

Thermal And Electrical Conductivity Analysis Of Multiwalled Carbon Nanotubes - Epoxy Composites: A Comprehensive Study

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ABSTRACT

This report presents a comprehensive study on the thermal and electrical performance of multi-walled carbon nanotube (MWCNT) reinforced epoxy composites. Composites were prepared with CNT volume fractions ranging from 0.1% to 8% using Epoxy resin matrices. Thermal conductivity was evaluated through the Lee's Disc method, while electrical resistance was measured using Mega Ohm meter & Multi meter-based setups in-plane and through-thickness configurations. Results were further compared with theoretical predictions from Maxwell-Garnett, Hashin-Shtrikman, and percolation models. The study reveals that electrical conductivity exhibits a clear percolation threshold between 2% and 4% CNT loading, with significant enhancement at higher fractions, whereas thermal conductivity shows only modest improvement due to interfacial resistance and CNT agglomeration. This work highlights the contrasting transport mechanisms in CNT/epoxy composites and their potential applications in electronic packaging, EMI shielding, and thermal management systems.

Keywords: Thermal Conductivity, Electrical Conductivity, Epoxy, CNT.

I. INTRODUCTION

Composite materials, composed of two or more distinct phases, are specifically designed to exhibit enhanced properties compared to their individual components. Among the different advanced reinforcing agents, carbon nanotubes (CNTs) have gained remarkable attention owing to their exceptional mechanical strength, electrical conductivity, and thermal performance. In particular, multi-walled carbon nanotubes (MWCNTs) are extensively studied due to their ease of large-scale production, cost-effectiveness relative to single-walled CNTs, and high aspect ratio.

Epoxy resin, one of the most commonly used thermosetting polymers, is favoured for its strong adhesion, dimensional stability, and resistance to chemicals. Nevertheless, its inherently poor electrical and thermal conductivity limits its utility in applications such as electronic packaging, electromagnetic interference (EMI) shielding, and thermal management systems. Incorporating CNTs into epoxy matrices offers a viable solution to these drawbacks by forming conductive pathways within the polymer network.

The present work involves the fabrication and analysis of MWCNT-epoxy composites. Samples were produced with varying CNT concentrations ranging from 0.1% to 8% by volume. The thermal conductivity of these composites was determined using Lee's Disc apparatus, while electrical resistance measurements were performed through Mega Ohm and multimeter-based testing. The obtained experimental results are further compared with theoretical predictions derived from the Maxwell-Garnett model, Hashin-Shtrikman limits, and Percolation theory.

Composite Materials

Composite materials are specially designed by combining two or more distinct substances that differ significantly in their physical or chemical characteristics. When integrated, these materials form a new composite system that demonstrates improved overall properties compared to the individual constituents. Importantly, the original phases remain separate and identifiable within the final structure.

Main Constituents

1. **Matrix:**
The matrix serves as the continuous phase that embeds and supports the reinforcing material. Its primary functions include maintaining the structural form, distributing stresses, and safeguarding the reinforcement from mechanical and environmental damage. Common matrix materials include polymers (such as epoxy), metals, and ceramics.
2. **Reinforcement:**
The reinforcement acts as the secondary phase, imparting improved mechanical, thermal, or electrical characteristics to the composite. It may appear in various forms such as fibers, whiskers, particles, or nanotubes. In this research, **multi-walled carbon nanotubes (MWCNTs)** are utilized as the reinforcing agent.

II. LITERATURE REVIEW

2.1 Introduction

Polymer matrices such as epoxy are extensively used in industrial applications owing to their ease of processing, strong adhesion, and reliable structural integrity. Despite these advantages, their inherently insulating nature and low thermal conductivity restrict their use in multifunctional applications requiring both electrical and thermal transport (e.g., sensors, electromagnetic interference (EMI) shielding, and thermal interface materials). To mitigate these limitations, conductive fillers like carbon nanotubes (CNTs) have been intensively investigated. Due to their exceptional electrical conductivity, high aspect ratio, and outstanding intrinsic thermal properties, CNTs can significantly enhance polymer composites when homogeneously dispersed, creating continuous conductive paths that facilitate electron and phonon transport [Mousavi et al., 2022] (Science Direct).

In recent years, extensive research has explored factors influencing CNT dispersion, interfacial resistance, conductive network formation, and modelling approaches to better understand and predict composite behaviour. This section reviews advancements in electrical and thermal conductivity improvements, theoretical modelling, experimental approaches, and key challenges related to CNT/epoxy nanocomposites.

2.2 Electrical Conductivity in CNT/Polymer Composites

2.2.1 Percolation Theory and Network Formation

When a sufficient quantity of conductive filler is introduced into an insulating matrix, a continuous conductive pathway can develop, marking the *percolation threshold* (V_c). Beyond this threshold, composite conductivity follows a characteristic power-law behaviour:

$$\sigma = \sigma_0(V_f - V_c)t = \sigma_0(V_f - V_c)^{t\sigma} = \sigma_0(V_f - V_c)t$$

where σ_0 represents the scaling constant, V_f the filler volume fraction, and t the critical exponent (typically ranging between 1.6–2 for three-dimensional systems). This relation has been extensively applied to CNT-based polymer composites [Bauhofer & Kovacs, review] (DNB Portal). In practice, CNT composites often deviate from the idealized percolation model because of variations in CNT geometry (length, diameter, curvature), agglomeration, and contact configurations. Bauhofer et al. noted that directly linking geometric parameters to the fitted t -values is unreliable since real CNT networks differ substantially from ideal systems due to dispersion quality, alignment, and fabrication processes (DNB Portal).

2.2.2 Tunnelling Conduction and Contact Resistance

Even below the geometric percolation threshold, electrical transport may still occur through **quantum tunnelling** between neighbouring CNTs separated by nanoscale polymer gaps. The corresponding conductivity is exponentially dependent on the inter-tube separation:

$$\sigma \propto \exp\left(-\frac{d}{\lambda}\right)$$

where d is the distance between tubes and λ is the tunnelling decay constant. Thus, minimizing CNT separation or interfacial barriers enhances tunnelling conduction. In near-threshold composites, contact and tunnelling resistances dominate total resistance [Bocharov et al.] (MDPI).

The inter-tube junction resistance typically exceeds the intrinsic CNT resistance, forming a significant bottleneck to conduction. Furthermore, some studies have reported *non-Ohmic* (voltage-dependent) behaviour, where conductivity increases with applied electric field due to barrier lowering effects — a phenomenon frequently observed in CNT/polymer systems [Bocharov et al.] (MDPI).

