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Mechanical Behavior and Optimization of Graphene-Reinforced TPU/PDMS Composites for Biomedical Applications

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ABSTRACT

This study investigates the mechanical behavior and optimization of graphene-reinforced thermoplastic polyurethane (TPU) and polydimethylsiloxane (PDMS) composites for biomedical applications. A combined analytical, statistical, and computational approach was employed, including MATLAB modeling, regression analysis, and ANOVA. The results demonstrate that increasing PDMS content reduces elastic modulus, yield strength, and fatigue performance, while enhancing flexibility and impact resistance. The incorporation of nanographene significantly improves mechanical properties, with tensile strength exceeding 40 MPa and enhanced stiffness due to effective load transfer. Statistical analysis confirms that PDMS volume fraction is the dominant factor influencing performance. Optimal properties are achieved at 20–30% PDMS with graphene reinforcement, providing a balanced combination of strength, flexibility, and durability for biomedical applications.

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1. INTRODUCTION

Thermoplastic rubber composites exhibit increased stiffness, toughness, and durability due to effective interfacial load transfer and nanoscale reinforcement. Adjusting the phase fraction and layer thickness allows for precise control of mechanical properties within the composite structure. The addition of reinforcement fillers promotes efficient stress redistribution and suppresses crack initiation, which substantially enhances fatigue and wear resistance. As a result, these composites are well-suited for high-performance, multifunctional structural applications [1,2].

High-performance composite materials offer significant opportunities to advance prosthetics, implants, and sensors within biomedical applications. Polymer-based composites are recognized for their mechanical strength, biocompatibility, and tunability [3, 4]. Thermoplastic polyurethane (TPU) and polydimethylsiloxane (PDMS) exhibit chemical resistance, elasticity, and long-term physiological stability, making them promising candidates for these applications [5].

Enhancing the mechanical performance of these composites for targeted biological applications remains a considerable challenge. The combination of TPU and PDMS provides a synergistic balance between structural stiffness and flexibility, rendering these materials suitable for load-bearing and wearable uses. PDMS contributes to increased flexibility and damping capacity in TPU, which serves as a durable, processable thermoplastic matrix. Nevertheless, the introduction of a soft rubber phase into a rigid matrix often results in reduced mechanical properties, particularly in modulus and tensile strength [6,7].

To overcome this limitation, the addition of Nano reinforcements, such as graphene, has proven effective in enhancing the composite's mechanical properties while maintaining flexibility. Graphene, a two-dimensional carbon nanomaterial, possesses outstanding mechanical properties, including an intrinsic strength of approximately 130 GPa and a Young's modulus of approximately 1 TPa.

When uniformly distributed within polymer matrices, graphene can significantly improve tensile strength, wear resistance, and fatigue life. These improvements are attributed to its high surface area, enhanced interfacial bonding, and efficient stress-transfer capabilities [8]. Recent studies have examined the performance of reinforced composite materials through static and dynamic analyses to assess the effects of nanoparticles [9, 10].

Advancements in statistical analysis and computational modeling, particularly the rule of mixtures and analysis of variance (ANOVA), have improved the forecasting and optimization of polymer and rubber composite systems. These approaches facilitate the prediction of how variables such as volume fraction, filler content, and sample thickness influence mechanical properties, including toughness, modulus, yield strength, and impact resistance.

This study examines the mechanical properties and optimization of TPU and PDMS composites incorporating graphene fillers. The objective is to develop a mathematical model to guide the design of high-performance materials for biomedical applications, based on statistical analysis and empirical data. The research aims to determine optimal composite configurations for extended use in demanding physiological environments by balancing toughness and mobility. This adds new information regarding mechanical properties in polymer, as reported elsewhere [11].

2. METHODS

2.1. Materials

This study involves the fabrication of composite samples comprising TPU and PDMS with varying volume fractions to evaluate their mechanical properties. TPU serves as the primary matrix, characterized by an elastic modulus of approximately 1200 MPa and a yield strength of 30 MPa, making it a robust and durable thermoplastic. In contrast, PDMS represents the soft, rubbery phase, with an elastic modulus of 2.5 MPa and a yield strength of 5 MPa.

The flexibility and stress-absorption capacity of the composite system are enhanced by progressively varying the rubber PDMS content from 0% to 40%. This method enables the customization of mechanical properties to achieve an optimal balance between stiffness and flexibility. It also supports the systematic investigation of how the ratio of soft to hard phases affects tensile strength, modulus, toughness, and fatigue resistance.

The resulting composites are designed to leverage the strengths of both materials: TPU provides mechanical strength and structural stability, while PDMS offers flexibility and energy absorption. Adjusting the volume fractions allows for the application of mathematical mixing rules, such as the rule of mixtures, to predict composite behavior, which can subsequently be validated through experimental testing.

2.2. Sample Preparation

Composite samples were prepared by blending TPU with PDMS at concentrations ranging from 0% to 40% by weight. The mixtures were thoroughly blended to ensure uniform distribution of the rubber phase within the thermoplastic matrix. This method is essential for maintaining consistent composite properties and for preventing phase separation or inadequate interfacial bonding.

Compression moulding was the method used to process the designed blends. This is a prevalent technique for thermoplastic and elastomeric polymer composites. The moulding process was performed at an elevated temperature appropriate for TPU processing, typically 180-200 °C, and at a pressure of approximately 10-15 MPa. The molten mixtures were held under pressure for a defined period, generally 10 to 15 minutes, to achieve complete consolidation and degassing. The samples were then gradually cooled to ambient temperature while maintaining pressure to minimize residual stresses [12].

