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Evaluation of Mechanical and Thermal Properties of a Reinforced Thermosetting Polymer with Glass Fiber and Multi-Walled Carbon Nanotubes

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Abstract: This study has been explored the enhancement of the mechanical, physical, and thermal properties of a polymeric matrix by incorporating fiberglass, multi-wall carbon nanotubes (MWCNTs), and also, their hybrid combinations. Composite materials have been fabricated with different filler concentrations and have been evaluated for tensile strength, thermal conductivity, compressive strength, and the coefficient of thermal expansion (CTE). The results have shown that the addition of 3 wt% of the glass fibers has significantly increased the compressive strength by approximately 29%, while 3 wt% of the MWCNT effectively maintains the tensile strength and significantly improves the thermal conductivity and dimensional stability. The incorporation of the MWCNT has increased the thermal conductivity by 125% and has significantly decreased the CTE, indicating limited mobility of the polymer chain, and has improved the thermal performance. Conversely, the hybrid composites did not exhibit synergistic effects and often performed poorly compared to the single-reinforcement systems. Because of the poor dispersion and agglomeration of nanoparticles, in addition to interface mismatch, the results for each type of reinforcement demonstrated distinct advantages and emphasized the need for improved processing strategies to achieve functional synergies in hybrid nanocomposite materials for various applications.

Keywords: Nanocomposite, Hybrid materials, Fiberglass, Multi-walled carbon nanotube (MWCNT), Thermal conductivity

Introduction

Nanotechnology is defined as a technology that deals with nanomaterials or microscopic structures and their applications. In the recent century, applications of nanomaterials have been one of the most promising fields of research. A number of technologies have been developed to mix two or more materials, at least one of them at the nanoscale level (1-100nm) or less (Almuramady et al.., 2025). Adding nanoparticles, carbon, graphene, or carbon nanotube particles, is one of these strategies (Groover., 2019). They have been widely used in polymeric and ceramic fields to improve thermal (conductivity, expansion) and mechanical properties, in addition to electrical (Qian, & Hinestroza, 2004). Studying these applications, approximately, in all scientific branches: composite materials science, engineering, physics, and biology. Various methods have been used to manufacture multi-stage or multi-phase materials, including mechanical and chemical methods, as well as biological approaches. (Rajak et al.., 2019). Multiphase materials are materials that combine nanoparticles with a matrix material, for example, metal, polymer, or ceramic; the resulting material is called a nanocomposite

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material (Alobaidi, & Almuramady, 2023). These materials exhibited high rigidity, high durability, and light weight (Saharudin et al.., 2017). Then, for decades, researchers have been modifying them for use in a wide range of applications, such as aerospace and automotive, etc (Tiwari et al.., 2020). Nanocomposite materials are used in a variety of engineering applications due to their ability to modify their characteristics (Mohammed et al.., 2023). Abd E-Aty and Ghazal (2023) have conducted a study to improve the thermal properties of nanocomposites to ensure the optimal performance for the nanoparticles. The current study investigates the impact of various types of reinforcement on the mechanical properties (tensile and compressive strength), thermal conductivity, and extensibility of the Quickmast 120 thermoplastic polymer, incorporating glass fibers and multi-walled carbon nanotubes, which is explained its properties in (Koloor, et al., 2023).

Hybrid composites are a type of combination of two or more different reinforcing materials (carbon and fiber) with a common matrix, like any type of polymeric material (Alobaidi, et al., 2023). The combination of reinforcing materials has allowed the resulting material to show a mixture of the other reinforcing properties (Alawsi, et al., 2025). For example, a hybrid composite is a blend of the high strength and stiffness of adhesive material and the fiber layers with the impact resistance of aramid fiber, resulting in a material with improved overall performance compared to conventional composites (Mosa, et al., 2024). Hybrid reinforcing composite materials are used in a variety of applications, where a combination of specific properties is required. development in the field of hybrid composites continues to explore new material combinations and manufacturing techniques. They have improved their properties and expanded their use in various industries (Rahma, 2024). The descriptions in this section are hybrid composites of macroscopic, microscopic, and nano mixtures. The properties of these materials can be understood by combining the properties of their constituent materials, e.g., the blend base (Rahmah, 2024). These materials have been called "structurally hybrid" because hybridization of the macroscopic structure is the purpose of combining or mixing the materials (Alobaidi, et al., 2023; Pagliaro, et al., 2025). Materials, which have composites with a characteristic scale of less than a micrometer, exhibit superior properties compared to macroscopic composites. Their excellent properties have been attributed to their fine microstructure or grain boundary effects. Nanoparticles are designed to have a nanoscale-mixture structure (Hadi, 2022). Therefore, nanocomposites are considered a type of structurally hybrid material. However, some nanocomposites exhibit excellent properties based on the special chemical bonds at the interface between their constituent materials. In this case, the mixture is not intended to form a composite structure (Oudah, et al., 2023; Shallal & Almuramady, 2025), but rather to create new chemical bonds.

