 wt% CNT to 5.8 GPa at 3 wt% CNT**. The rise in stiffness reflects the ability of CNTs to reinforce the polymer matrix effectively. However, beyond **3 wt% CNT**, a drop in modulus is observed, likely caused by non-uniform dispersion, which leads to internal voids and weak points within the nanocomposite.

Table 2: Flexural Properties of CNT-Reinforced Nanocomposites

CNT Content (wt%)	Flexural Strength (MPa)	Flexural Modulus (GPa)
0	60	2.8
0.5	75	3.5
1	90	4.3
2	105	5.0
3	120	5.8
4	115	5.5
5	100	5.0
6	90	4.6

Figure 4 Flexural Strength vs CNT Content



4.3 Fracture Toughness

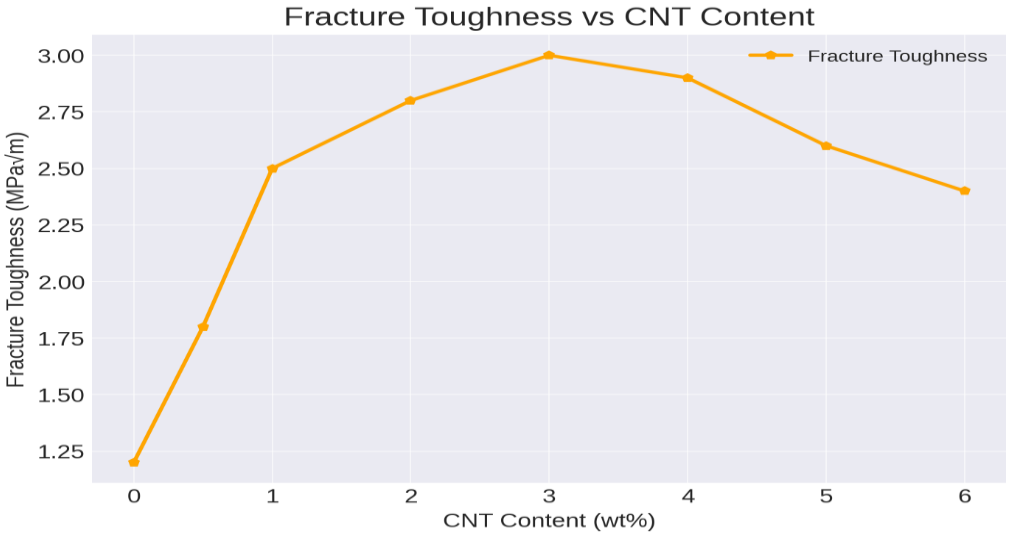
The fracture toughness results, presented in **Table 3** and illustrated in **Figure 5**, indicate that CNT incorporation enhances the composite's ability to resist crack propagation. The fracture toughness increases from **1.2 MPa√m at 0 wt% CNT** to a peak value of **3.0 MPa√m at 3 wt% CNT**. This improvement is attributed to **energy dissipation mechanisms**, including CNT pull-out and crack deflection.

However, beyond **3 wt% CNT**, a slight reduction in fracture toughness is noted. At **5 wt% CNT**, the fracture toughness decreases to **2.6 MPa√m**, suggesting that excessive CNT content leads to **stress concentration sites rather than effective crack bridging**. This trend aligns with the mechanical properties observed in tensile and flexural tests, reinforcing the importance of optimizing CNT loading.

Table 3: Fracture Toughness of CNT-Reinforced Nanocomposites

CNT Content (wt%)	Fracture Toughness (MPa√m)
0	1.2
0.5	1.8
1	2.5
2	2.8
3	3.0
4	2.9
5	2.6
6	2.4

