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Impact of reinforcement ratio on mechanical properties and wear behaviour of graphene nanoplatelet reinforced epoxy composites

Takviye oranının grafen nanoplatelet takviyeli epoksi kompozitlerin mekanik özellikleri ve aşınma davranışı üzerindeki etkisi

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Impact of Reinforcement Ratio on Mechanical Properties and Wear Behaviour of Graphene Nanoplatelet Reinforced Epoxy Composites

Highlights

- *The addition of graphene nanoparticles to the epoxy material resulted in an increase in its strength and elasticity module. However, it was observed that there was an optimal reinforcement ratio, and when the graphene reinforcement exceeded 0.2%, the strength of the material started to decrease.*
- *The amount of reinforcement and the addition of reinforcement had a positive effect on the coefficient of friction of the epoxy material. Specifically, as the reinforcement ratio increased, the coefficient of friction decreased, indicating improved tribological properties.*
- *The study revealed that increasing the amount of reinforcement, such as graphene nanoplatelet, in the epoxy material resulted in a decrease in wear volume. However, it was also observed that increasing the load and sliding distance had the opposite effect, leading to an increase in wear volume.*

Graphical Abstract

Composite materials were manufactured by incorporating graphene nanoplatelets into the epoxy matrix at various reinforcement ratios. Subsequently, tensile and abrasion tests were conducted to assess the impact of the reinforcement ratio on the material's behavior and performance. Experimental stage is given in figure 1.

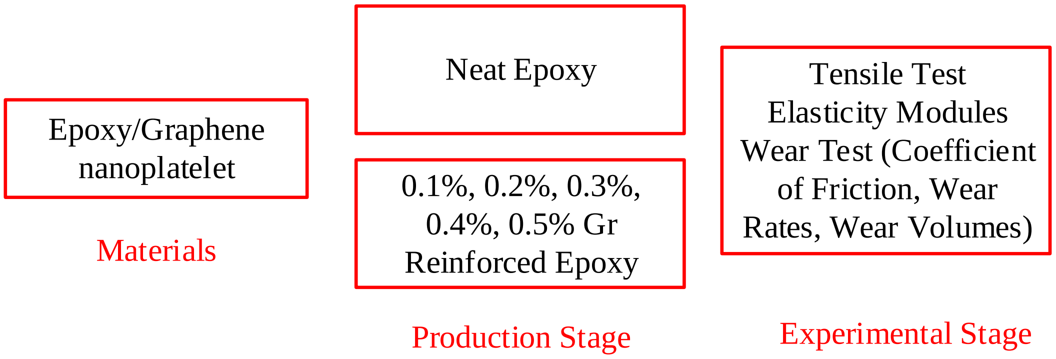

Figure. Experimental process

Aim

This study was carried out to determine how the wear volume, wear rate, friction coefficient and tensile strength change depending on the graphene nanoplatelet ratio.

Design & Methodology

By providing homogeneous particle distribution in the magnetic stirrer, epoxy matrix nanoparticle composites were produced by pouring into a silicone mold.

Originality

The study aimed to examine the influence of varying nanoparticle content in the epoxy matrix on the mechanical and tribological properties of the material. By systematically altering the amount of nanoparticles added to the epoxy, the researchers sought to assess the extent of their impact on the material's mechanical behavior (such as strength,, elasiticty modules) as well as its tribological performance (such as friction coefficient and wear resistance).

Findings

Although exceeding a certain reinforcement ratio negatively affects the mechanical properties of the material, an increase in the amount of reinforcement leads to an improvement in its tribological properties..