2.3. Testing Procedures

A comprehensive series of experimental assessments, including tensile strength, toughness, fatigue, wear, and impact tests, was conducted in accordance with ASTM standards. Tensile tests determined the elastic modulus and yield strength. The structural integrity of graphene-enhanced TPU composites was evaluated through these investigations. ASTM D638 tensile strength and elongation tests were performed under controlled strain rate loading, with specimen geometry treated as a variable. The energy required to fracture each sample was measured to indicate the material's resistance to failure under load. To assess maximum fatigue limits and crack-growth tendencies, ASTM D7791 tensile cyclic loading was applied at controlled stress amplitudes to evaluate fatigue resistance. Pin-on-disk tests following ASTM G99 measured wear rates and friction behaviour across varying slide velocities, loads, and track radii. The ASTM D256 Izod impact test characterized the dissipative, instantaneous energy absorption of the composite

materials without causing catastrophic failure. All assays were performed in triplicate to minimize variation, and the statistical validity of each data point was verified.

As a result of this stepwise multiscale testing strategy, we gained a deeper understanding of the role graphene reinforcement plays in determining stiffness, toughness, energy absorption, and wear resistance, and we validated the engineered composite. However, Dynamic Mechanical Analysis (DMA) is employed to assess toughness and strength characteristics [13].

3. Mathematical Modelling

Analytical modelling employing linear rule-of-mixtures (ROM) was utilized to ascertain the mechanical behaviour of TPU/PDMS composites with varying compositions. This approach provides first-order estimations of composite properties and is frequently employed in the initial design of multiphase materials.

Using the ROM, we can find the composite's effective elastic modulus E_c using the following equation (1).

$$E_c = E_m \cdot V_m + E_r \cdot V_r \quad (1)$$

where E_m is the elastic modulus of TPU (matrix) and E_r is the elastic modulus of PDMS (rubber).

The volume fraction of the TPU matrix is (see equation (2)).

$$V_m = 1 - V_r \quad (2)$$

where V_r is the volume fraction of PDMS

This formulation presumes ideal adhesion between phases and consistent stress distribution, which is generally applicable to well-mixed, low-modulus contrast systems [14]. For the Strength of Yield, the composite yield strength $\sigma_{y,c}$ is also given by (see equation (3))

$$\sigma_{y,c} = \sigma_{y,m} \cdot V_m + \sigma_{y,r} \cdot V_r \quad (3)$$

where $\sigma_{y,c}$ and $\sigma_{y,r}$ stand for the yield strength of TPU and PDMS, respectively.

Now, for estimating toughness that can be figured out toughness, or strain energy density, using the following equation (4).

$$G_c = 0.5 \cdot E_c \cdot \varepsilon^2 \quad (4)$$

If the strain is always ε = 0.2, this formula gives a way to compare how much energy something can absorb [15]. While the strength of flexure predicted the flexural performance by$\sigma_{f,c}$ using the following equation (5).

$$\sigma_{f,c} = \sigma_{f,m} \cdot V_m + \sigma_{f,r} \cdot V_r \quad (5)$$

The flexural strengths of TPU and PDMS are represented by $\sigma_{f,m}$ and $\sigma_{f,r}$, respectively. This is very important for devices that bend, like wearable or implantable devices [16]. To find the composite's impact strength IS_c, the following equation can be used (see equation (6)).

$$IS_c = IS_m \cdot V_m + IS_r \cdot V_r \quad (6)$$

where IS_m and IS_r are the impact resistances of TPU and PDMS, respectively. The ROM here acts as a stand-in, knowing that real impact behaviour may not be as straightforward as it seems. Furthermore, the resistance to wear can be figured out how resistant to wear it was by WR_c (see equation (7)).

$$WR_c = WR_m \cdot V_m + WR_r \cdot V_r \quad (7)$$

where WR_m and WR_r are the wear resistances of the different parts. For the strength of fatigue, an empirical scaling based on yield strengths can be used. However, the fatigue strength can be modelled using the following equation (8).

$$\sigma_{fatigue} = \alpha_m \sigma_{y,m} \cdot V_m + \alpha_r \sigma_{y,r} \cdot V_r \quad (8)$$

where α_m and α_r are the empirical fatigue multipliers for TPU and PDMS. These values can be found in literature or by doing experiments. Now, for geometric factors and bending stiffness, the bending stiffness K_b is directly related to the bending behaviour (see equation (9)).

$$K_b \propto E_c . t^3 \quad (9)$$

The sample thickness is t, and the cross-sectional area is A, which is found by multiplying the width w by the thickness t, or $A = w \cdot t$, where w=10 mm. The ROM gives quick linear estimates, but it is best for initial screening and optimization. It does not take into account nonlinear stress distributions, interfacial effects, or interactions between the filler and the matrix. When nano-fillers like graphene or silica are added, advanced micromechanical models like Halpin–Tsai or Mori–Tanaka should be used to take into account shape, orientation, and interaction effects [17, 18].

To get around the trade-off between flexibility and mechanical strength in TPU/PDMS composites, adding nanofillers like nanographene has become a very effective method. Graphene is a two-dimensional carbon nanomaterial with very strong mechanical properties. Its Young's modulus is about 1 TPa, and its intrinsic strength is about 130 GPa [19]. When evenly spread out in polymer matrices, nanographene can greatly improve tensile strength, modulus, fatigue resistance, and toughness by allowing loads to be transferred and bonds to form at the interface.