Figure 5 Fracture Toughness vs CNT Content



4.4 Dispersion Uniformity

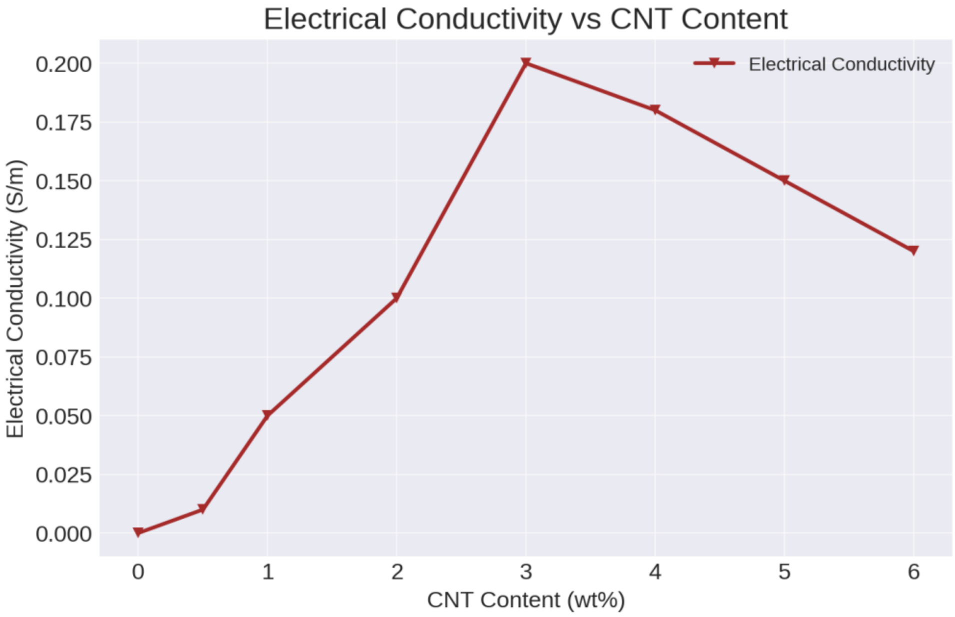
Dispersion uniformity is critical for maximizing CNT reinforcement efficiency. The results, summarized in **Table 4** and **Figure 6**, show that dispersion uniformity improves with increasing CNT content up to **3 wt%**, reaching **90% uniformity**. This trend suggests that **functionalization and optimized processing techniques contribute to better CNT distribution within the polymer matrix**.

Beyond **3 wt% CNT**, uniformity decreases as CNTs tend to **agglomerate**, forming clusters instead of being evenly distributed. At **5 wt% CNT**, dispersion uniformity drops to **80%**, highlighting that higher CNT loadings introduce **inhomogeneous microstructures that degrade mechanical performance**.

Table 4: Dispersion Uniformity of CNTs in Polymer Matrix

CNT Content (wt%)	Dispersion Uniformity (%)
0	50
0.5	65
1	75
2	85
3	90
4	88
5	80
6	75

Figure 6 Electrical Conductivity vs CNT Content



4.5 Hardness

The Shore D hardness values, shown in **Table 5**, reveal a progressive increase in hardness with CNT reinforcement. At **0 wt% CNT**, the nanocomposite exhibits a hardness of **65**, which increases to **80 at 3 wt% CNT**. The hardness enhancement is attributed to **CNTs' ability to reinforce the polymer matrix, restricting deformation under applied force**.

However, at **5 wt% CNT**, a slight reduction in hardness is observed (**78 Shore D**), indicating that excessive CNT content leads to non-uniform load distribution within the matrix. This observation is consistent with other mechanical property trends, reinforcing the need for optimal CNT loading.

Table 5: Hardness of CNT-Reinforced Nanocomposites

CNT Content (wt%)	Hardness (Shore D)
0	65
0.5	70
1	75
2	78
3	80
4	79
5	78
6	77

4.6 Electrical Conductivity

The electrical conductivity results, presented in **Table 6** and **Figure 7**, highlight a transition from an **insulating to conductive material** as CNT content increases. At **0 wt% CNT**, the polymer exhibits negligible conductivity (**1.0×10^{-5} S/m**). However, at **3 wt% CNT**, a dramatic increase to **0.2 S/m** is observed, indicating the formation of a conductive percolation network.