Conclusion

The use of nanoparticles has improved the wear resistance and tensile strength of the material.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Impact of Reinforcement Ratio on Mechanical Properties and Wear Behaviour of Graphene Nanoplatelet Reinforced Epoxy Composites

Araştırma Makalesi / Research Article

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ABSTRACT

New features are gained to the enhanced characteristic of composites with the addition of nanoscale particles. Graphene nanoplatelet has an important place among nanoparticle reinforcing elements due to its two-dimensional structure and high strength. In this study, tribological behaviour and mechanical properties of the nano particle reinforced composite material investigated. Nanoparticles were incorporated into the non-reinforced sample at varying weight ratios, ranging from 0.1% to 0.5%. The findings indicated that the addition of graphene nanoplatelet into the epoxy matrix material enhances the mechanical properties of the specimens across all reinforcement ratios.The failure load of the neat epoxy samples was determined as 415.94 N and the modulus of elasticity as 2.4 GPa. The best mechanical results in graphene nanoplatelet reinforced composites were obtained in 0.2% reinforced composites, and the failure load and elasticity modulus values were found as 903.13 N and 4.46 GPa, respectively. Furthermore, the tribological performance of the samples was examined under dry sliding conditions. The worn surfaces were examined using SEM. The incorporation of graphene nanoplatelet reinforcement has been observed to positively impact the wear resistance of the epoxy matrix material.

Keywords: Graphene nanoplatelet , nano-particle, epoxy composite, wear, tensile test.

Grafen nanoplatelet takviyeli epoksi kompozitlerin mekanik özellikleri ve aşınma davranışı üzerinde takviye oranının etkisi

ÖZ

Nano ölçekteki parçacıkların eklenmesiyle kompozitlerin özellikleri geliştirilmekte ve yeni özellikler kazanılmaktadır. Grafen, iki boyutlu yapısı ve yüksek mukavemeti nedeniyle nanoparçacık takviye elemanları arasında önemli bir yere sahiptir. Bu çalışmada, nano parçacık takviyeli kompozit malzemenin tribolojik davranışı ve mekanik özellikleri incelenmiştir. Nano parçacıklar, %0,1 ila %0,5 ağırlık oranları arasında değişen oranlarda takviyesiz numuneye katılmıştır. Bulgular, grafen nanoparçacıklarının epoksi matris malzemesine eklenmesinin, tüm takviye oranlarında numunelerin mekanik özelliklerini artırdığını göstermiştir. Takviyesiz epoksi numunelerin kopma yükü 415,94 N ve elastisite modülü ise 2,4 GPa olarak belirlenmiştir. Grafen nanoplatelet takviyeli kompozitlerde en iyi mekanik sonuçlar, %0,2 takviyeli kompozitlerde elde edilmiş olup, kopma yükü ve elastisite modülü değerleri sırasıyla 903,13 N ve 4,46 GPa olarak bulunmuştur. Ayrıca, numunelerin tribolojik performansı kuru kayma koşullarında incelenmiştir. Aşınmış yüzeyler SEM kullanılarak incelenmiştir. Grafen nanoplatelet takviyesinin epoksi matris malzemesinin aşınma direncini olumlu yönde etkilediği gözlemlenmiştir.

Anahtar kelimeler: Grafen nanoplatelet, nano-parçacık, epoksi kompozit, aşınma, çekme testi.

1. INTRODUCTION

Composites are heterogeneous materials that can act together as a structure, consisting of different phases, one is a reinforcing element, and the other is a matrix material. Correct design and manufacturing of the reinforcing element and matrix in composites can lead to the development of engineering materials with unique properties that surpass those of metal alloys and ceramics. These properties include high strength, excellent corrosion resistance, superior thermal resistance, and enhanced hardness. [1]. Composites are preferred in various main structural components and

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system productions due to their high specific modulus and specific strength [2]. Epoxy, which is one of the most important thermoset materials used as matrix material, has a wide application area as an electronic encapsulant adhesive and coating material for structural composites due to its low cost and superior performance [3-6]. Recently, it has been observed that nano-sized reinforcing elements have been added to the epoxy in the production of composite materials. The reinforcing elements, which have different geometric shapes and sizes, can change polymers' chemical, mechanical and tribological properties [7].

These reinforcing materials can be one, two or three-dimensional. Recently, carbon nanotubes, graphene and nanofibers have been widely used as fillers in composites since they have better structural and functional properties and a wide range of applications in all areas [8]. In nanofiber composites, achieving a homogeneous distribution of fibers within the matrix is of utmost importance. Various methods such as ultrasonic mixing, solution mixing and polymerization in situ are used for homogenous distribution [9-11].