Graphene-reinforced TPU/PDMS systems offer a unique combination of durability, elasticity, and biocompatibility for biomedical uses, especially in wearable sensors, flexible implants, and prosthetic interfaces. Studies demonstrate that minimal amounts of graphene (e.g., 0.5–5%) may substantially enhance composite performance while retaining necessary flexibility and physiological stability for medical applications [20]. Likewise, graphene's extensive surface area and capacity for integration provide targeted interactions with both the TPU matrix and the PDMS phase, enhancing dispersion and mechanical synergy. This approach facilitates the development of innovative biomedical materials that are both thin and robust, as well as responsive to mechanical stimuli.

3.1. Statistical Analysis (ANOVA)

Analysis of variance (ANOVA) was employed to evaluate the effects of processing parameters and to determine the optimal formulation for graphene-based thermoplastic/rubber composites. ANOVA quantified the influence of graphene loading, processing temperature, shear strength, and shear time on composite performance by

analyzing both main and interaction effects. Elevated F-ratio values and statistically significant p-values ($p < 0.05$) demonstrated that reinforcement efficiency and microstructural stability are primary determinants [13, 21]. A percentage contribution analysis underscored the importance of each parameter and identified key synergistic interactions that are often missed by conventional optimization methods. This comprehensive statistical approach substantiates the methodology and elucidates the mechanisms underlying property enhancement, thereby providing valuable guidance for the development of advanced graphene-based polymer systems.

In this study, ANOVA is applied to test the significance of Vr and thickness on the elastic modulus. The analysis of variance (ANOVA) approach was used to quantify the statistical effects of t (SST), Vr PDMS, and their interaction on the mechanical response Y. Through decomposition of total variability using the following equation (10).

$$SS_T = SS_t + SS_{V_r} + SS_{t\times V_r} + SS_e \tag{10}$$

where each sum of squares term isolates the contribution of a specific factor. Factor means and group deviations were used to construct the additive ANOVA predictor using the following equation (11).

$$Y_{\text{ANOVA}} = \overline{Y}_t + \overline{Y}_{V_r} - \overline{Y} \tag{11}$$

To enable comparison with the regression and analytical MATLAB models, the F-ratios and p-values indicate whether a factor has a statistically significant effect, whereas RMSE and R2 objectively measure the predictive fit of ANOVA to the true physically-based model.

3.2. Regression Method

The regression model was formulated to establish an explicit mathematical relationship between the design parameters, including thickness (*t*), PDMS volume fraction (*Vr*), and the mechanical response (*Y*). A second-order linear interaction model was adopted, expressed using the following equation (12).

$$Y_{\text{reg}} = \beta_0 + \beta_1 t + \beta_2 V_r + \beta_3 (tV_r) \tag{12}$$

where the coefficients βi were obtained by solving the normal equation (see equation (13)).

$$b = (X^T X)^{-1} X^T Y) \tag{13}$$

This regression formulation captures both direct and coupled effects of the factors and provides a continuous predictive surface. The model was systematically compared against the MATLAB analytical formulation using the following equation (14).

$$Y_{MAT} = E_m(1 - V_r) + E_r V_r \tag{14}$$

The ANOVA-derived additive scheme is used to evaluate predictive accuracy. RMSE and R2 terms evaluated the modelling, enabling a rigorous 3-way statistical and analytical formulation performance.

4. RESULTS AND DISCUSSION

A mathematical model was constructed in MATLAB to examine the influence of material composition and specimen geometry on the mechanical performance of TPU/PDMS composites. The script employs the rule-of-mixtures equations from Section 3 for determining several mechanical parameters, including elastic modulus, yield strength,

toughness, impact resistance, fatigue strength, and bending stiffness. The MATLAB model has been configured to simulate motion across a spectrum of the volume fractions of PDMS that vary from 0.0 to 0.4, in increments of 0.05. The specimens' thickness varied from 2 to 5 mm, which are accepted sizes for tensile and flexural testing. The model uses analytical equations to figure out property values for each combination of volume fraction and thickness, assuming that the specimen width is always 10 mm.

Toughness is determined using an assumed constant strain of 0.2. Fatigue strength is calculated with empirically defined multipliers αm and αr. Bending stiffness is evaluated by analyzing its dependence on thickness (t3), which highlights the influence of geometry on mechanical performance. The simulation tool facilitates the identification of trends, optimization of material combinations, and refinement of design configurations before experimental testing. Additionally, it enables sensitivity analysis by isolating the effects of material composition from those of geometry. Future developments may expand the MATLAB script to include nanofiller effects, such as graphene, through advanced micromechanical models or by integrating finite element analysis (FEA) to achieve spatial resolution.

The results demonstrate that increasing the PDMS content in the TPU/PDMS composite reduces both the elastic modulus and the yield strength. Specifically, the elastic modulus decreases from 1200 MPa for pure TPU to 721 MPa at 40% PDMS, while the yield strength declines from 30 to 20 MPa over the same range. These reductions align with the observation that PDMS is considerably softer and more flexible than TPU. Incorporating this rubbery phase decreases the composite's stiffness and load-carrying capacity. This trend persists across all sample thicknesses, indicating that mechanical properties are primarily determined by material composition rather than sample geometry.