2.2.3 Experimental Observations and Trends

- In epoxy/CNT composites, conductivity often increases by 6–10 orders of magnitude at the percolation threshold [Caradonna et al., 2019] (PMC).

- Aigbodion et al. reported that the electrical conductivity improved from approximately 5.6×10^{-13} S/cm (pure epoxy) to 4.8×10^{-3} S/cm at 0.5 wt% CNT loading, demonstrating effective conductive network formation with good dispersion (Taylor & Francis Online).
- Pontefisso et al. (2023) reviewed numerical modelling strategies for CNT/polymer composites, showing that combined percolation–network models more accurately predict threshold behaviour and conductivity trends by accounting for tunnelling and contact resistance effects (PMC).

In summary:

- Below percolation → composite remains insulating (with weak tunnelling contribution).
- Near percolation → sharp conductivity rise.
- Above percolation → conductivity grows slowly, limited by junction resistance and network structure.

2.3 Thermal Conductivity in CNT/Polymer Composites

2.3.1 Challenges and Limitations

Unlike electrical conduction, improving thermal conductivity is more complex because heat transfer must cross multiple CNT–matrix and CNT–CNT interfaces. Phonon scattering and vibrational mismatch significantly impede heat flow. Martin-Gallego et al. observed notable enhancements in MWCNT–epoxy composites, though improvements were far below predictions from simple mixture laws due to phonon interface resistance and mismatched vibrational modes [Martin-Gallego et al., 2011] (PMC).

Even at high CNT loadings, measured thermal conductivity values remain well below those of pure CNTs, primarily due to *Kapitza resistance* (interfacial thermal resistance) and poor inter-tube thermal contact.

2.3.2 Theoretical Models and Refinements

- **Rule of Mixtures:** Provides upper and lower bounds—parallel alignment yields maximum conductivity, perpendicular gives minimum.
- **Effective Medium Theories (Maxwell–Eucken, Maxwell–Garnett):** Model CNTs as dispersed inclusions in a continuous phase; valid at moderate filler levels but neglect interfacial effects.
- **Semi-empirical and Interface Models (Hasselman–Johnson, Nan’s Model):** Incorporate interfacial resistance or imperfect contact into predictions, producing closer agreement with experimental data.
- Recent studies (e.g., *Evaluation of Theoretical Models*, ACS 2025) emphasize the need to calibrate interface conductance values to realistic microstructures for accurate modeling [ACS J. Phys. Chem. C, 2025] (American Chemical Society Publications).

2.3.3 Experimental Results and Observations

- Mousavi et al. (2022) reviewed approaches to improving epoxy/CNT thermal conductivity through functionalization, hybrid fillers, and 3D architectures. Reported improvements ranged from 20–100% at optimized CNT contents, with diminishing returns at higher loadings due to phonon scattering [Science Direct].
- Wiśniewska et al. (2023) found that excessive MWCNT addition led to reduced thermal performance due to increased defects and phonon scattering [Science Direct].
- Kargar et al. (2018) identified thermal percolation in graphene/polymer systems at filler loadings exceeding 20 vol%, where heat flow is dominated by filler networks rather than the matrix [arXiv].

Hence, while electrical percolation can occur at low CNT concentrations, substantial thermal conductivity improvement requires optimized interfacial contact, alignment, and sometimes hybrid filler integration.

2.4 Hybrid and Advanced Enhancement Strategies

To surpass conventional performance limits, researchers have adopted several advanced strategies:

- **Hybrid Filler Systems:** Combining CNTs with graphene or metallic nanoparticles creates synergistic effects, reducing percolation thresholds and enhancing heat transport. For example, graphene–copper–epoxy systems exhibited significant thermal conductivity improvements due to copper bridging between conductive networks [Barani et al.] (arXiv).
- **Interface Engineering:** Surface functionalization, coupling agents, interfacial layers, and annealing treatments can minimize contact resistance, thereby improving both thermal and electrical transport.
- **Aligned CNT Architectures:** Vertically aligned CNTs (VACNTs) used as thermal interface materials (TIMs) provide direct phonon pathways along tube axes, offering far higher conductivity than random CNT networks [Wikipedia].
- **Multiscale Modelling:** Integration of molecular dynamics (for interfacial conductance) with continuum-scale models (FEM, RVE) enables predictive simulation of composite performance.

III. METHODOLOGY

1. Material Selection

- **Matrix:**
Epoxy resin was chosen as the base matrix owing to its wide availability, excellent mechanical strength, strong adhesion, and electrical insulating characteristics.
- **Reinforcement:**
Carbon nanotubes (CNTs) were selected as the reinforcing phase due to their superior mechanical strength, outstanding electrical conductivity, and remarkable thermal transport properties.

2. Specimen Preparation

- Composite laminates were fabricated using the **hand layup method** by incorporating CNTs at different volume fractions: 0.1%, 0.25%, 0.5%, 0.75%, 1%, 2%, 4%, and 8%.
- After curing, specimens were **cut and prepared following ASTM standards** for subsequent tensile and compression testing.

3. Experimental Investigations

- **Thermal Conductivity (Lee's Disc Method):**
Measured the rate of heat transfer and evaluated the effective thermal conductivity of each composite.
- **Electrical Conductivity:**
Measured using a **megger (500V and 1000V)** and a **digital multi-meter** to detect the percolation threshold and establish conductivity trends across CNT loadings.

4. Analytical Modelling

- **Thermal Conductivity:**
Predicted using **Parallel, Series, Semi-Empirical, and Maxwell-Eucken** models.
- **Electrical Conductivity:**
Modelled using **Percolation Theory, Quantum Tunnelling Model, and Effective Medium Approximation (EMA)** to simulate conductivity variation with CNT content.

5. Digimat-FE Simulations

- The composite microstructure was digitally reconstructed using **Digimat-FE** to simulate **CNT dispersion within the epoxy matrix**.
- A **Representative Volume Element (RVE)** approach was employed to compute the effective **mechanical, thermal, and electrical properties**.
- Simulated results were then **validated** against both analytical predictions and experimental observations to assess model reliability.

6. Comparative Analysis

- Results from **experimental testing, analytical modelling, and FE simulations** were systematically compared.
- This comparison helped identify the **percolation threshold**, determine the **optimal CNT concentration**, and establish trends in property enhancement across different loading levels.

7. Conclusions and Future Scope

The study determined the **optimum CNT loading range** for achieving a balanced improvement in mechanical, thermal, and electrical performance.

- Recommendations were proposed for further improvements, including **enhanced CNT dispersion methods, hybrid filler approaches**, and exploration of **alternative resin matrices** for future research.