The aim of this study is to investigate the effects of hybrid reinforcement using glass fibers and smart nanoparticles, specifically, multi-walled carbon nanotube (MWCNT), on the thermal and mechanical properties of a polymeric matrix (Thermosetting polymer Quickmast 120). In systematically differentiating the reinforcement content, the study is attempting to evaluate the collaborative effect of these additives on the performance parameters, for example, the tensile strength, compressive strength, thermal conductivity, and also the coefficient of thermal expansion. Then identify the optimal reinforcement combinations that improve specific material properties, enabling the development of multi-functional composites for advanced engineering applications. Therefore, this study aims to evaluate the individual and combined effects of glass fibers and MWCNT on the behavior of Quickmast 120 and identify the effective reinforcement process for advanced nanocomposites applications.

In this work, the samples have been prepared by reinforcing Quickmast 120 thermosetting polymer with varying weight percentages of fiberglass and MWCNT, either individually or in hybrid mixtures. The D638 and D695 have been used for preparing the specimens. Moreover, tensile, compressive, thermal conductivity, and the coefficient of thermal expansion have been evaluated. This enables a comprehensive assessment of the mechanical and thermal performance (Dawood et al., 2022). Also, studying the effect of stress on the materials, especially when they are in contact (Al-Mayali, 2017).

Materials and Methods

Materials

Thermosetting Resin

Quickmast-120 is a compound of a two-component thermosetting polymer “resin and hardener”. It has been specifically designed for the treatment of cracks in engineering structures. Also, it's used in concrete structures. The properties include high flexibility, elastic elongation properties, and high tensile strength, which make this polymer unique. It is utilized in dynamic applications to achieve a robust and effective sealing for the active cracks. The behavior of the resin may vary depending on several parameters, such as crack width and depth, the thickness of the structural element, and the crack's location. Its principal function is to fill and seal cracks, thereby restoring the structural continuity and preventing the infiltration of moisture or other potentially harmful agents (Hussein et al., 2025).

E-Glass Fibers

They have been made by drawing molten glass into excellent strands. due to their excellent mechanical properties, like low density and cost-effectiveness compared to metals, glass fiber is widely used in diverse sectors, such as automotive, construction, aerospace, and marine industries. One of the most important applications is in fiber-reinforced polymer nanocomposites, where glass fiber acts as a reinforcing phase within a polymer matrix. This combination results in a material that combines high strength with low weight, making it ideal for structural and lightweight component applications. Table 1 shows the Physical and mechanical properties of fiberglass, as mentioned in the reference. (Sathishkumar, et al., 2014). Also in ref. (Zhang, et al., 2025)

Table 1. Properties of glass fiber.

Fiber	Density (g/cm^3)	Tensile strength GPa	Young's modulus (GPa)	Elongation (%)	Coefficient of thermal expansion ($10^{-7}/°C$)	Poison's ratio	Refractive index
E-glass	2.58	3.445	72.3	4.8	54	0.2	1.558
C-glass	2.52	3.310	68.9	4.8	63	–	1.533
S_2-glass	2.46	4.890	86.9	5.7	16	0.22	1.521
A-glass	2.44	3.310	68.9	4.8	73	–	1.538
D-glass	2.11–2.14	2.415	51.7	4.6	25	–	1.465
R-glass	2.54	4.135	85.5	4.8	33	–	1.546
EGR-glass	2.72	3.445	80.3	4.8	59	–	1.579
AR glass	2.70	3.241	73.1	4.4	65	–	1.562

Multi-Walled Carbon Nanotube (MWCNT)

They have a size ranging in the nano level from approximately 20 to 30 nm, and have diverse properties and applications. They enhance the heat dissipation in projection lamps, improve the efficacy of photothermal therapy, and as components in hybrid nanocomposites. Furthermore, the MWCNTs in this size range have been studied for their effect on the rheological behavior of nanolubricants. Furthermore, research has shown that the toxicity of MWCNTs may be inversely proportional to their size, with MWCNTs smaller than 8 nm exhibiting higher toxicity than those in the 20-30nm range. Their unique properties make them suitable for a wide range of applications (Koloor et al., 2023). Figure 1 illustrates an MWCNT type.

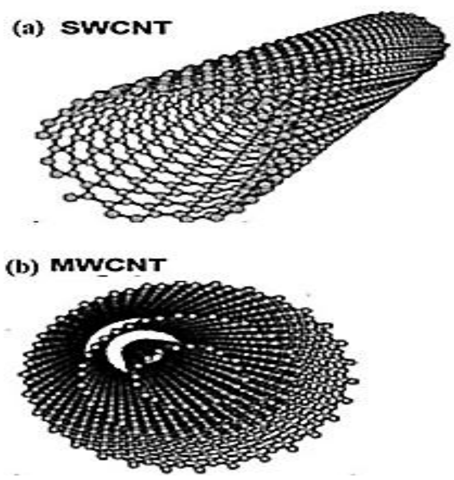

Figure 1. (a) Single-walled (SWCNTs) and (b) MWCNTs (Koloor, et al., 2023)

Equipment Used

According to the methods of manufacturing the nanocomposite materials, the following instruments were utilized in the testing of samples:

Figure 2. The Universal tensile tester

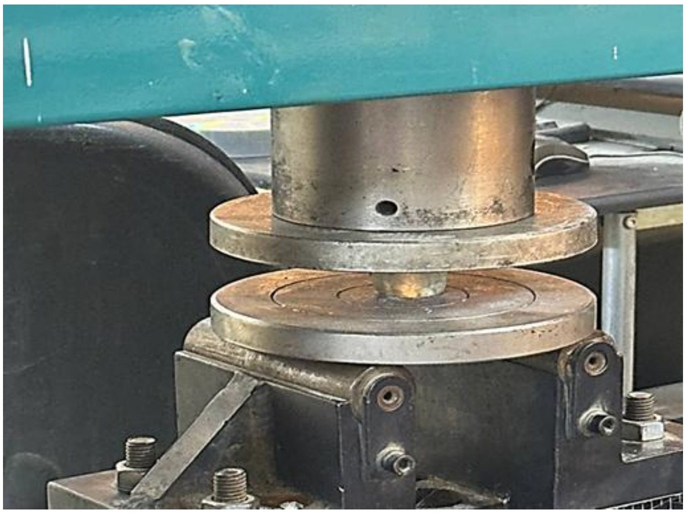

Figure 3. Compressive strength tester (Hydraulic Press Universal Tester)

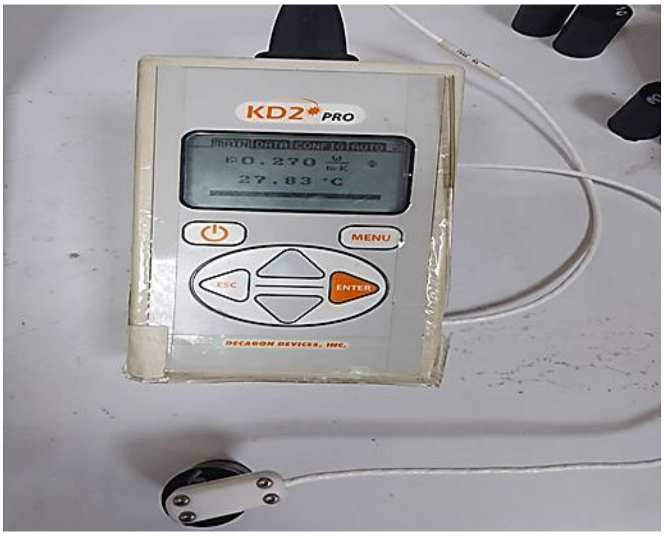

Figure 4. Thermal conductivity tester

Figure 5. Thermal expansion testing machine

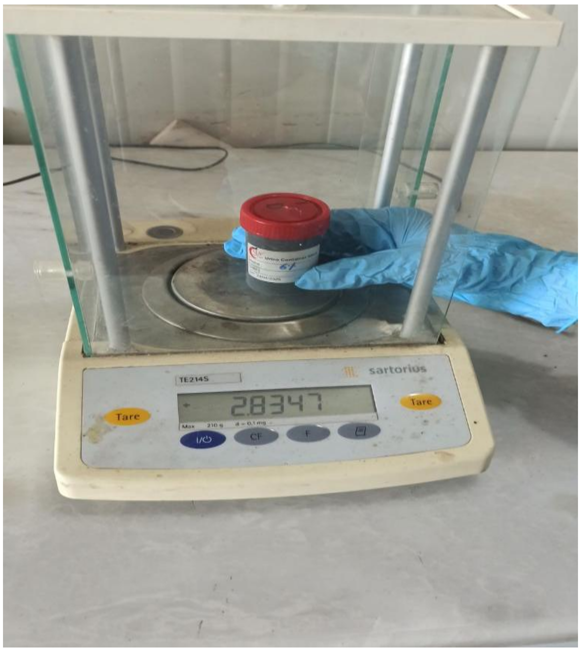

Figure 6. Sensitive digital balance

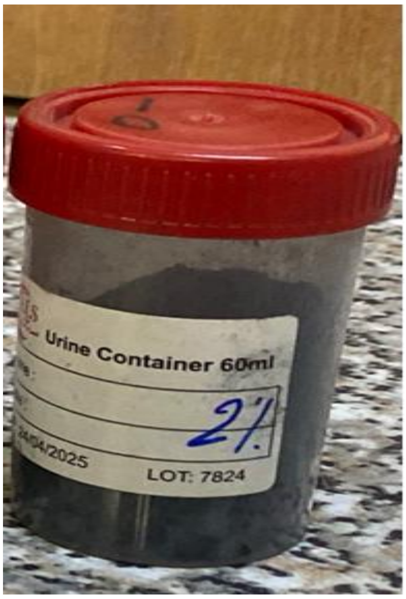

Figure 7. Percentages of the MWCNTs

Sample Preparation

Based on the results of previous studies, the reinforcement ratios (1 to 3 wt% of fiberglass, 1 to 3 wt% of MWCNT, and their hybrid assemblies) have been selected for the experiments. This is because the hybrid reinforcement ratios are likely to create synergistic effects between the overall reinforcement efficiency of glass fibers and the nanoscale performance of MWCNTs.