Graphene is a two-dimensional carbon allotrope composed of carbon atoms arranged in a tightly packed honeycomb lattice structure. [12]. It has a lot of application potential due to its outstanding electron transport properties and other distinctive features. Various graphene production techniques have been developed, mechanical, physical and chemical. Chatterjee et al. investigated the mechanical properties of graphene nanoparticles, and carbon nanotube reinforced epoxy composites. They added 0.1%, 0.5%, 1% and 2% nanoparticles into the epoxy composite as a reinforcing element. They have seen that increased particle size improves mechanical and thermal properties for both material types. They achieved the highest fracture strength in 2% graphene reinforcement and the highest bending modulus in samples using 1% graphene reinforcement [13]. Tang et al. conducted a study to investigate the impact of varying the amount of mixture on the mechanical properties of composites reinforced with graphene nanoparticles. The mixing process is provided by using a ball mill. According to their results, it has been shown that well-mixed samples had higher glazing temperature and strength. However, it was observed that the bending and elasticity modules did not change [14]. Chatterjee et al. examined the tensile, flexural and thermal properties of graphene nanoparticle-reinforced epoxy composites. They mixed expanded graphene particles and epoxy using a high-pressure three-shaft mixer. They observed that expanded graphene nanoparticles increase flexural modulus and hardness. It also increased the fracture toughness of the composite by 60% [15]. Polat et al. conducted a study to examine the impact of a graphite nanoparticle-reinforced nylon 66 layer on the fatigue strength of single lap bonding in aluminum-carbon fiber composites. They determined that the composites containing wt. 1%, 3% and 5% graphene nanoparticles have higher fatigue strength than pure epoxy for all ratios [16]. Chandrasekaran et al. examined the influence of graphene, graphite and carbon nanotube reinforcement on the fracture behaviour and damage mechanism of the epoxy composite. They examined the effect of nanoparticle ratio on fracture toughness by applying a three-point flexural test with a single edge notch. They obtained the best fracture toughness of 0.5% [17]. Boumaza et al. studied the tensile strength and hardness properties of nano particle-reinforced coatings. They have determined that even the nanoparticle reinforcement they use at very low rates provides high mechanical, thermal and adhesion properties. The 2% by weight ZrO2, ZnO, Fe_2O_3, and SiO_2 nanoparticle reinforcement increased the hardness of the composites by 28%, 56%, 61% and 71% and their modules by 4%, 25%, 21% and 26%, respectively. [18]. Sepetcioglu and Tarakcioglu conducted a study on the mechanical properties and explosion behavior of pressure vessels (B-CPVs) made of 0.25 wt% graphene nanoplatelet (GnPs) reinforced and unreinforced filament winding basalt/epoxy composite. They determined that the mechanical properties of GnP reinforced composites improved compared to unreinforced B-CPVs. They attributed this to the homogeneous distribution of GnP within the matrix and the enhanced strength of the fiber-matrix interface[19]. Du et al. studied the impact of graphene nanoparticle layer reinforced carbon reinforced composites on the fracture behaviour and delamination. They found that 1% by weight graphene nanoparticles reinforced composites increased matrix rupture energy by 150% and reduced the thermal expansion coefficient by 30% [20]. Upadhyay and Kumar (2019) conducted a study examining the hardness and abrasion resistance of composites reinforced with graphene and MoS_2, utilizing various reinforcement ratios. In their abrasion tests conducted under varying humidity conditions (40%, 60%, and 80%), Polat et al. observed an decrease in wear resistance as the humidity level increased. Additionally, they reported the wear rate (WR) of graphene-reinforced samples was lower compared to MoS_2-reinforced composites. [21]. Wang et al. (2014) produced multilayer graphene (MLG) filled polyvinyl chloride (PVC) composites with traditional melt mixing methods and analyzed the wear behavior of these materials. They investigated the effects of filler ratio on hardness, microstructure, wear resistance and COF in MLG/PVC composites. They found that incorporating MLG (multi-layered graphene) had a notable impact on increasing wear resistance PVC material. Additionally, they observed that the hardness of the composite decreased as the graphene reinforcement ratio increased [22]. Graphene nanoparticle materials are used not only for structural materials but also for the reinforcement of epoxy-based adhesives. Gültekin et al. examined the impact of incorporating graphene nanoparticles into an epoxy adhesive on the strength of single lap bonds. The findings revealed that the addition of graphene nanoparticles led to an increase in both the bond strength and total strain amount of the epoxy adhesive. [23].