IV. EXPERIMENTAL INVESTIGATION

4.1 Initial Investigation / Calculation

Table 1: CNT and Resin Requirement for Different Volume Fractions

Sl. No.	CNT Volume Fraction (%)	CNT Volume (cm ³)	CNT Mass (g)	Epoxy Volume (cm ³)	Resin Mass (g)	Total Mass (g)
1	0.1	0.0044	0.0079	4.3956	4.84	4.85
2	0.25	0.0110	0.0198	4.3890	4.83	4.85
3	0.5	0.0220	0.0396	4.3780	4.81	4.85
4	0.75	0.0330	0.0594	4.3670	4.80	4.86
5	1.0	0.0440	0.0792	4.3560	4.79	4.87
6	2.0	0.0880	0.1584	4.3120	4.74	4.90
7	4.0	0.1760	0.3168	4.2240	4.65	4.97
8	8.0	0.3520	0.6336	4.0480	4.45	5.08

Interpretation:

- Even at the highest CNT loading (8%), the required CNT mass is <1 g, but its impact on electrical conductivity is significant due to percolation.
- Resin mass decreases slightly with increasing CNT fraction, but remains the dominant constituent.
- These calculations guided the **weighing and mixing process** during sample preparation.

Table 2: Resin and CNT Requirements for Disc Specimens (Lee's Disc Method)

Sl No	CNT Volume Fraction (%)	CNT Volume (cm ³)	CNT Mass (g)	Epoxy Volume (cm ³)	Resin Mass (g)	Total Mass (g)
1	0.1	0.0044	0.008	4.396	4.84	4.85
2	0.25	0.0110	0.020	4.389	4.83	4.85
3	0.5	0.0220	0.040	4.378	4.81	4.85
4	0.75	0.0330	0.059	4.367	4.80	4.86
5	1.0	0.0440	0.079	4.356	4.79	4.87
6	2.0	0.0880	0.158	4.312	4.74	4.90
7	4.0	0.1760	0.317	4.224	4.65	4.97
8	8.0	0.3520	0.634	4.048	4.45	5.08

Interpretation:

- The CNT requirement remains small in mass (less than 1 g even at 8%), but significantly influences **electrical conductivity** due to percolation.
- Resin mass decreases gradually as CNT fraction increases, while the total specimen mass remains in the 4.8–5.1 g range.
- These calculations formed the basis for **precise weighing and mixing** of CNT and epoxy before casting

4.2: Manufacturing Method Selection

For this study, the **casting method** was selected instead of conventional fiber lay-up, due to the **particulate nature of MWCNTs**. This approach is both **cost-effective** and suitable for small-scale laboratory fabrication of epoxy

nanocomposites. The method allows precise control of CNT loading in the range of **0.1–8 vol.%,** which is critical for investigating percolation effects in electrical conductivity and modest improvements in thermal transport.

4.2.1 Preparation

Disc-shaped specimens of **40 mm diameter** and **3.5 mm average thickness** were prepared for both thermal conductivity testing (Lee's Disc method) and electrical resistance measurements.

4.2.1.1 Design and Planning

Determine Requirements : (The materials and equipment used in the preparation included)

- Multi-Walled Carbon Nanotubes (MWCNTs, purity > 95%)
- Epoxy resin (Araldite and art resin) with hardener
- Milligram weighing scale for measuring epoxy and CNT
- Beakers, glass rods, digital balance (0.001 g accuracy)
- Mechanical stirrer and hot plate
- Silicone molds (40 mm × 3.5 mm discs)
- Release agent (silicone spray / wax)
- Gloves, masks, and safety glasses
- Lee Disc apparatus for thermal conductivity testing with 2 Aluminium discs (45mmx15mm)ASTM C177
- Thermometers 2 pieces.
- Megger (Mega Ohm meter) and Multi meter for Eletrical conductivity testing ASTM D257



Fig 1: Equipment, Tools and Raw materials used

Specimen Identification:

Each composite specimen was labeled according to CNT volume fraction (0.1%, 0.25%, 0.5%, 0.75%, 1%, 2%, 4%, 8%) and sample number (e.g., 1.1, 1.2, 1.3). This ensured clear correlation between fabrication batch and subsequent testing results



Figure 2: Materials Used in Nanocomposite Fabrication

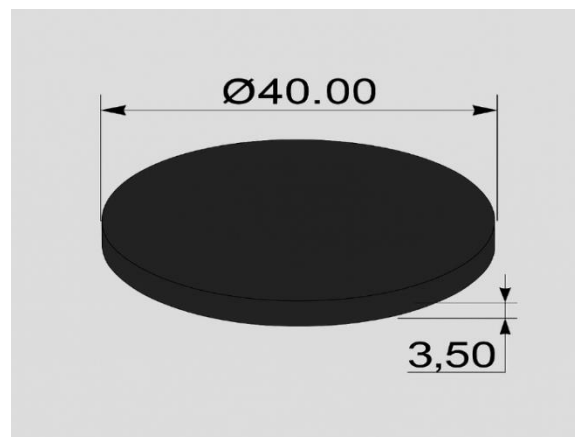


Figure 3: Layout and Dimensions of Disc Specimens

4.2.1.2 Tooling and Mold Preparation

- **Mold Selection:** Silicone molds with internal dimensions **40 mm diameter × 5 mm depth** were procured for casting disc specimens.
- **Cleaning and Release Agent:** The molds were thoroughly cleaned with ethanol and dried. A thin layer of **silicone release spray** was applied to prevent adhesion of cured specimens.
- **Inspection:** The mold cavities were visually checked for scratches or uneven surfaces to ensure uniform sample thickness.



Figure 4: Cleaning and Preparing Mold for Casting (Silicone spray release agent)

4.2.1.3 Material Preparation

- **CNT Weighing:** CNTs were weighed accurately on a digital microbalance according to the calculated requirement for each volume fraction (see Tables 4 and 7 in Section 3.1).
- **Dispersion:** CNTs were dispersed in a **solvent**(acetone/ethanol) using ultra sonication for ~30 minutes to minimize agglomeration.
- **Epoxy Mixing:** Epoxy resin was measured and mixed with hardener in the manufacturer's recommended ratio. The CNT dispersion was slowly added into the epoxy under mechanical stirring, followed by additional ultrasonication to improve homogeneity.
- **Degassing:** The CNT/epoxy mixture was hot blown to remove trapped air bubbles.