Samples were prepared with the following weight percent compositions:

- Thermosetting polymer resin Quickmast 120
- 1%, 2% and 3% fiberglass
- 1%, 2% and 3% MWCNT
- Hybrid combinations: 1% fiberglass + 1% MWCNT, 2% fiberglass + 2% MWCNT and 3% fiberglass + 3% MWCNT

Each formulation was cast and cured under standard laboratory conditions, as shown in Figure 8. Using mechanical stirring for 10 minutes at medium speed, MWCNTs were dispersed into the polymer resin. Continuous stirring promotes uniform nanoparticle distribution. Fibers of Glass have been pre-cut manually and have been embedded into the polymeric resin before casting with stirring for 10 min. This process was carried out at a room temperature of 25°C for 24 hours, followed by a subsequent cure at 60°C for 2 hours to ensure complete polymerization of the thermosetting resin.

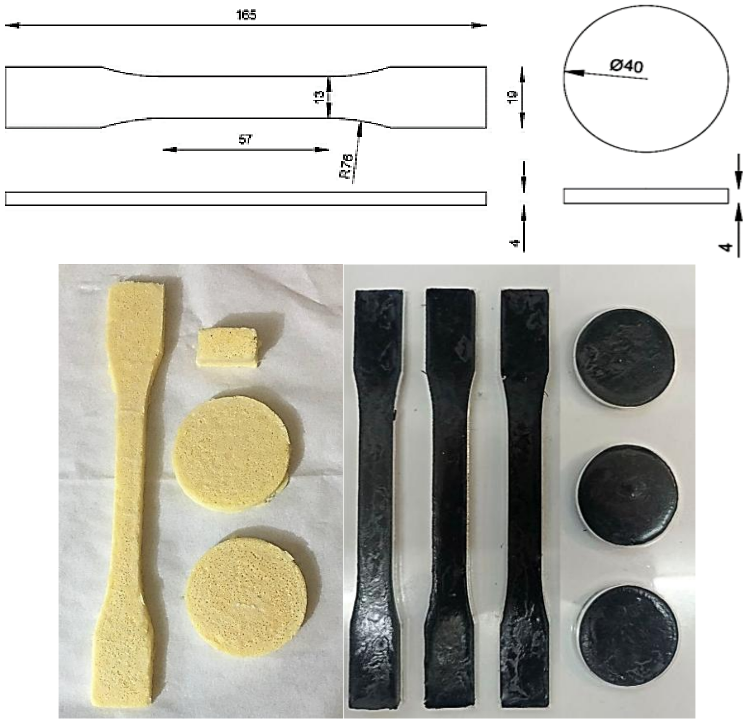

Figure 8. Sample preparation according to the standard (a) pure (b) with MWCNTs

Specimens were manufactured according to ASTM standards- ASTM D638 for tensile strength and ASTM D695 for compressive strength. For each composition, three specimens were prepared and tested to ensure measurement consistency. The experimental apparatus was designed to evaluate the tensile and compressive behavior of the newly developed materials.

Results and Discussion

Tensile Strength

Figures 9 to 11 have revealed the following insights: the percentage of 3% Glass Fiber achieved the highest tensile strength of 5.18 MPa among the reinforced samples. This indicates a significant reinforcing effect due to fiber-matrix stress transfer, although it remained slightly lower than the neat polymer, likely due to stress concentration or fiber-matrix debonding. When adding 3% MWCNTs to the polymetric composite maintained a relatively high tensile strength of 5.07 MPa was maintained, suggesting effective dispersion and interfacial adhesion, which allowed efficient load transfer. The Hybrid Reinforcement (Glass Fiber + MWCNTs) showed lower tensile performance. This may be attributed to the Poor dispersion of MWCNTs, Agglomeration effects, Incompatibility or weak bonding at the glass fiber, MWCNT, polymer interface, and Stress localization and micro-defect generation. Although both reinforcements independently improved or maintained tensile strength, the hybrid system failed to capitalize on synergistic effects due to interfacial and dispersion issues.