When the studies are examined, it has been observed that chemists and material scientists have recently conducted many studies on graphene and its derivatives.

Upon examining the studies, chemists and material scientists have recently conducted many studies on graphene and its derivatives. In this study, the effects of graphene nanoplatelet addition to RIMR300 resin at different rates on the tensile strength, elasiticity modules and abrasion properties of the reinforced samples were investigated.

2. MATERIAL AND METHOD

The matrix used in the study was Propox brand RIMR300 epoxy, while the hardener employed was RIMH300. Graphene nanoplatelet with a diameter of 5µm and a thickness ranging from 6-9 nm was utilized as the nano-particle reinforcement material. For the epoxy resin and hardener, a mixture of 2:1 was provided and neat, 0.1 wt.%, 0.2 wt.%, 0.3 wt.%, 0.4 wt.% and 0.5 wt.% graphene nanoparticle reinforced epoxy matrix composites were prepared. Heidolph brand MR Hei-Standard model magnetic stirrer was used to ensure the complete mixing of nanoparticles in epoxy. The production steps and test setup of of samples are given in Figure 1.

Epoxy-graphene mixtures prepared according to the desired ratios on the sensitive balance were mixed for 45 minutes. The prepared mixture was poured into the silicone mold prepared according to ASTM D-638 standard and cured under room temperature for 24 hours. The aforementioned procedures were replicated for each reinforcement ratio, and tensile samples were prepared accordingly. Tensile tests were conducted utilizing a Shimadzu test equipment. During the tests, the test speed was chosen as 1 m/min. To determine the Young's Modulus and Poisson's Ratio, two strain gauges were fixed to the samples in two orientations: one aligned with the load direction and the other positioned perpendicular to the load direction.