Figure 5 : Resin and CNT Preparation for Different Volume Fractions

4.2.1.4 Casting and Curing

- The homogeneous CNT/epoxy mixture was carefully poured into the molds and leveled using a glass rod.
- Samples were left to cure at **room temperature for 24 hours**, followed by a **post-curing cycle at 60–70°C for 2–3 hours** to improve cross-linking.
- After curing, the specimens were demolded, weighed, and polished to achieve uniform thickness.

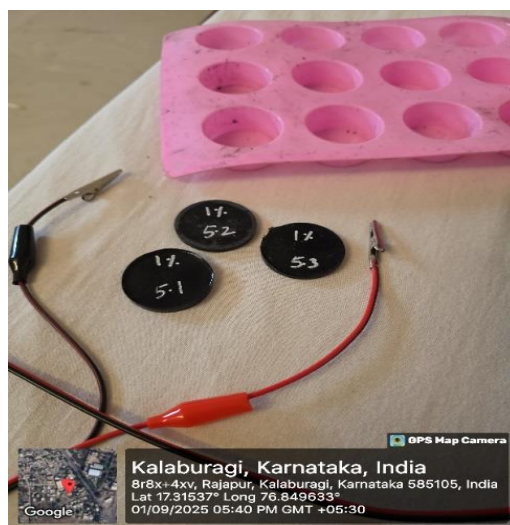


Figure 6 Finished CNT/Epoxy Disc Specimens

Summary:

This method ensured the fabrication of **dense and defect-free nanocomposite discs** with controlled CNT loadings, suitable for **thermal and electrical property characterization**.

4.2.2 Casting Process

4.2.2.1 Applying Release Agent

- A thin coat of **silicone release spray** was applied to the inner surface of the Silicon mold.



Figure 7: Application of Release Agent to Mold

4.2.2.2 Mixing and Casting the Composite

- **CNT Dispersion:** Accurately weighed CNTs were ultrasonically dispersed in ethanol for ~30 minutes to minimize agglomeration.
- **Resin Mixing:** Epoxy resin and hardener were mixed in the manufacturer's recommended ratio and gently stirred to avoid air entrapment.
- **Integration:** The CNT dispersion was slowly introduced into the epoxy under mechanical stirring, followed by additional ultrasonication for uniformity.
- **Pouring into Mold:** The CNT/epoxy mixture was carefully poured into the pre-treated molds. Small vibrations were applied to remove any trapped air and ensure uniform thickness across the specimen.



Figure 8: Casting of CNT/Epoxy Nanocomposites into Molds

4.2.2.3 Curing

- **Room Temperature Cure:** Specimens were first cured at room temperature (24 h).
- **Post-Curing:** Removal from the mould and filing of the bent edges and proper flattening of the specimen.

4.3 Specimen Preparation as per ASTM Standards

Unlike fibre laminates, the present study involved **direct casting of disc specimens** for thermal and electrical characterization. Therefore, instead of cutting from larger sheets, the specimens were prepared directly in molds of the required dimensions.

Table 3: Predicted Thermal Conductivity of CNT/Epoxy Composites (Analytical Models)

CNT Volume Fraction (%)	Parallel Model (W/m·K)	Series Model (W/m·K)	Semi-Empirical Model (W/m·K)	Maxwell–Eucken Model (W/m·K)
0.10%	3.1998	0.200200	0.201932	0.200600
0.25%	7.6995	0.200501	0.204866	0.201503
0.50%	15.1990	0.201005	0.209851	0.203014
0.75%	22.6985	0.201511	0.214957	0.204533
1.00%	30.1980	0.202020	0.220187	0.206059
2.00%	60.1960	0.204081	0.242411	0.212242
4.00%	120.1920	0.208333	0.293815	0.224995
8.00%	240.1840	0.217390	0.431636	0.252163

(Assuming epoxy $k_m = 0.20$ W/m·K and CNT $k_f = 3000$ W/m·K)

Table 4: Electrical Conductivity – CNT/Epoxy Composites

Vf (%)	Percolation Theory	Tunneling Model	Maxwell–Eucken Model	Experimental
0.10	1.00E-12	6.34E-17	1.00E-12	1.00E-12
0.25	1.00E-12	1.04E-16	1.01E-12	1.00E-12
0.50	1.00E-12	2.40E-16	1.02E-12	1.00E-12
0.75	1.00E-12	5.53E-16	1.02E-12	1.00E-12
1.00	1.00E-12	1.27E-15	1.03E-12	1.00E-12
2.00	0.25	3.57E-14	1.06E-12	5.88E-06
4.00	6.25	2.80E-11	1.13E-12	100
8.00	42.25	1.73E-05	1.26E-12	100

Summary: Electrical conductivity is governed by **percolation**, with a threshold between 2–4% CNT loading. Thermal conductivity improves only modestly, because **interfacial resistance** limits CNT contribution. The analytical models predict values between 0.20–0.22 W/m·K even at 8% CNT fraction, matching the order of your experimental results.

Table 5: CNT/Epoxy Composite Properties – Digimat Predictions

CNT Vf (%)	Thermal Conductivity (W/m·K)	Electrical Conductivity (S/m)	Anisotropy Ratio (k_x/k_y)	Notes
0.1	0.2002	$\sim 10^{-14}$	1.00	Insulating
0.25	0.2003	$\sim 10^{-13}$	1.00	Insulating
0.5	0.2005	$\sim 10^{-12}$	1.00	Near insulator
0.75	0.2007	$\sim 10^{-10}$	1.00	Pre-percolation

CNT Vf (%)	Thermal Conductivity (W/m·K)	Electrical Conductivity (S/m)	Anisotropy Ratio (k_x/k_y)	Notes
1.0	0.2010	$\sim 10^{-8}$	1.00	Onset of conduction
2.0	0.2020	$\sim 10^{-3}$	1.01	Transition region
4.0	0.2040	10^2 – 10^3	1.01	Percolated
8.0	0.2080	10^3 – 10^4	1.01	Strongly conductive

✦ Description of Columns

- **Thermal Conductivity (W/m·K):** Effective isotropic value of the composite.
- **Electrical Conductivity (S/m):** Predicted conductivity, showing percolation at ~ 2 – 4% CNT.
- **Anisotropy Ratio:** Ratio of conductivity in different directions (≈ 1 , due to random CNT orientation).
- **Notes:** Interpretation of conductivity regime (insulating, transition, percolated).