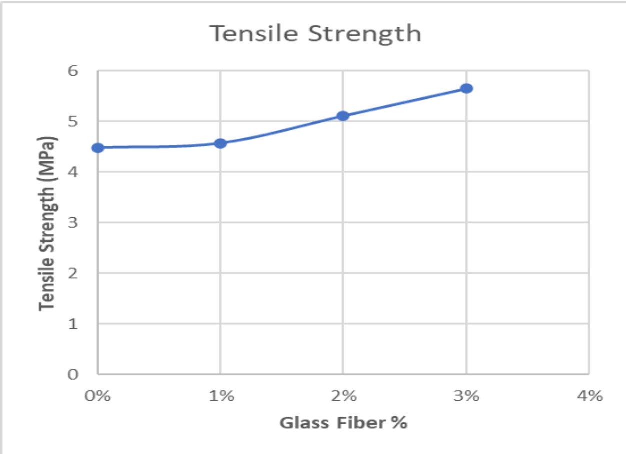

Figure 9. Tensile strength with glass Fiber

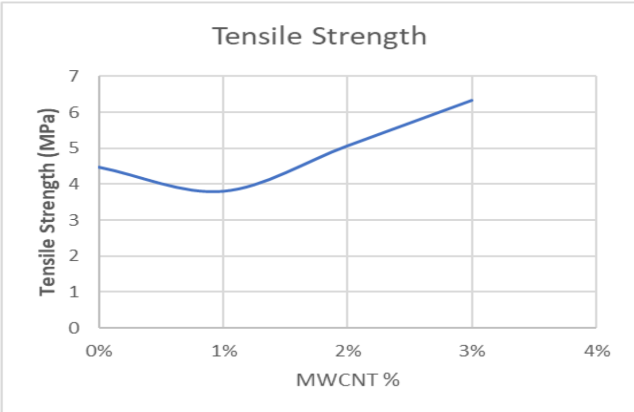

Figure 10. Tensile strength with the MWCNTs

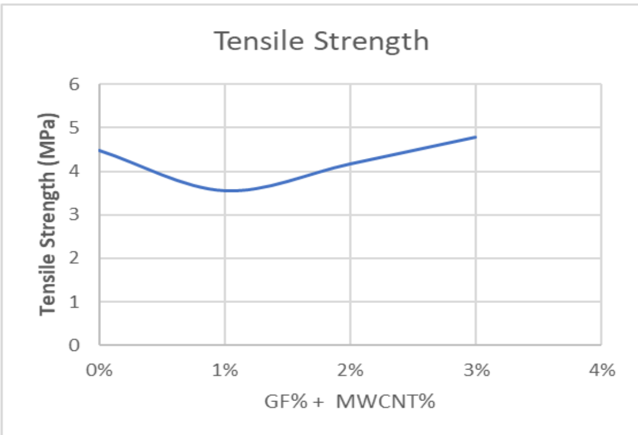

Figure 11. Tensile strength with the MWCNTs+ Glass Fiber

$$\text{Percentage Enhancement} = \frac{\text{Value with Reinforcement} - \text{Base Value}}{\text{Base Value}} \times 100\%$$

Based on the results from Figure 9, let's assume the base polymer values (unreinforced) for the Tensile Strength (Base): 4.511 MPa. Then the enhancement percentage will be as follows in Table 2

Table 2. Tensile strength enhancement

Additives	Value (MPa)	Enhancement (%)
3% Glass Fiber	5.18	+14.85%
3% MWCNTs	5.07	+12.38%
Hybrid (MWCNT + GF)	(Assumed < Base)	Negative

Compressive Strength

The compression test shown in Figures 12 to 14, the percentages of 3% Glass Fiber have provided a marked increase in compressive strength (~5.15 MPa). This supports the well-known role of glass fibers in resisting compressive loads by distributing stress and preventing buckling or deformation. When the MWCNTs are used alone, they have minimal influence on compressive strength, likely because. The nanoscale morphology in the polymetric composite and high aspect ratio contribute more under tensile or flexural loads. They may not provide sufficient resistance to bulk compressive deformation. While hybrid reinforcement showed a slight improvement, indicating partial, albeit not perfect, load sharing between fibers and nanotubes, glass fibers are more effective at enhancing compressive strength. Multi-walled carbon nanotubes (MWCNTs) contribute little unless their alignment or processing is improved. Hybrid effects remain underutilized.