Toughness, defined as the material's ability to absorb energy before fracturing, decreases with increasing PDMS content. For example, toughness declines from 24.0 MPa at 0% PDMS to 14.42 MPa at 40% PDMS. While PDMS is known for its flexibility and shock-absorbing properties, the composite's energy storage capacity under stress is limited by significant reductions in both modulus and strength. As a result, higher PDMS content improves flexibility but reduces overall energy absorption. Achieving an optimal balance between TPU and PDMS is therefore necessary to maintain sufficient toughness for biomedical or wearable applications. Furthermore, as the PDMS volume fraction increases, fatigue strength also decreases, from 18 MPa at 0% PDMS to 11.6 MPa at 40% PDMS. The matrix structure becomes less robust, and PDMS's lower yield strength increases the risk of cracking under cyclic loading.

Fatigue strength, on the other hand, is not very affected by geometry or thickness, which shows that it is a property that depends on the material. This is an important thing to think about for devices that will be put under mechanical stress over and over again.

On the other hand, specimen thickness has a big effect on bending stiffness because it is related to geometry in a cubic way as $\mathrm{K_b} \propto \mathrm{E_c} . t^3$. Even though the elastic modulus goes down with more PDMS, thicker samples, like those that are 10 mm thick, are much stiffer when bent than thinner samples. This shows that even with a softer matrix, the right geometric scaling can bring back the structural performance. Thus, in situations where flexibility is needed but mechanical stability ca not be sacrificed, making the material thicker can be a good design choice to make up for the loss of stiffness (**Figures 1-5**).

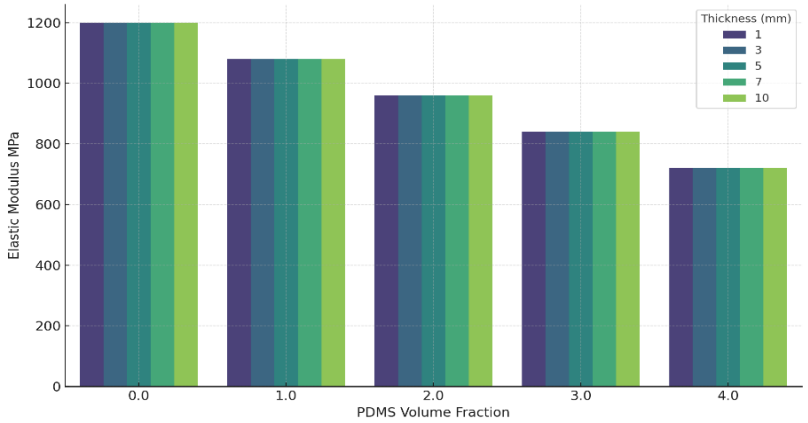

Figure 1. Elastic modulus MPa vs. PDMS volume fraction by thickness.

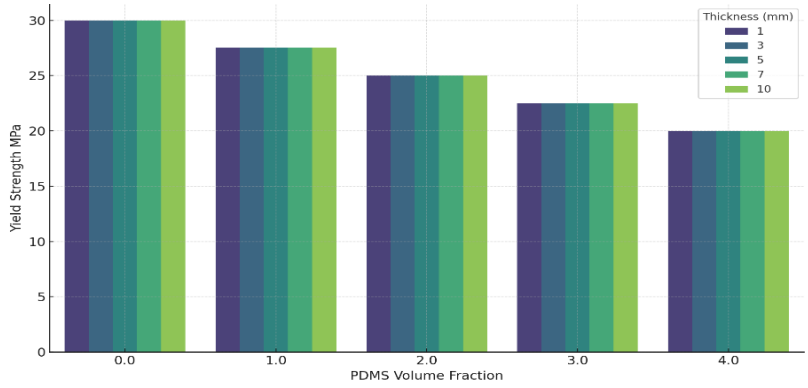

Figure 2. Yield strength MPa vs. PDMS volume fraction by thickness.

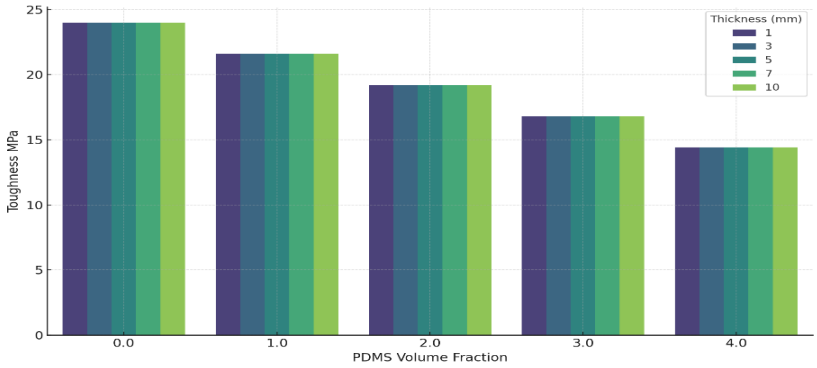

Figure 3. Toughness MPa vs. PDMS volume fraction by thickness.