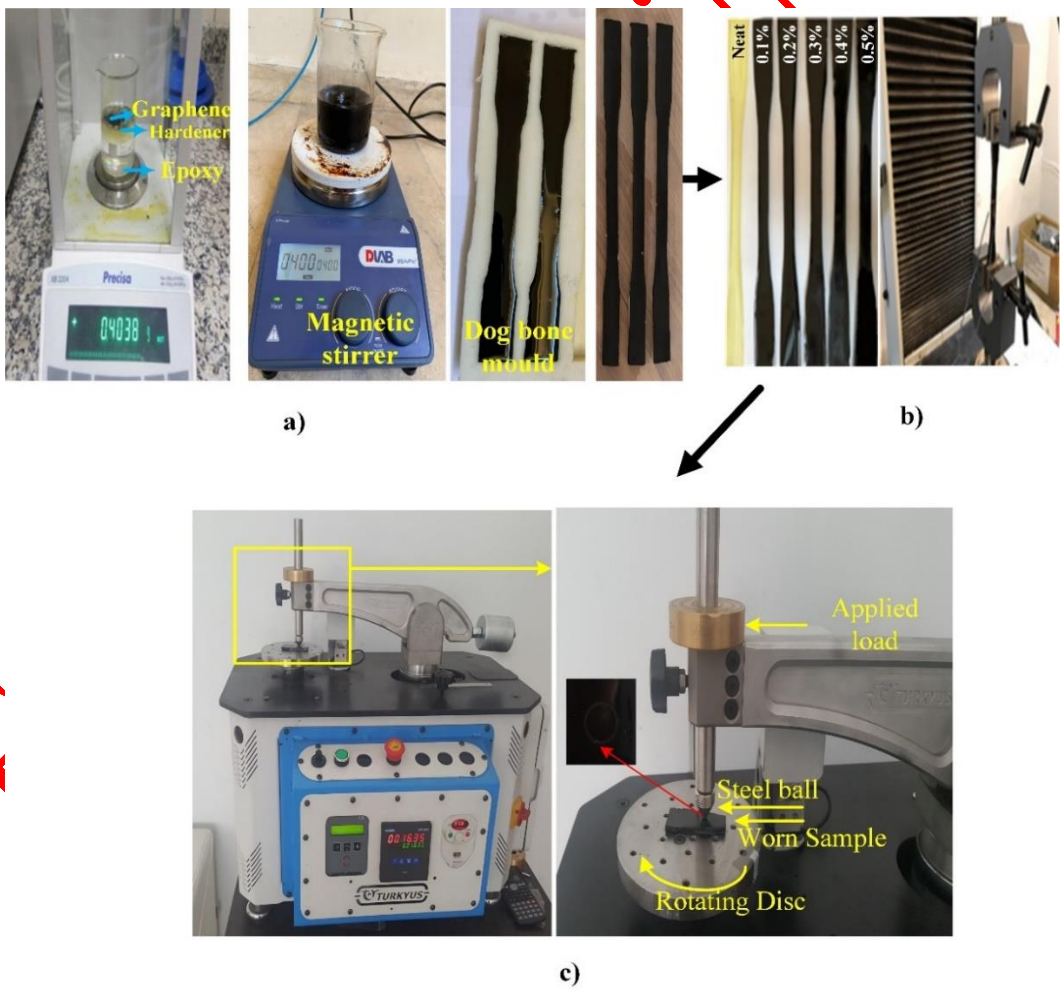

Figure 1. Production stages of composites and tensile/wear test setup; a) manufacturing the samples b) mechanical characterization tests c)wear tests

The wear behavior of graphene nanoplatelet reinforced epoxy composites was investigated with the help of a pin on disc device in accordance with ASTM G-99 standards. 20 mm x 20 mm sized samples were cut from the sample prepared to perform adhesion wear tests. Steel balls with high thermal conductivity were used to wear the samples in the abrasion tests. The reason for this is to ensure that the heat generated in the wear zone is quickly removed. In the tests, the track diameter and revolution were determined as 0.65 cm and 375 rpm, respectively. After the abrasion tests, the WR and the coefficient of friction (COF) of the samples were determined.

The specific wear rate (SWR) is an important parameter that expresses the resistance of a material to wear. The equation used in this parameter is shown as follows [34]

$$Ks = \frac{\Delta V}{F_N \times L} \left(\frac{mm^3}{Nm}\right) \quad (1)$$

Where, ΔV = Volume of wear loss; F_N = Normal load and L = Sliding distance

Xiao et al. explained how to calculate the wear values in detail [24]. The track depth and average track width values used in the formula were determined with the Time TR 200 surface roughness device, and the WR was determined. Table 1 shows the parameters and levels used in the wear tests.

Table 1. Wear Parameters

Parameters	Levels
Applied Load (N) Sliding Distance (m)	10, 15 ve 20 250, 500, 750

3. RESULTS AND DISCUSSION

3.1. Tensile Test Results

In the current study, the effect of reinforcing the epoxy matrix material with graphene nanoplatelet on tensile strength and abrasion resistance has been investigated experimentally. The obtained results are given below.

Figure 2 presents the force-displacement curve of both the unreinforced epoxy samples and the reinforced samples. The maximum tensile strength recorded for the unreinforced epoxy samples was determined to be 415.94 N. Tensile force of 0.1% graphene nanoplatelet reinforced composite increased to 548.13 N. The highest tensile strength was obtained from 0.2% graphene nanoplatelet reinforced composite, and the maximum tensile strength increased by 117% compared to the neat sample, reaching 903.13 N. Tensile strength tended to decrease at reinforcement ratios above 0.2%. A slight increase in tensile strength was observed for the 0.5% reinforcement ratio, but it could not catch the 0.2% reinforced sample. Alexopoulos et al. also stated that graphene reinforcement at values below 1% reinforcement significantly increased the strength of the material [25]. Furthermore, according to Li et al. [26], the tensile strength and hardness properties of graphene-reinforced composites exhibited improvement across various reinforcement ratios (0.3-0.9%). This enhancement was attributed to the rough surface structure of graphene, which promoted enhanced mechanical lock and load transfer between reinforcement and matrix. The primary cause for the reduction in tensile stress at reinforcement ratios above 0.2% can be expressed as agglomeration and pure bonding, which reduces the interaction between epoxy and graphene nanoplatelet, weakening the interfacial bond, and thus the occurrence of stress concentrations in these agglomeration regions [27]. In many studies, it has been observed that the 0.2-0.25% reinforcement ratio range provides the highest increase in strength. [25, 28].