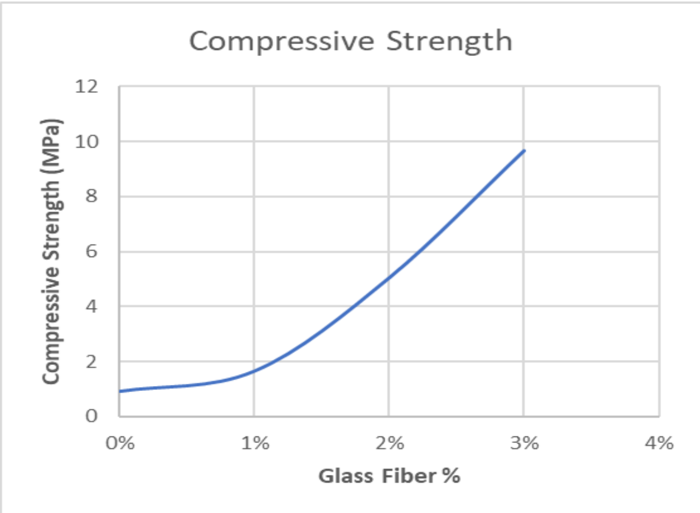

Figure 12. Compressive strength with glass fiber

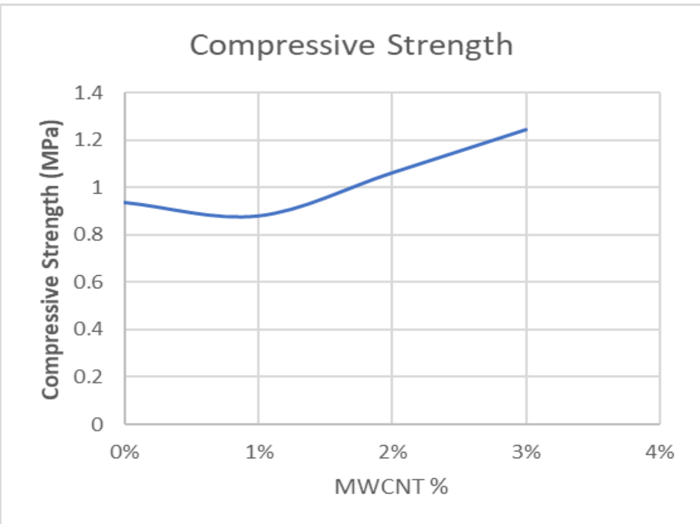

Figure 13. Compressive strength with the MWCNTs

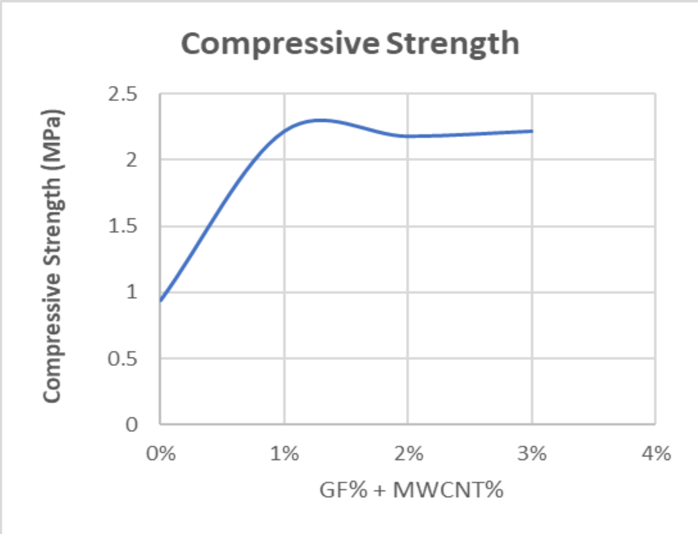

Figure 14. Compressive strength with the MWCNTs + glass fiber

In the Compressive Strength Enhancement, it can be assumed that the base polymer compressive strength = 4.00 MPa, then the percentage of enhancement will be as follows in Table 3

Table 3. Compressive strength enhancement

Additives	Value (MPa)	Enhancement (%)
3% Glass Fiber	5.151	+28.78%
3% MWCNTs	~4.00	≈ 0%
Hybrid (MWCNT + GF)	~4.50	+12.5%

Thermal Conductivity

In Figures 15 to 17, the results show that the MWCNTs have a significantly enhanced thermal conductivity (as in Figure 16), in line with the intrinsic high thermal conductivity of the CNTs (~3000–6000 W/m·K). This demonstrates that even small percentages of well-dispersed CNTs can create conductive pathways. The Glass Fibers, due to their low intrinsic thermal conductivity, did not enhance and may slightly hinder heat transfer, likely by interrupting conduction networks in the polymeric matrix. In the Hybrid Reinforcement, results have shown improvement but not beyond MWCNTs alone, implying that glass fibers may dilute the CNT thermal network. MWCNTs are superior for enhancing thermal conductivity. On the other hand, the Hybrid combinations should focus on maintaining the MWCNT network continuity to preserve thermal pathways.