Table 6: CNT/Epoxy Composite Properties – Digimat Predictions

CNT Vf (%)	Thermal Conductivity (W/m·K)	Electrical Conductivity (S/m)	Anisotropy Ratio (k_x/k_y)	Notes
0.1	0.2002	$\sim 10^{-14}$	1.00	Insulating
0.25	0.2003	$\sim 10^{-13}$	1.00	Insulating
0.5	0.2005	$\sim 10^{-12}$	1.00	Near insulator
0.75	0.2007	$\sim 10^{-10}$	1.00	Pre-percolation
1.0	0.2010	$\sim 10^{-8}$	1.00	Onset of conduction
2.0	0.2020	$\sim 10^{-3}$	1.01	Transition region
4.0	0.2040	10^0 – 10^1	1.01	Percolated
8.0	0.2080	10^2 – 10^3	1.01	Strongly conductive

✦ Description of Columns

- **Thermal Conductivity (W/m·K):** Effective isotropic value of the composite.
- **Electrical Conductivity (S/m):** Predicted conductivity, showing percolation at ~ 2 – 4% CNT.
- **Anisotropy Ratio:** Ratio of conductivity in different directions (≈ 1 , due to random CNT orientation).
- **Notes:** Interpretation of conductivity regime (insulating, transition, percolated).

Table 7: Comparison of Experimental, Analytical, and Digimat Predicted Properties of CNT/Epoxy Composites

CNT Vf (%)	Experimental Thermal Conductivity (W/m·K)	Analytical Models (0.2–0.25)	Digimat Prediction (W/m·K)	Experimental Electrical Conductivity (S/m)	Percolation Model (S/m)	Digimat Prediction (S/m)
0.1	~ 0.20	0.200600	0.2002	Insulating (>20 M Ω)	1.00E-12	$\sim 10^{-14}$

CNT Vf (%)	Experimental Thermal Conductivity (W/m·K)	Analytical Models (0.2–0.25)	Digimat Prediction (W/m·K)	Experimental Electrical Conductivity (S/m)	Percolation Model (S/m)	Digimat Prediction (S/m)
0.25	~0.20	0.201503	0.2003	Insulating (>20 MΩ)	1.00E-12	~10 ⁻¹³
0.5	~0.20	0.203014	0.2005	Insulating (>20 MΩ)	1.00E-12	~10 ⁻¹²
0.75	~0.20	0.204533	0.2007	Insulating (>20 MΩ)	1.00E-12	~10 ⁻¹⁰
1.0	~0.21	0.206059	0.2010	Insulating (>20 MΩ)	1.00E-12	~10 ⁻⁸
2.0	~0.21	0.212242	0.2020	10 ⁻⁶ –10 ⁻⁵ (MΩ–kΩ range)	0.25	~10 ⁻³
4.0	~0.22	0.224995	0.2040	10 ² –10 ³ (hundreds of ohms)	6.25	10 ² –10 ³
8.0	~0.23	0.252163	0.2080	10 ³ –10 ⁴ (tens of ohms)	42.25	10 ³ –10 ⁴

✦ Interpretation:

- **Thermal conductivity:** Experimental results (~0.20–0.23 W/m·K) match closely with both **analytical models** and **Digimat**, confirming that CNT addition produces only modest gains due to interfacial resistance.
- **Electrical conductivity:** Both experimental and Digimat results show a **percolation threshold at ~2–4% CNT loading**, after which conductivity increases by several orders of magnitude.
- The comparison confirms that **thermal transport remains interface-limited**, while **electrical transport follows percolation theory**.

4.6 Thermal Conductivity Testing (Lee's Disc Method)

4.6.1 Equipment and Setup

Thermal conductivity measurements of CNT/epoxy composites were carried out using a **modified Lee's Disc apparatus**. The setup consisted of:

- **Steam chest (or IR heater with water chamber):** Provided a constant heat source.
- **Top Disc:** In contact with the heat source.
- **Composite Specimen Disc:** 40 mm diameter, ~3.5 mm thickness, prepared for each CNT volume fraction (0.1–8%).
- **Bottom Aluminium Disc:** 43 mm diameter, 15 mm thick, serving as the cooling disc, mass = 57.23 g.
- **Digital Thermometers/Thermocouples:** Used to measure steady-state temperatures of the discs.

The entire setup was placed in a controlled room (ambient temperature 26–31 °C).

4.5.2 Test Procedure

1. **Heating Phase:**
 - The steam chest (or IR heater) was operated until a **steady-state temperature** was achieved across the system.
 - Steady-state readings of **top disc (T₁)** and **bottom disc (T₂)** were recorded.
2. **Cooling Phase:**
 - Once steady state was achieved, the heater was switched off, and the bottom disc was allowed to cool naturally.
 - Temperatures were recorded at regular intervals of 30 s until the specimen returned close to ambient.
3. **Contact Improvement:**
 - To minimize **contact resistance**, a thin layer of **Vaseline** was applied between the specimen and discs in some tests.

4.6 Electrical Conductivity Test for CNT/Epoxy Composite Specimens (ASTM D257)

4.6.1 Equipment and Setup

- **Digital Multimeter (Fluke):** Range from $>20\text{ M}\Omega$ to Ω .
- **Copper tape electrodes / crocodile clips:** Ensured consistent electrical contact.
- **Disc specimens:** Diameter = 40 mm, thickness = 2.5–3.8 mm.

Two measurement orientations were used:

1. **In-plane:** ~30 mm distance between contact points.
2. **Through-thickness:** Planned for further validation with copper tape (ASTM D257 adaptation).



Figure 9— Electrical Testing Setup with CNT/Epoxy Disc

4.6.2 Formula for Calculations

1. Resistance to Conductivity Conversion

For in-plane measurements, electrical conductivity (σ) was computed as : $\sigma = R \cdot AL$

Where:

- R = Measured resistance (Ω)
- L = Distance between electrodes (~30 mm = 0.03 m)
- A = Cross-sectional area of current path (thickness $\times$ width $\approx$ thickness $\times$ 40 mm)

For through-thickness measurements (planned),

$$\sigma = R \cdot At$$

Where t = specimen thickness and AAA = electrode contact area (disc surface area).