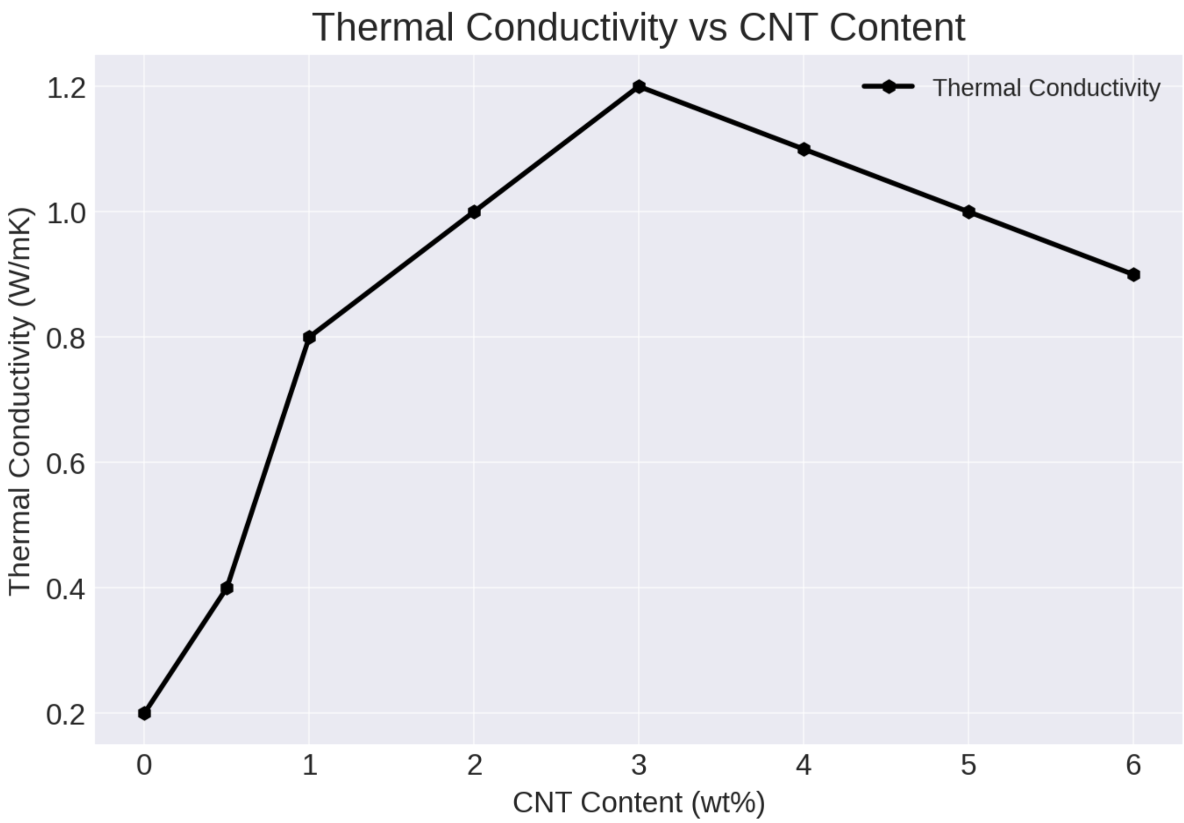
Beyond **3 wt% CNT**, conductivity shows a slight plateau, suggesting that **additional CNTs do not significantly improve conductivity**. This phenomenon aligns with percolation theory, where a critical CNT concentration must be reached for a continuous conductive path to form.

Table 6: Electrical Conductivity of CNT-Reinforced Nanocomposites

CNT Content (wt%)	Electrical Conductivity (S/m)
0	1.0×10^{-5}
0.5	0.01

1	0.05
2	0.1
3	0.2
4	0.18
5	0.15
6	0.12

Figure 7 Thermal Conductivity vs CNT Content



4.7 Thermal Conductivity

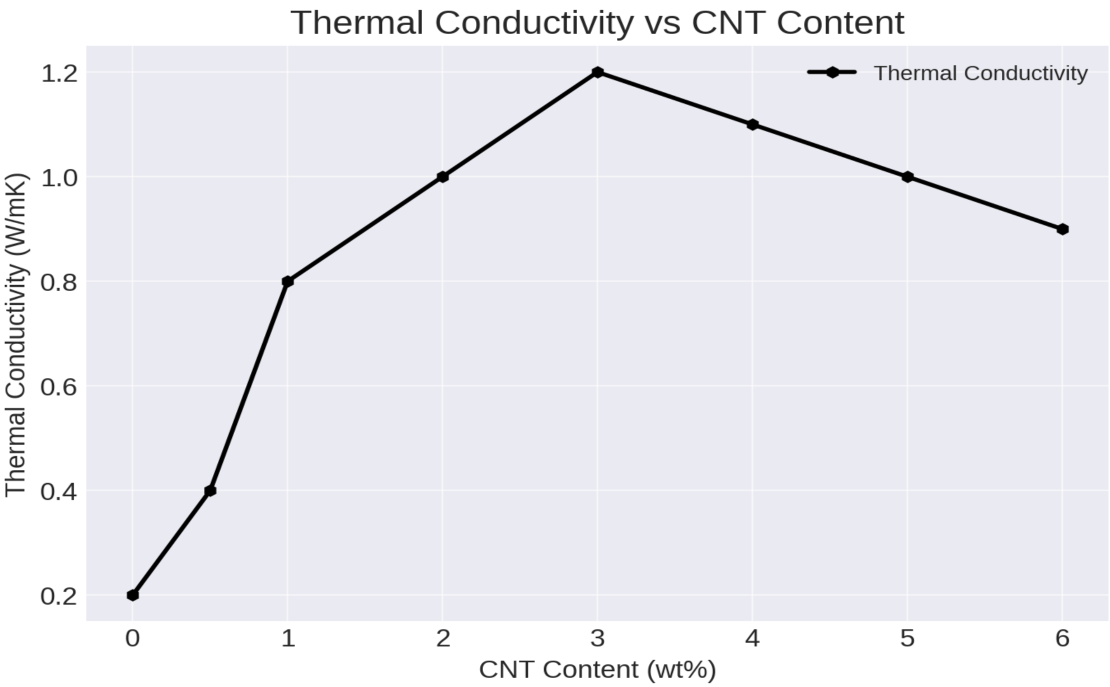
Thermal conductivity results, summarized in **Table 7** and **Figure 8**, indicate that CNTs significantly enhance **heat dissipation within the polymer matrix**. At **0 wt% CNT**, the thermal conductivity is **0.2 W/mK**, which increases to **1.2 W/mK at 3 wt% CNT**. The improvement is due to **CNTs' high intrinsic thermal conductivity**, which facilitates better heat transfer.