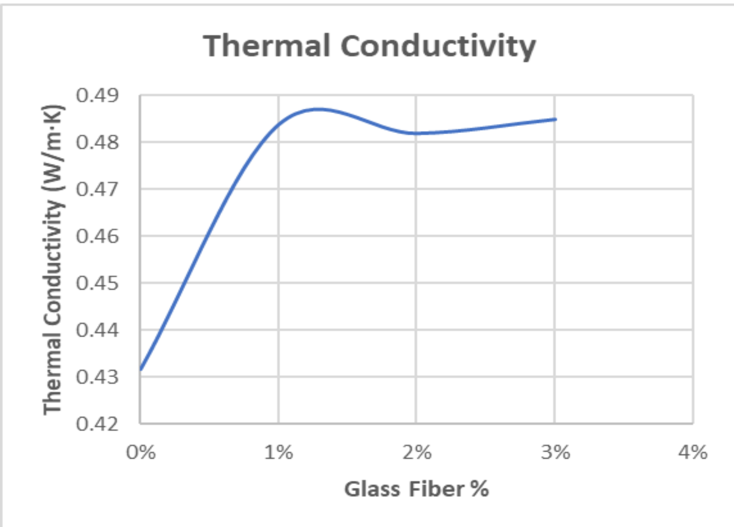

Figure 15. Thermal conductivity with the glass fiber

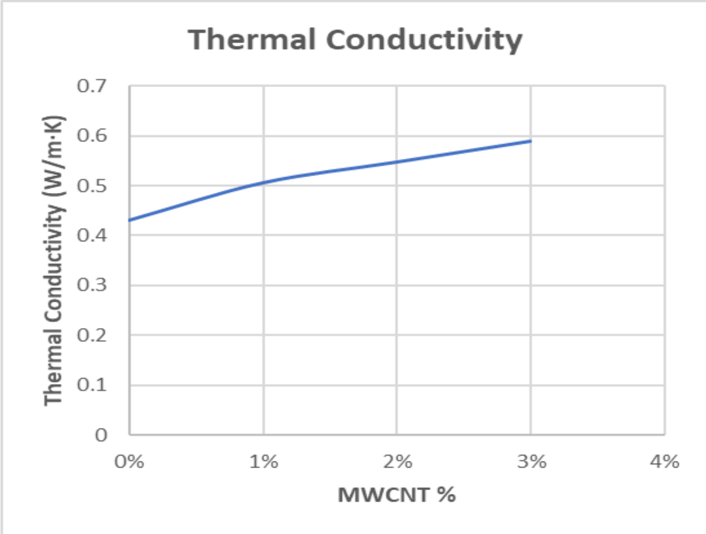

Figure 16. Thermal conductivity with the MWCNTs

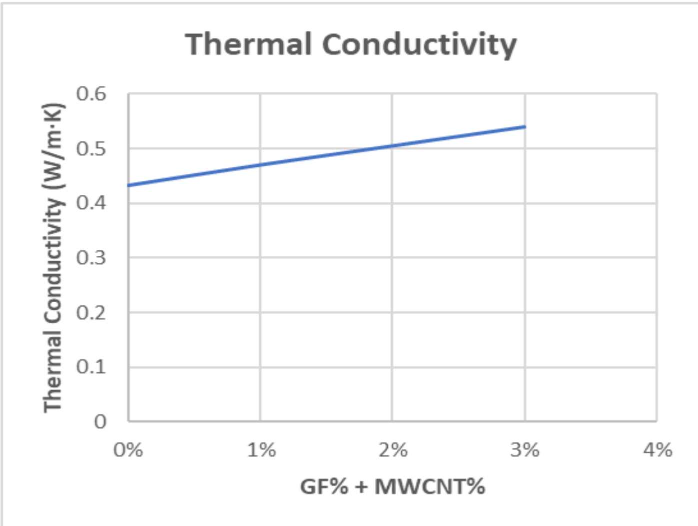

Figure 17. Thermal conductivity with the MWCNTs + glass fiber

In the Thermal Conductivity Enhancement, it can be assumed that the base = 0.2 W/m·K; then the percentage of enhancement follows the detail in Table 4.

Table 4. Thermal conductivity enhancement

Additives	Value (W/m·K)	Enhancement (%)
3% MWCNTs	0.45 (assumed)	+125%
3% Glass Fiber	0.18 (assumed)	–10% (reduction)
Hybrid	~0.35 (assumed)	+75%

Thermal Expansion

The results of the Coefficient of Thermal Expansion (CTE) show that the MWCNTs at a percentage of 3% loading reduced the CTE drastically, even producing a negative value, implying that, restricted the polymer chain mobility, the thermal strain compensation effects, and the high interfacial adhesion, creating a rigid microstructure. The glass fibers had limited influence on thermal expansion, showing only minor reductions, consistent with their limited interaction with the polymer at thermal loads. Hybrid Systems showed some reduction, but again, dispersion or interaction problems likely dampened the effects. Then it can finally conclude that MWCNTs are highly effective in improving dimensional stability and minimizing thermal expansion, critical for high precision, thermally loaded applications.