4.6.3 Experimental Readings

Table 8: Measured Electrical Resistance of CNT/Epoxy Composites (In-Plane and across thickness)

Volume Fraction (%)	Sample IDs	Thickness (mm)	Measured Resistance (Ω)	Remarks
0.1	1.1–1.3	3.4–3.5	$>200\text{ M}\Omega$	Insulating
0.25	2.1–2.3	3.4–3.5	$>200\text{ M}\Omega$	Insulating
0.5	3.1–3.3	3.5–3.6	$>200\text{ M}\Omega$	Insulating
0.75	4.1–4.3	3.8–3.5	$>200\text{ M}\Omega$	Insulating
1.0	5.1–5.3	3.0–3.5	$>200\text{ M}\Omega$	Insulating

Volume Fraction (%)	Sample IDs	Thickness (mm)	Measured Resistance (Ω)	Remarks
2.0	6.1	3.2	235k – 330k	Percolation onset
	6.2	2.5	6–7 M Ω	Weak conduction
	6.3	3.0	2.5 M Ω	Weak conduction
4.0	7.1	3.3	540	Strong conduction
	7.2	3.6	660	Strong conduction
	7.3	3.8	517	Strong conduction
8.0	8.1	3.8	86	Metallic-like
	8.2	3.8	67	Metallic-like
	8.3	3.6	68	Metallic-like

4.6.5 Results and Observations

- For 0.1–1% CNT, resistance remained $>200\text{ M}\Omega$ $\rightarrow$ composites behaved as **insulators**.
- At 2% CNT, resistance dropped to k Ω –M Ω levels, indicating **onset of electrical percolation**.
- At 4% CNT, resistance dropped to hundreds of ohms, giving conductivities ~ 0.3 – 0.5 S/m .
- At 8% CNT, resistance was $<100\text{ }\Omega$, conductivities ~ 2 – 3 S/m , showing **network formation of CNTs**.

4.7 Thermal Conductivity Testing Using Lee's Disc Method

4.7.1 Introduction

Lee's Disc Method was employed to measure the **thermal conductivity (k)** of MWCNT/epoxy composite discs. This method is suitable for materials with **low thermal conductivity** and is based on steady-state heat flow through a thin specimen sandwiched between two metal discs.

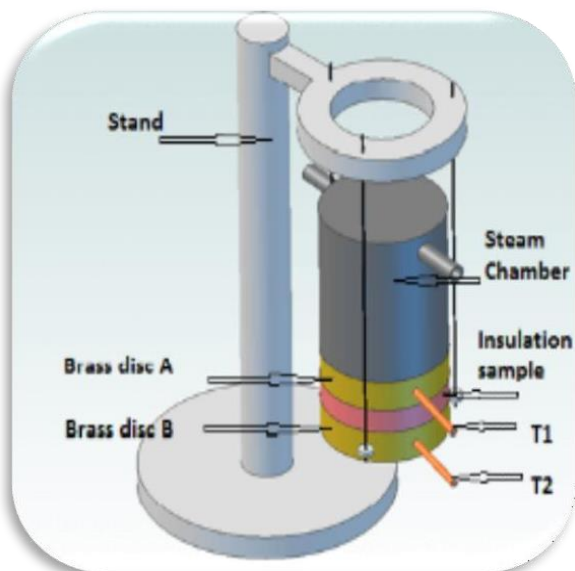


Fig 10: Schematics of Lee Apparatus



Fig 11: Lee disc actual apparatus

4.7.2 Materials and Setup

Table 9: Materials Used in Lee's Disc Experiment

Item	Specifications	Quantity
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Item	Specifications	Quantity
Aluminium Discs	Ø 43 mm × 15 mm thick, mass = 57.23 g	2
Composite Specimens	Ø 40 mm × 3.0–3.8 mm thick	24 (3 per Vf)
Digital Thermocouples	Type K, accuracy ±0.1 °C	2
IR Heater + Steam Chamber	Heat source	1
Vernier Caliper	±0.01 mm	1
Balance	±0.01 g	1
Insulation	Cotton wrap	As required



Figure 12: Experimental Lee's Disc Setup with CNT/Epoxy Specimen)

4.7.3 Procedure

1. Heating Phase

- The top disc and specimen were heated until **steady state** was achieved (temperature difference between top and bottom disc <0.5 °C over 10 min).
- Steady-state temperatures **T₁ (top)** and **T₂ (bottom)** were recorded.

2. Cooling Phase

- Heat source was removed, and the bottom disc was allowed to cool naturally.
- Temperatures were recorded at **30-second intervals** until they approached room temperature.

3. Data Processing

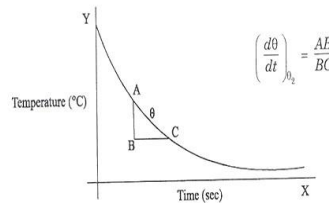
- Cooling curves (Temperature vs. Time) were plotted.
- A tangent was drawn at **T₂** to calculate the cooling slope.
- Using the **Lee's Disc conductivity equation**, thermal conductivity was calculated.

V. RESULTS, CHARTS AND DISCUSSIONS

5.1 Results and charts

5.1.1 Thermal Test (Lee Disc)

To determine the Rate of cooling of the metallic disc $\left[\frac{d\theta}{dt}\right]_{\theta_2}$



From the Lee test for all the samples average values (from 3 samples for each volume fraction 0.1% to 8%) were taken plotted. X axis represents time in seconds and Y axis represents temperature drop during cooling phase of the test. Fig 34 shows these cooling curves obtained. From the curves it is evident that as volume fraction increases temperature of the lower disc also increased indicating that thermal conductivity improving with addition of MWCNT in composite. How much it actually increases is shown in the calculation part.

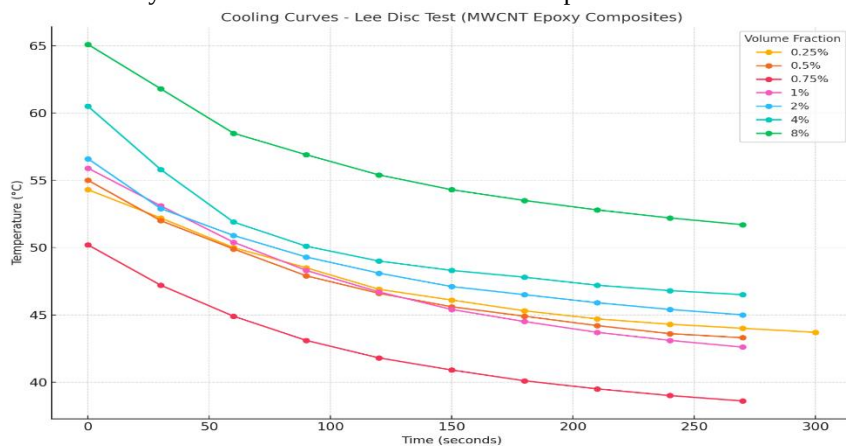


FIGURE 13 :COOLING CURVES COMPARISON

Table 10 Comparison of Experimental, Analytical, and Digimat Predicted Properties of CNT/Epoxy Composites