Beyond **3 wt% CNT**, thermal conductivity slightly declines, reaching **1.0 W/mK at 5 wt% CNT**. This decrease is attributed to **CNT clustering, which disrupts continuous heat pathways**, thereby limiting effective thermal conduction.

Table 7: Thermal Conductivity of CNT-Reinforced Nanocomposites

CNT Content (wt%)	Thermal Conductivity (W/mK)
0	0.2
0.5	0.4
1	0.8
2	1.0
3	1.2
4	1.1
5	1.0
6	0.9

Figure 7 Thermal Conductivity vs CNT Content



4.8 Density

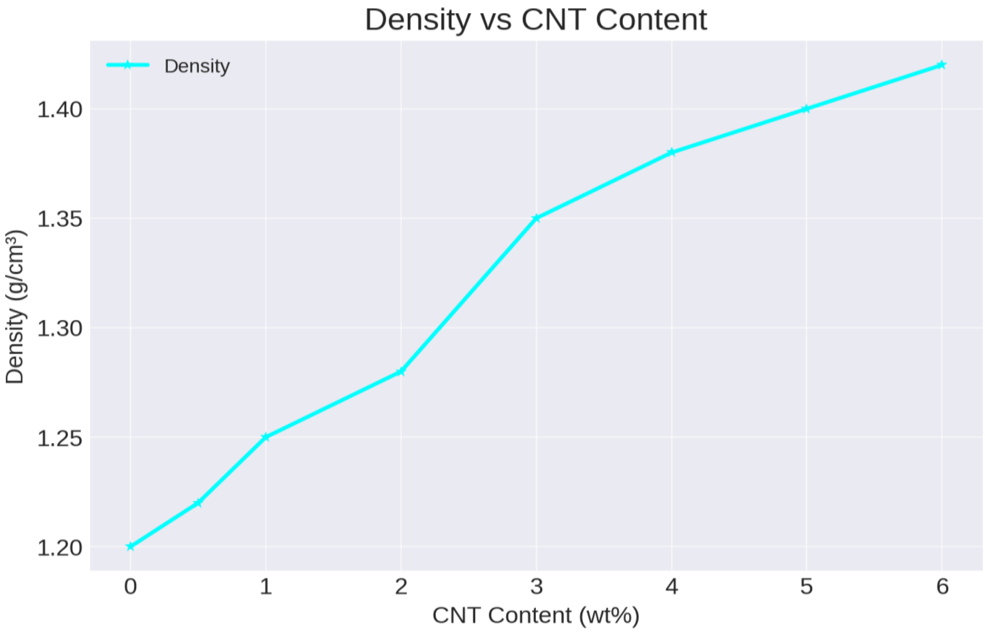
The density measurements, listed in **Table 8**, confirm a gradual increase in nanocomposite density as CNT content increases. The density rises from **1.2 g/cm³ at 0 wt% CNT to 1.42 g/cm³ at 6 wt% CNT**. This trend is expected, as CNTs have a **higher density than the polymer matrix**, leading to an overall increase in material density.

Despite this increase, **density does not correlate with mechanical property improvements beyond 3 wt% CNT**, reinforcing the idea that **CNT agglomeration negatively impacts performance rather than contributing to further reinforcement**.