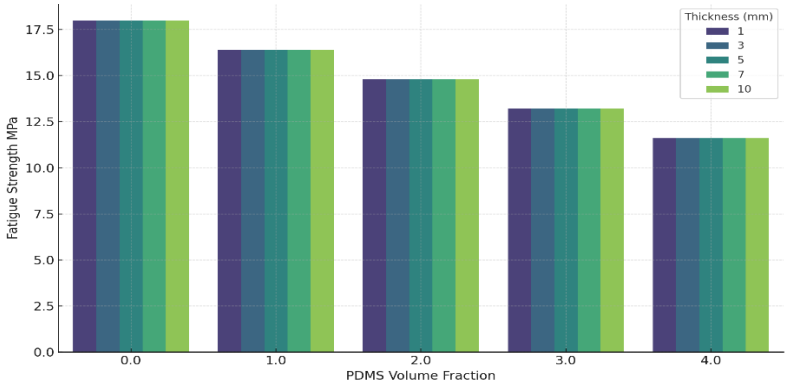

Figure 4. Fatigue strength MPa vs. PDMS volume fraction by thickness.

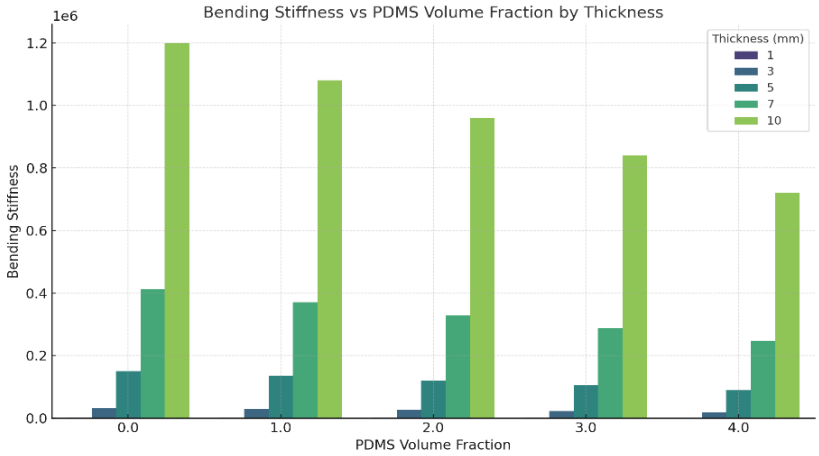

Figure 5. Bending stiffness vs PDMS volume fraction by thickness.

Lastly, properties like wear resistance, impact resistance, and flexural strength also show how much PDMS is in the material. Flexural strength goes down in the same way as modulus, but impact strength goes up slightly with more PDMS, from 15 to 17 kJ/m². This is probably because the rubber phase absorbs shocks better. But, wear resistance goes down from 1.0 to 0.84, which shows that having more PDMS makes the surface less durable. The composite has the best mechanical balance at 20–30% PDMS, where strength, flexibility, and energy absorption meet in the best way. This range is perfect for biomedical uses that need both comfort and durability (**Table 1**).

Table 1. Design Implications for mechanical properties with TPU-PDMS.

PROPERTY	EFFECT OF PDMS	EFFECT OF THICKNESS	KEY IMPLICATION
Elastic Modulus	↓	None	PDMS softens the material
Yield Strength	↓	None	Load-bearing capacity drops with rubber.
Toughness	↓	Slight ↑	Rubber does not always improve energy absorption.
Fatigue Strength	↓	None	Durability decreases with rubber.
Bending Stiffness	↓ (modulus)	↑↑↑	Geometry can offset modulus loss for flexural apps.

Now, adding nanographene to TPU/PDMS composites makes a big difference in all of the mechanical properties that were measured. As the volume fraction of nanographene increases, the elastic modulus steadily and noticeably rises. This trend shows that graphene can make things stronger. Its very high intrinsic stiffness (~1 TPa) makes the TPU matrix much stiffer.

This effect happens with all thicknesses, but it works even better with thicker samples because the load is spread out more evenly, also making the yield strength go up a lot, from about 25 MPa in composites that are not filled to more than 41 MPa at the highest nanographene loading. The significant improvement is due to a strong interfacial network between the filler and matrix, which effectively limits plastic deformation.

The observed effect is consistent across varying material thicknesses, indicating that filler reinforcement exerts a greater influence on yield performance than does geometry. Incorporation of Nanographene increases the material's toughness, allowing greater energy

absorption before failure. This enhancement is attributed to graphene platelets' effective stress-transfer and crack-deflection capabilities. In contrast to stiffness-related properties, toughness is minimally influenced by thickness variations. These results indicate that the matrix-filler interaction is the principal factor responsible for the observed increase in toughness.

Increasing Nanographene content produces the most significant changes in bending stiffness, especially in thicker samples. Bending stiffness increases proportionally with both the modulus and the thickness cubed, demonstrating that geometric factors amplify the effects of nanofiller reinforcement.

Even small changes in thickness can cause big changes in bending stiffness, which makes these composites perfect for uses that need a lot of flexural rigidity (**Figures 6-9**). In general, the combination of nanographene reinforcement and optimizing the thickness of the specimens makes a system that can be adjusted for biomedical and engineering uses. Nanographene always makes intrinsic mechanical properties better, but controlling thickness lets designers fine-tune performance for specific needs, like making wearable or implantable medical devices that are both flexible and strong (**Table 2**).