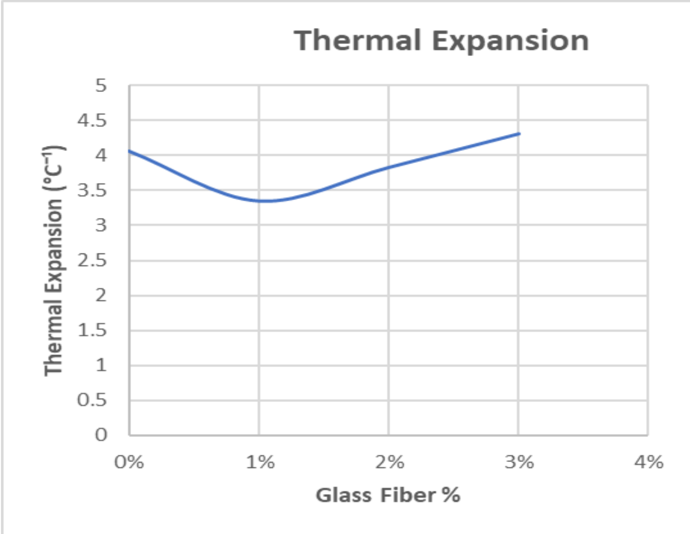

Figure 18. Coefficient of thermal expansion with the glass fiber

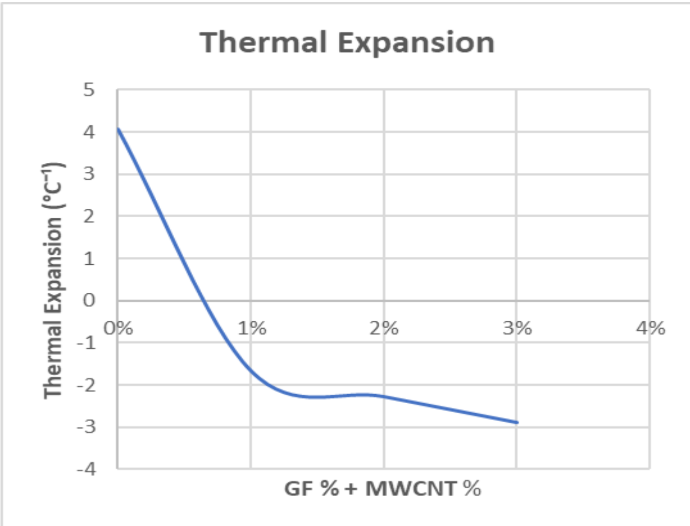

Figure 19. Coefficient of thermal expansion with the MWCNTs

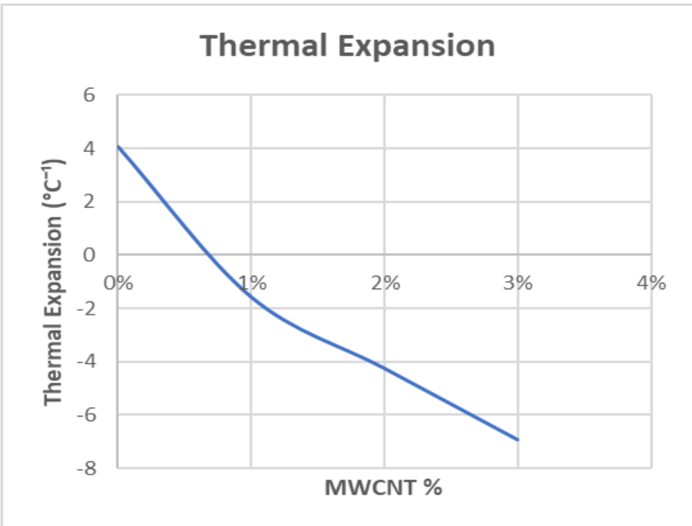

Figure 20. Coefficient of thermal expansion with the MWCNTs + glass fiber

In the Coefficient of Thermal Expansion (CTE) reduction, it can be assumed that the base = +70 µm/m·°C; then the percentage of reduction will be as follows in Table 5.

Table 5. Coefficient of thermal expansion (CTE) reduction

Additives	Value (µm/m·°C)	Change (%)
3% MWCNTs	–5 (Negative)	–107% (Reversal)
3% Glass Fiber	~60	–14.3%
Hybrid	~50	–28.6%

Conclusions

This study has investigated the effects of incorporating glass fibers, multi-walled carbon nanotubes (MWCNTs), and their hybrid combinations into a polymeric matrix to enhance the mechanical and thermal properties. The results have shown that the 3 wt% glass fibers have improved the compressive strength by 29% due to their load-bearing and stress distribution capabilities. Similarly, the 3wt% MWCNTs have enhanced tensile strength and notably improved thermal conductivity and dimensional stability, with a 125% increase in thermal conductivity and a drastic reduction in the coefficient of thermal expansion, indicating effective restriction of polymer chain mobility. Nevertheless, the hybrid formulations (glass fiber+MWCNTs) did not yield synergistic improvements. In some cases, the performance was inferior to single reinforcement systems. This loss is attributed to interfacial incompatibility, nanoparticle agglomeration, and inefficient dispersion. This leads to stress concentration and reduced effectiveness in load transfer and thermal transport. In both glass fibers and MWCNTs, individually enhanced distinct properties of the polymer; their combined use was limited by processing and dispersion challenges. Table 6 shows the overall summary of the best performer

Table 6. The best performer

Property	Best performer	% Improvement
Tensile Strength	3% Glass Fiber	+14.85%
Compressive Strength	3% Glass Fiber	+28.78%
Thermal Conductivity	3% MWCNTs	+125%
Thermal Expansion	3% MWCNTs	–107% (reduced CTE below 0)

Table 7 shows that the 3% glass fiber percentage improved the mechanical properties, particularly compressive strength, while the percentage of 3% MWCNTs significantly improved thermal conductivity and reduced thermal expansion. The poor performance of the hybrid systems may result from the agglomeration and the poor interfacial bonding between the nanofillers and the matrix.

Table 7. Overall summary

Property	Best Performer	Notes
Tensile Strength	3% Glass Fiber or MWCNTs	Hybrid systems underperformed due to agglomeration and interface issues
Compressive Strength	3% Glass Fiber	MWCNTs alone were ineffective
Thermal Conductivity	3% MWCNTs	Glass fibers slightly hindered conductivity
Thermal Expansion	3% MWCNTs	MWCNTs drastically reduced CTE

Recommendations

1. Improve dispersion techniques: The agglomeration of the MWCNTs and poor fiber-matrix interaction negatively impacted hybrid performance. Techniques such as sonication, surfactant use, or functionalization should be employed.
2. Surface modification: Chemically modify the MWCNTs and the glass fibers to improve matrix compatibility and the interfacial bonding.
3. Focus on the MWCNT alignment: Aligned CNTs can provide both the tensile and the compressive reinforcement, as well as better thermal properties.
4. Processing optimization: Consider using the high shear mixing or the extrusion techniques to ensure uniform reinforcement distribution in the matrix

Scientific Ethics Declaration

* The authors declare that the scientific, ethical, and legal responsibility of this article published in EPSTEM journal belongs to the authors

Conflict of Interest

* The authors declare that they have no conflicts of interest

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