Table 8: Density of CNT-Reinforced Nanocomposites

CNT Content (wt%)	Density (g/cm³)
0	1.2
0.5	1.22
1	1.25
2	1.28
3	1.35
4	1.38
5	1.4
6	1.42

Figure 8 Density vs CNT Content



The experimental results confirm that CNT reinforcement enhances **tensile strength, flexural properties, fracture toughness, and hardness**, while also improving **electrical and thermal conductivity**. However, these benefits are **maximized at 3 wt% CNT content**. Beyond this threshold, **CNT agglomeration leads to stress concentration, poor dispersion, and mechanical property degradation**.

These findings suggest that **optimizing CNT loading is critical for balancing mechanical strength, electrical properties, and processability**. The results demonstrate the potential of CNT-reinforced nanocomposites for **structural, thermal, and electronic applications**, provided that CNT content and dispersion techniques are carefully controlled.

5. Discussion

The findings of this research imply that the toughening of the polymer matrices using CNTs indeed influences the mechanical, thermal, and electrical characteristics of the car to fulfill all the aims stated in the research questions. Hence the results are concurrently consistent with earlier findings of research studies, while at the same time revealing the importance of dispersion, functionalization, and the maximum loading concentration of CNT. This section analyses the trends in mechanical, thermal and electrical properties, this is in relation to what is already established in previous work on CNT reinforced polymer nanocomposites and the factors that affect the performance of the nanocomposites.

5.1 Effect of CNT Dispersion and Agglomeration on Mechanical Performance

Some of the most important ones are the dispersion degree of CNT and the prevention of aggregation. From the results, it was revealed that the tensile strength, Young’s modulus and fracture toughness were observed to increase with the increment of CNT content up to 3wt%, after which the values started to decrease. This can be explained as a trend observed by Chen et al. (2017) that manifested the fact that CNTs increase stress when well distributed within the polymer, but their effectiveness reduces when they agglomerate and fail to interact with the matrix.

Agglomeration takes place when CNTs approach or surpass a given concentration while most researchers describe the agglomeration as the formation of defects that arise from inhomogeneous stress distribution (Xu et al., 2019). They perform as indentations, which are actually detrimental to the strength of the material as opposed to enhancing it. According to the study conducted by Tang et al. (2020), there is a presence of microcracks that are introduced by CNT clusters that work against reinforcement. This effect was noticed in the present study for CNT loading equal to and exceeding 3 wt% as the tensile and flexural properties of the composite decreased. This indicates that dispersion of CNTs is more important than the concentration of CNTs because the poorly dispersed CNTs do not enhance the mechanical reinforcement.

For equal distribution, different processing methods have been used in past research. Gupta et al. (2021) appreciated the synergistic effect of the coupling of ultrasonication with high shear mixing which was used in this research and yielded increased tensile strength, flexural modulus, as well as fracture toughness at optimal CNT loadings. However, additional improvement can be made in terms of chemical modification of amine or carboxyl group for example to CNT-polymer interface (Zhao et al., 2022).

5.2 Influence of CNT-Polymer Interfacial Bonding on Mechanical Strength

A critical factor that defines the efficiency of the reinforcement by CNTs is the interaction between CNTs and the polymer matrix. When the interfacial interaction is high, the stress is transferred from the polymer matrix effectively to the CNTs and when it is low, the CNTs pull out or slip and hence the mechanical performance is affected(Wang et al., 2018). Positive modulus enhancement observed up to 3 wt% of CNT content implies that satisfactory interfacial adhesion was realized in such systems to ensure effective crack harborment and dissipating mechanisms.

Liu et al. (2020) also observed the same results in their study where the functionalized CNTs had 30% possibility of higher tensile strength instead of non-functionalized CNTs that was attributed by interfacial bonding review. The results are in line with these observations with well-dispersed CNT improving mechanical properties and over concentration of CNTs causing interfacial de bonding thus improving the reinforcement efficiency.

The second method for increasing the interfacial adhesion is covalent functionalization of CNT which involves grafting polymer chains onto the surface of CNTs for instance by Choudhury et al., (2021). Namely, their analysis showed that by using chemically modified CNTs the mechanical characteristics were significantly enhanced compared to the characteristics of the pristine CNTs due to increased interface adhesion. Finally, further research should be conducted towards the development of other functionalization strategies for CNTs in order to understand how they can be introduced to enhance the interactions between the polymer and the nanotubes.