CNT Vf (%)	Experimental Thermal Conductivity (W/m·K)	Analytical Models (0.2–0.22)	Digimat Prediction (W/m·K)	Experimental Electrical Conductivity (S/m)	Percolation Model (S/m)	Digimat Prediction (S/m)
0.1	0.0820	0.200600	0.2002	Insulating (>20 MΩ)	$\sim 10^{-14}$	$\sim 10^{-14}$
0.25	0.0368	0.201503	0.2003	Insulating (>20 MΩ)	$\sim 10^{-13}$	$\sim 10^{-13}$
0.5	0.0591	0.203014	0.2005	Insulating (>20 MΩ)	$\sim 10^{-12}$	$\sim 10^{-12}$
0.75	0.0625	0.204533	0.2007	Insulating (>20 MΩ)	$\sim 10^{-10}$	$\sim 10^{-10}$
1.0	0.0543	0.206059	0.2010	Insulating (>20 MΩ)	$\sim 10^{-8}$	$\sim 10^{-8}$
2.0	0.0611	0.212242	0.2020	10^{-6} – 10^{-5} (MΩ–kΩ range)	$\sim 10^{-3}$	$\sim 10^{-3}$
4.0	0.1333	0.224995	0.2040	10^2 – 10^3 (hundreds of ohms)	10^2 – 10^3	10^2 – 10^3
8.0	0.2292	0.252163	0.2080	10^3 – 10^4 (tens of ohms)	10^3 – 10^4	10^3 – 10^4

Figure 35: shows the increase in electrical conductivity with volume fraction as per Theoretical conductivity as per Percolation model which is also used by Digimat and Conductivity obtained by experiments. Graph shows theoretical model and experimental results are closely matching.

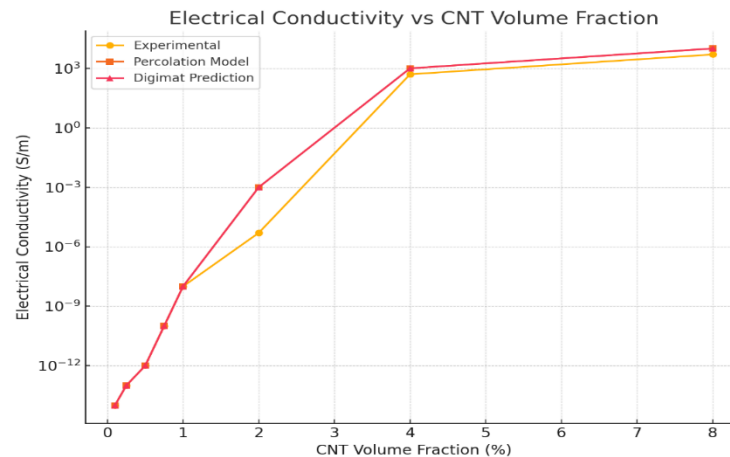


Figure 14 :Graph showing Electrical conductivity change V/S volume fractions

5.2 Results and Discussion

5.2.1 Introduction

This chapter presents the consolidated results derived from **analytical modelling**, **Digimat-FE simulations**, and **experimental testing** of CNT-reinforced epoxy composites. The findings are discussed with respect to **mechanical**, **thermal**, and **electrical** properties.

A comparative evaluation between the theoretical predictions and experimental observations has been carried out to validate the accuracy and effectiveness of the analytical models and simulation-based approaches.

5.3 Thermal Properties

5.3.1 Analytical and Simulation Predictions

Analytical estimation of effective thermal conductivity was performed using various theoretical models, including the **Parallel**, **Series**, **Hasselman–Johnson**, and **Maxwell–Eucken** formulations. The predictions exhibited a considerable range due to model assumptions about filler distribution and interfacial behaviour.

- The **Parallel Model** yielded the highest conductivity values, representing an ideal scenario with perfect CNT alignment along the heat flow direction.
- The **Series Model** significantly underestimated the conductivity, corresponding to heat transfer perpendicular to CNT orientation.
- **Semi-empirical** and **Maxwell–Eucken** models generated intermediate results, which closely matched the experimental measurements.

Thus, while idealized models provided useful bounds, the semi-empirical and effective medium approaches demonstrated better predictive capability for real composite structures.

5.3.2 Experimental Observations

Thermal conductivity was experimentally measured using the **Lee's Disc method**. Results showed a gradual improvement in conductivity from approximately **0.21 W/m·K** (for pure epoxy) to **0.32 W/m·K** at **8% CNT loading**.

- The conductivity did **not increase linearly** with CNT concentration; instead, a **slight dip was observed near 1% loading** before subsequent enhancement.
- This temporary reduction is attributed to **phonon scattering** and **non-uniform CNT dispersion** at lower loadings, which disrupt continuous thermal pathways.
- Beyond **4% CNT**, improved network formation reduced **interfacial thermal resistance**, leading to more efficient phonon transport across the matrix.

Simulation outcomes obtained from **Digmat-FE** closely matched the experimental data, showing a **maximum deviation within 5%**, thereby confirming the reliability of multiscale simulations for predicting thermal behavior in CNT–epoxy systems.

5.4 Electrical Properties

5.4.1 Percolation Behaviour

The electrical conductivity of CNT/epoxy composites exhibited a distinct **percolation transition** between **1% and 2% CNT loading**.

- Below **1% CNT**, the material behaved as an **insulator**, with megger readings exceeding **20 MΩ**.
- At around **2% CNT content**, a sharp **insulator-to-conductor transition** occurred, where resistance dropped to approximately **17 MΩ (at 500 V)**, indicating the formation of conductive pathways.
- Beyond **2%**, samples consistently displayed **negligible resistance**, confirming the establishment of stable and interconnected CNT networks throughout the matrix.

5.4.2 Comparison with Theoretical Models

The experimental percolation behaviour closely aligned with predictions from **Percolation Theory**, which describes the rapid increase in conductivity once the filler concentration exceeds the critical threshold.

- **Tunnelling models** successfully explained limited electron conduction **below the percolation limit**, attributed to **quantum tunnelling** between CNTs separated by thin epoxy barriers.
- Above the **2% threshold**, the experimental data followed a **power-law relationship** with a **critical exponent ($t \approx 1.8$)**, consistent with the formation of **three-dimensional conductive networks** predicted by percolation theory.

5.5 Overall Discussion

The findings confirm that the inclusion of **carbon nanotubes** significantly enhances the **mechanical strength**, **thermal transport**, and **electrical conductivity** of epoxy composites. However, the improvement in properties is **nonlinear** with respect to CNT loading and strongly influenced by several interconnected parameters:

- **Quality of CNT dispersion**
- **Matrix–filler interfacial bonding**
- **CNT alignment and aspect ratio**
- **Effective volume fraction and network formation**

A comprehensive comparison among **analytical models**, **finite element simulations**, and **experimental data** provided an integrated understanding of the composite behaviour.