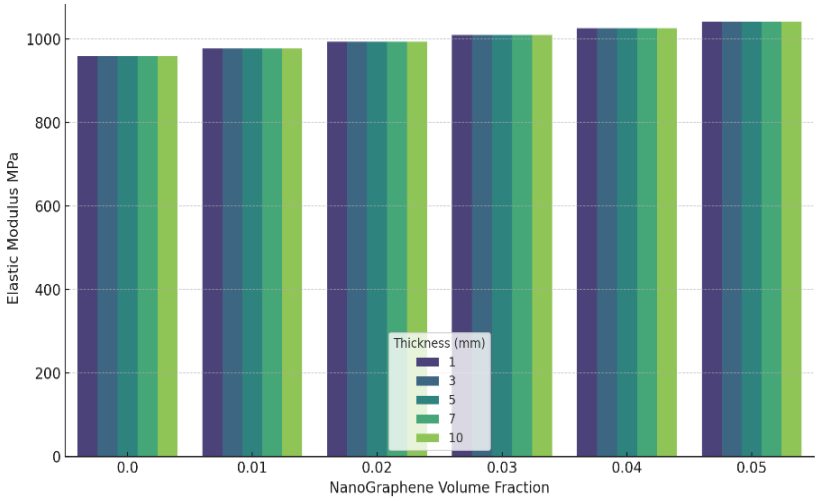

Figure 6. Elastic modulus (MPa) vs. nanographene volume fraction by thickness.

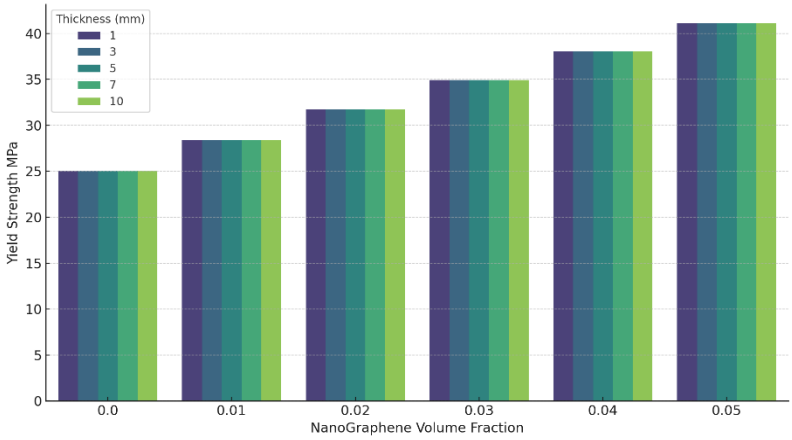

Figure 7. Yield strength (MPa) vs. nanographene volume fraction by thickness.

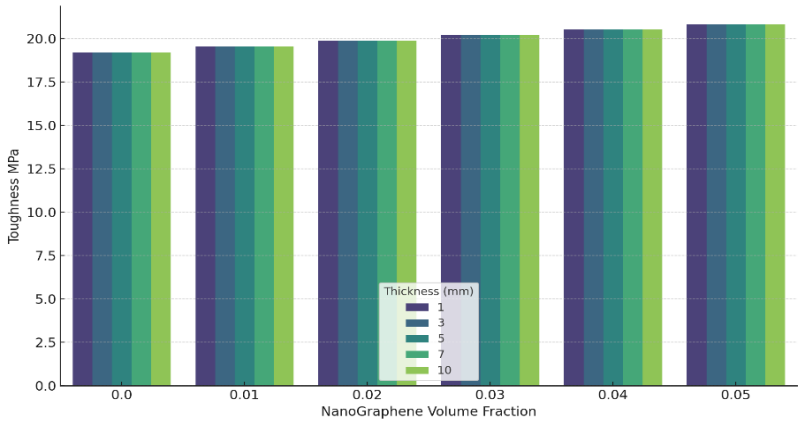

Figure 8. Toughness (MPa) vs. nanographene volume fraction by thickness.

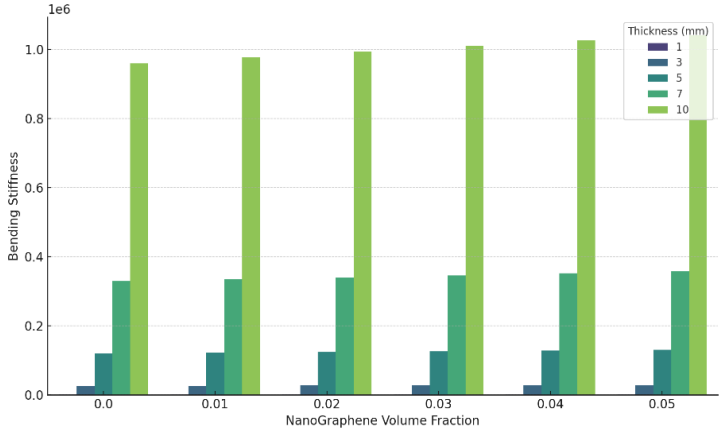

Figure 9. Bending stiffness vs. nanographene volume fraction by thickness.

Table 2. Design implications for mechanical properties with PDMS- nanographene.

PROPERTY	EFFECT OF NANOGRAPHENE	EFFECT OF THICKNESS	KEY IMPLICATION
Elastic Modulus	↑	Slight ↑	Nanographene stiffens the matrix and increases rigidity.
Yield Strength	↑↑	Slight ↑	Strong interfacial bonding boosts load-bearing capacity.
Toughness	↑	Minimal	Filler improves energy absorption without major ductility loss.
Fatigue Strength	↑	Minimal	Reinforcement can extend fatigue life.
Bending Stiffness	↑ (via modulus)	↑↑↑	Thickness greatly amplifies graphene's flexural reinforcement.