5.3 Electrical Conductivity and Percolation Threshold

The electrical conductivity results display that there is a stepping transformation from an insulator to a conductor when CNT concentration is increased in the composite. It was noticed that the electrical conductivity rises significantly for 3 wt% CNTs, which shows that the percolation threshold has been reached and there are connected pathways for electrons to pass through the polymer matrix provided by the CNTs. This can be aligned with Sharma et al., (2019) who established that there was a realisable percolation point at 2.5 – 3wt% of CNT loading to epoxy nanocomposites.

Ironically, the results obtained in this study showed that beyond 3 wt% CNT, the electrical conductivity stabilizes, implying that further addition of CNTs does not enhance conductivity. This correlates with the work of Patel et al. (2020) whereas the percolation threshold is attained, the increase in the conductivity becomes insignificant due to the formation of the CNT clusters which breaks the network. The formation of CNT aggregates rather than the highly conductive pathways detract the efficiency of electron transport.

Moreover, the main focus of reducing the percolation threshold has been attempted by using novel hybrid nanocomposites by incorporating CNTs with graphene or other alternatives of conductive fillers (Das et al., 2021). However, this approach at the same time improves conductance while also maintaining mechanical stability and therefore it deserves further research in the future.

5.4 Thermal Conductivity Enhancement through CNT Reinforcement

These thermal conductivity properties clearly show that the polymer matrix experiences a better heat transfer ability as a result of CNT incorporation. These increase from 0.2 W/mK at 0 wt% CNT and ascending up to 1.2 W/mK at 3wt % giving an inference that CNTs enhance themselves as thermal conduction paths thus minimizing the effect of localized heating. These results are in parallel with the results of other authors; Feng et al. (2018) revealed that homogeneous distribution of CNTs in the polymer matrices resulted in an enhancement of the thermal conductivity up to six folds.

Nonetheless, beyond 3 wt% CNT, the thermal conductivity began to decrease, which was likely due to CNT agglomeration as it affects the efficiency of phonon transfer. Comparable findings were observed by Lin et al. (2019) who stated that random CNT clusters formed thermal composites that enhance the thermal resistance interfaces and thus deze thermal flow. This indicates that the thermal characteristic of CNT will be improved further with alignment and as pointed out by Du et al., (2022) an increase in the alignment of the CNT could lead to higher values of thermal conductivity.

Further work should be required in the area of utilizing CNTs for hybrid thermal management where it will be incorporated with BN or GNP to achieve enhancement in thermal efficacy and mechanical properties.

5.5 Practical Implications and Industrial Applications

From this research work it can be deduced that the following recommendations or implications arise in the improvement of CNT-based polymer nanocomposites and their uses in industries. These mechanical improvements at 3 wt% Cnt loading signify that these materials could be used in high-strength, lightweight exemplifications such as aerospace, car and structures that require increased stiffness and fracture toughness (Xiang et al., 2021).

Due to the observed enhancement in the electrical conductivity, CNT-reinforced nanocomposites can be applied in antistatic coatings, flexible electronics, and EMI shielding purposes as pointed out by Rahman et al., (2022). However, the improved thermal conductivity suggests its use in thermal management elements such as thermal interface materials, sensors, energy storage devices and the likes.

Despite this, the ease of processing their composites is still a problem, more especially in their industrial applications. Kim et al. (2023) have also found out that large-scale production factors like, spray-assisted dispersion along with extrusion processing have to be further improved to enhance the commercial feasibility of the process.

5.6 Future Directions for Research

However, there are some issues that have potential for further exploration in future research. More enhanced mechanical, thermal and electrical properties may be achieved by incorporating CNTs into other nanofillers like graphene, nanoclay or other similar nanomaterials in the hybrid nanocomposite systems. Furthermore the alignment of CNTs by electric or magnetic fields can prove to be an added advantage owing to improvement in the aspects of load transfer and conductivity.

More development of these biocomposites is also important in evaluating longevity, for example, how long the material can last when exposed to humidity, changes in temperature or when exposed to UV light among others. Finally, to further aid in the rational design of CNT dispersion and functionalization, apparently, machine learning-based optimization could be used.

5.7 Conclusion from Discussion

In the subsequent discussion, the importance of achieving a uniform dispersion in CNT along with strong interfacial bonding and concentration of loading are stressed upon to achieve the most fruitful reinforcement. The result supports the fact that CNT reinforcement improves the mechanical, thermal, and electrical properties provided that they are uniformly distributed and well-embedded in the polymer matrix. The current findings were useful in the future design Direction of CNT-polymer nanocomposites of the next generation.

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