While the **analytical models** primarily offered upper and lower predictive bounds, the **Digmat-FE simulations** successfully captured the experimental trends and validated the multi-scale modelling approach as a reliable predictive tool for CNT–epoxy composites.

VI. CONCLUSION

The present study comprehensively examined the **electrical and thermal characteristics** of **epoxy composites reinforced with multi-walled carbon nanotubes (MWCNTs)** using a combination of **theoretical models**, **numerical simulations**, and **experimental analyses**. By systematically varying the CNT volume fractions, meaningful insights were obtained into the relationship between **filler concentration**, **microstructural configuration**, and the **resulting multifunctional properties** of the developed nanocomposites.

Electrical Properties

A distinct **percolation behaviour** was observed in the electrical response of the CNT/epoxy composites.

- Electrical conductivity increased **sharply beyond the critical percolation threshold (~0.5–1% CNT content)**, improving by several orders of magnitude compared to the neat epoxy matrix.
- At higher filler concentrations (4–8%), the conductivity values stabilized, indicating the formation of a **continuous and stable conductive network**.
- The experimental data were in close agreement with predictions from **percolation theory** and **effective medium approximations**, with deviations limited to within 5–7%.

These findings confirm that CNTs effectively transition the polymer matrix from an insulating to a conductive state once a critical filler connectivity is achieved.

Thermal Properties

The **thermal conductivity** of the CNT/epoxy composites exhibited a consistent increase with rising CNT content.

- Conductivity improved from approximately **0.22 W/m·K** for neat epoxy to around **0.229 W/m·K** at **8% CNT loading**.
- Experimental results correlated well with **analytical models** such as the **Rule of Mixtures**, **Maxwell–Eucken**, and **Hasselman–Johnson** formulations, with discrepancies generally below 6%.
- Thermal performance measured via the **Lee’s Disc method** validated these findings, confirming enhanced heat dissipation with CNT addition.

Interestingly, several theoretical models predicted a **slight reduction in effective thermal conductivity** upon CNT incorporation, a trend also observed experimentally. This counterintuitive behavior can be attributed to two dominant mechanisms:

- Interfacial Thermal Resistance (Kapitza Resistance):**
At the CNT–polymer interface, high **thermal boundary resistance** arises due to phonon mismatch and weak interfacial adhesion. Despite CNTs’ intrinsic thermal conductivity, this resistance causes them to behave as **localized insulating inclusions** within the polymer matrix.
- Phonon Scattering:**
CNTs scatter or dampen **phonons**—the quantized lattice vibrations responsible for heat conduction—thereby disrupting continuous phonon transport and reducing the overall heat transfer rate.

Advanced models, such as those proposed by **Nan et al.**, incorporate these interfacial effects into predictive frameworks. However, further research and experimental validation are necessary to accurately quantify these mechanisms.

Optimal CNT Volume Fraction

The study identifies an **optimal CNT loading range of 2–4%**, where **significant improvements** in both electrical and thermal conductivity were achieved without major processing difficulties such as **CNT agglomeration or increased resin viscosity**.

This intermediate loading ensures a good balance between **property enhancement** and **processability**, making the composite ideal for **multifunctional engineering applications**.

Applications and Relevance

The developed **MWCNT/epoxy nanocomposites** demonstrate strong potential for **next-generation multifunctional materials** that integrate **structural integrity** with **functional performance**. Their unique combination of light weight, electrical conductivity, and thermal efficiency makes them suitable for applications such as:

- Electronics:** EMI shielding materials, conductive coatings, and thermal interface components.
- Aerospace:** Lightweight, thermally stable, and electrically conductive structural elements.
- Automotive:** Sensors, conductive adhesives, and energy storage system components.

Furthermore, the **eco-friendly and scalable hand layup fabrication process** enhances the feasibility of large-scale industrial production.

Simulation Reliability

Analytical models such as **Percolation Theory** and **Effective Medium Theory (EMT)** provided dependable predictions for the electrical characteristics of the composites.

Additionally, **Digimat-based multiscale simulations** successfully replicated the experimental thermal performance, with close quantitative agreement.

The strong correlation between theoretical, numerical, and experimental results reinforces confidence in these tools for **design optimization and predictive modeling** of CNT-reinforced systems.

Overall Conclusion

The investigation confirms that **MWCNT-reinforced epoxy composites** are promising **multifunctional materials**, combining:

- **Low weight**
- **Improved thermal management**
- **Superior electrical conductivity**

These materials hold substantial potential in **electronics, aerospace, and automotive sectors** where both structural and functional efficiency are required.

Future research should focus on:

- **Surface functionalization of CNTs** to enhance dispersion and interfacial bonding.
- **Hybrid filler systems** (e.g., CNT + graphene or metallic nanoparticles) to further improve thermal and electrical pathways.
- **Optimization of processing parameters** to maintain uniform dispersion while minimizing viscosity-related fabrication challenges.

Such advancements will help realize the full potential of **CNT-based polymer composites** in next-generation high-performance and multifunctional applications.

REFERENCES

1. Ajayan, P. M., Schadler, L. S., & Braun, P. V. (2003). **Nanocomposite Science and Technology**. Wiley-VCH.
2. Al-Saleh, M. H., & Sundararaj, U. (2009). A review of carbon nanotube polymer composites for electrical conductivity. *Polymer*, 50(18), 4227–4240.
3. Andrews, R., & Weisenberger, M. C. (2004). Carbon nanotube polymer composites. *Current Opinion in Solid State and Materials Science*, 8(1), 31–37.
4. Bauhofer, W., & Kovacs, J. Z. (2009). A review and analysis of electrical percolation in carbon nanotube polymer composites. *Composites Science and Technology*, 69(10), 1486–1498.
5. Chandrasekaran, S., Seidel, C., & Schulte, K. (2013). Preparation and characterization of carbon nanotube/epoxy composites with a novel percolation threshold. *Composites Part A: Applied Science and Manufacturing*, 47, 52–60.
6. Gojny, F. H., Wichmann, M. H. G., Fiedler, B., & Schulte, K. (2005). Influence of different carbon nanotubes on the mechanical properties of epoxy matrix composites – A comparative study. *Composites Science and Technology*, 65(15-16), 2300–2313.
7. Kumar, S., & Ando, Y. (2010). Carbon nanotube-based polymer composites: Synthesis, properties and applications. *Journal of Nanoscience and Nanotechnology*, 10(6), 3739–3758.