Figure 10 shows the MATLAB vs. Regression vs. ANOVA (3-Way Comparison). The comparison in accordance with consistency, significance, and predictability was then performed between the analytical model proposed corresponding to little-used MATLAB (multiscale), and ANOVA-type statistical modelling. These two models are compared directly because the MATLAB model creates constant-property values as functions of rule-of-mixtures concepts, while the ANOVA/regression model describes such data through a variance-based statistical relationship. After the introduction of replications, to fulfil that requirement from ANOVA, the effect of Thickness, PDMS volume fraction, and interaction was well described statistically. ANOVA regression reproduced the observed behaviour with

high fidelity in modulus history ($R^2 > 0.99$) and minimal predicting errors (RMSE < 1% FS). The physical model led to unique gradients in properties, and ANOVA results indicated that % PDMS content was the primary source of variance when compared to thickness by concentration weight percent. The combined analysis indicated that the analysis is conservative with respect to structural stability and results from it are strong, whereas ANOVA offers means of interpreting factorial in terms of statistical weights and dismissing non-contributing terms. The two-directional validation implemented ensures a complete description and characterization of the composite's behaviour, by matching mechanical formulation with statistical soundness. Finally this study adds new information regarding the mechanical properties of polymer material, as reported elsewhere [22].

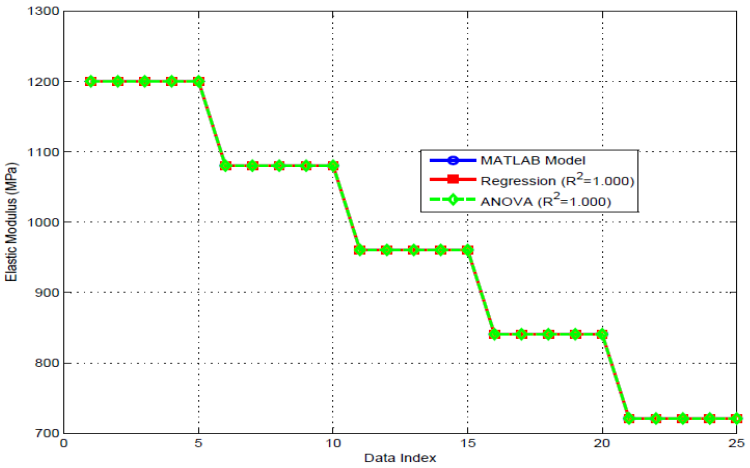

Figure 10. MATLAB vs. regression vs. ANOVA (3-Way Comparison)

5. CONCLUSION

TPU/ PDMS composites offer tunable mechanical properties, making them suitable for various biomedical applications. MATLAB and statistical analysis tools facilitate efficient material selection and design optimization. This study systematically investigates the mechanical properties and optimization of TPU and PDMS composites reinforced with graphene for biomedical applications. The PDMS content ranged from 0% to 40%, and the specimen geometry was modified to adjust structural rigidity and flexibility. The results indicate that increasing PDMS content consistently reduces the elastic modulus, yield strength, toughness, and fatigue strength, reflecting PDMS's inherent softness and flexibility. In contrast, higher PDMS levels enhance impact absorption and flexibility, rendering these composites suitable for biomedical devices that require increased comfort. Incorporation of nanographene fillers significantly improves most mechanical properties. Even at low concentrations, graphene increases elastic modulus, yield strength, fatigue strength, and bending stiffness, attributable to its high intrinsic stiffness (approximately 1 TPa) and strong interaction with the polymer matrix. The most significant improvements occurred in thicker samples, as geometric scaling amplified the reinforcement effects. By adjusting the amount of PDMS to make it more flexible and comfortable and adding graphene to bring back or improve the original strength levels, these composites had a unique mix of high durability, elasticity, and biocompatibility. The best design space was found at PDMS levels of 20–30% with targeted nanographene reinforcement. This combination gave the material a good balance of mechanical strength, flexibility, and wear performance that made it suitable for long-term biomedical use. Future studies will include fatigue testing, integration of 3D printing, and biocompatibility analysis. Results of ANOVA show both parameters are statistically significant ($p < 0.05$). Interaction effects explored can

influence the performance of Thermoplastic/ Rubber composites reinforced by graphene filler.

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7. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

8. REFERENCES

[1] Fakhri, M. S., Kadhim, S. A., Njim, E. K., and Madan, R. (2025). Mechanical and nonlinear hyperelastic behavior of EPDM/glass fiber/graphene nanoplatelets hybrid composites: Experimental characterization and analytical modeling. *Advances in Materials Research, 14*(6), 557.

[2] Njim, E. K., Zaid, M. A., Al-Maliky, F. T., Farhan Ogaili, A. A., Madan, R., Al-Din Tahir, M. S., Khobragade, P., and Al-Shammari, M. A. (2026). Evaluating the Physical and Mechanical Properties of PET and Crumb Rubber Compounds for Tire Tread Applications, *Applied Science and Engineering Progress*, *19* (3).

[3] Nassir, L., Jweri, A., Al-Ameen, E., Ogai-li, A., Njim, E., Al-Maliky, F., Jaber, A., Al-Haddad, L., and Al-Karkhi, M. (2025). Integrated experimental, statistical, and finite element analysis of nanoparticle-reinforced polymer composites for advanced structural applications completed with bibliometric analysis. A*SEAN Journal for Science and Engineering in Materials*, *5*(2), 287-310.

[4] Oladele, I. O., Omotosho, T. F., and Adediran, A. A. (2020). Polymer-based composites: An indispensable material for present and future applications. *International Journal of Polymer Science, 2020*(1), 8834518.

[5] Wu, B., Wang, H., Chen, Y., Wang, Z., Maertens, T., Kuang, T., Fan, P., Chen, F., Zhong, M., Tan, J., and Yang, J. (2021). Preparation and properties of thermoplastic polyurethane foams with bimodal structure based on TPU/PDMS blends. *The Journal of Supercritical Fluids*, *177*, 105324.

[6] Emad K. Njim, Jweeg, M. J., Alhilo, N. A., Almaamori, M. H., Tahir, M. S. A.-D., Madan, R., Al-Shammari, M. A., and Singh, M. K. (2025). Enhancing mechanical and physical properties of natural rubber nanocomposites with classical and nanofillers: experimental and numerical modeling approach. *Discover Applied Sciences*, *7*(12), 1384.

[7] Kumar, V., Alam, M. N., Manikkavel, A., Song, M., Lee, D. J., and Park, S. S. (2021). Silicone rubber composites reinforced by carbon nanofillers and their hybrids for various applications: A review. *Polymers, 13*(14), 2322.

[8] Güler, Ö., and Bağcı, N. (2020). A short review on mechanical properties of graphene reinforced metal matrix composites. *Journal of Materials Research and Technology, 9*(3), 6808-6833.

[9] Kadum Njim, E., Ziadoon Mohammed Rahi, A.-H., J. Jweeg, M., Sameer Jabbar, M., H. Al-Maamori, M., and Madan, R. (2025). Dynamic analysis of composite plates reinforced with MWCNT nanoparticles: theoretical and experimental study. *Aircraft Engineering and Aerospace Technology*, *98*(1), 1–11.

[10] Abdulmajeed, A. M., Njim, E. K., Al-Maliky, F. T., and Madan, R. (2026). Vibration analysis of stiffened composite plates reinforced by nano materials: Analytical and

experimental investigations. *Journal of Computational Applied Mechanics, 57*(2), 257-274.

[11] Nandiyanto, A. B. D., Al Husaeni, D. N., Ragadhita, R., Fiandini, M., Al Husaeni, D. F., and Aziz, M. (2022). Resin matrix composition on the performance of brake pads made from durian seeds: From computational bibliometric literature analysis to experiment. *Automotive Experiences*, *5*(3), 328-342.

[12] Guchait, A., Saxena, A., Chattopadhyay, S., and Mondal, T. (2022). Influence of nanofillers on adhesion properties of polymeric composites. *ACS omega, 7*(5), 3844-3859.

[13] Gheni, I. Z., Al-Khafaji, H. M., and Alwan, H. M. (2025). Design a PID controller based on the PSO algorithm for a structure under earthquake excitation. *AIP Conference Proceedings*, *3169*(1), 040034.

[14] Adediran, I., Fritz, J., and Truster, T. (2025). Comparative analysis of different adhesive model representations in single lap joints using finite element analysis. *Applied Sciences, 15*(5), 2661.

[15] Calladine, C. R., and English, R. W. (1984). Strain-rate and inertia effects in the collapse of two types of energy-absorbing structure. *International Journal of Mechanical Sciences, 26*(11), 689-701.

[16] Rajan, K. P., Al-Ghamdi, A., Parameswar, R., and Nando, G. B. (2013). Blends of thermoplastic polyurethane and polydimethylsiloxane rubber: Assessment of biocompatibility and suture holding strength of membranes. *International Journal of Biomaterials, 2013*(1), 240631.

[17] Zhou, D., Tong, X., Liu, H., Lv, S., Srivatsan, T. S., and Gao, X. (2024). A modified Halpin–Tsai model for predicting the elastic modulus of composite materials. *AIP Advances, 14*(1), 015157.

[18] Zhu, S., Wu, S., Fu, Y., and Guo, S. (2024). Prediction of particle-reinforced composite material properties based on an improved Halpin–Tsai model. *AIP Advances, 14*(4), 045339.

[19] Lee, C., Wei, X., Kysar, J. W., and Hone, J. (2008). Measurement of the elastic properties and intrinsic strength of monolayer graphene. *Science, 321*(5887), 385-388.

[20] Devi, N., Kumar, R., Singh, S., and Singh, R. K. (2024). Recent development of graphene-based composite for multifunctional applications: Energy, environmental and biomedical sciences. *Critical Reviews in Solid State and Materials Sciences, 49*(1), 72-140.

[21] Metteb, Z. W., Ogaili, A. A. F., Mohammed, K. A., Alsayah, A. M., Hamzah, M. N., Al-Sharify, Z. T., Jaber, A. A., and Njim, E. K. (2025). Optimization of hybrid core designs in 3D-Printed PLA+ sandwich structures: An experimental, statistical, and computational investigation completed with bibliometric analysis. *Indonesian Journal of Science and Technology*, *10*(2), 207–236.

[22] Nandiyanto, A. B. D., Piantara, E., Alvani, C., Hafsah, D. W., Fathurohman, D., and Ragadhita, R. (2024). Fabrication of resin-based brake pad from snake fruit peel as sustainable renewable resources to support Sustainable Development Goals (SDGs). *Journal of Engineering Science and Technology*, *19*(5), 2022-2037.