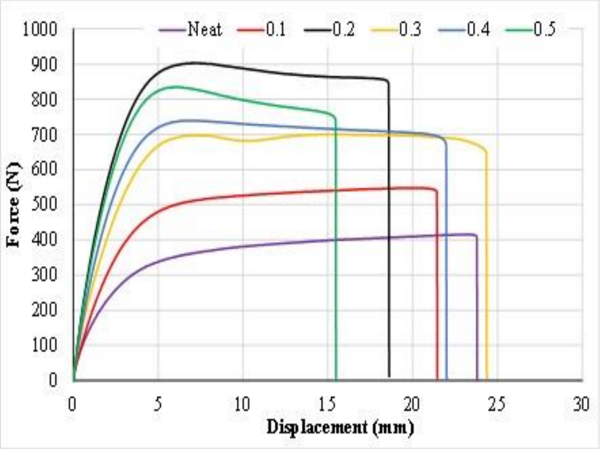

Figure 2. Applied Force –Displacement chart for epoxy composites with different reinforcement ratios

During the tensile tests, the percent strain changes were measured with the help of the TML brand BFLAB-5-3LJB-F series strain gauge attached to the specimens. The Young's Modulus of the specimens was determined for different reinforcement ratios by using the stress values and percent elongation values obtained from the universal test device (Figure 3).

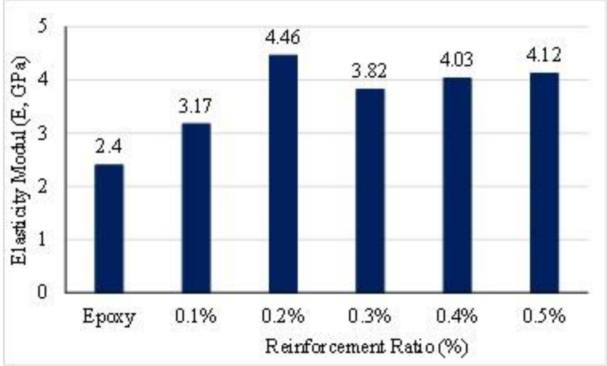

Figure 3. The elasticity modulus of neat and composites samples

The modulus of elasticity of the neat epoxy sample was determined as 2.4 GPa. The modulus of elasticity of the 0.1% graphene nanoplatelet-reinforced composite increased to 3.17 GPa. Similar to the tensile test, the highest modulus of elasticity was obtained at a 0.2% nanoparticle reinforcement ratio. For the 0.2% reinforcement ratio, the modulus of elasticity increased by 86%, reaching a value of 4.46 GPa. With an increase in the reinforcement ratio to 0.3%, there was a decrease in the modulus of elasticity, which dropped to 3.82 GPa. For 0.4% and 0.5% reinforcement ratios, the elastic modulus of the samples increased again but did not exceed that of the 0.2% reinforced sample. The modulus of elasticity for 0.4% and 0.5% reinforcement ratios were determined as 4.03 GPa and 4.12 GPa, respectively.

During the tests, strain gauges perpendicular to the tensile direction were attached to the samples, and the Poisson ratios were determined. The Poisson ratio of the neat epoxy samples was determined as 0.41. It was observed that the poison ratio decreased up to 0.2% reinforcement ratio. When this ratio is exceeded, it rises again, but then it tends to decrease.

The ε values of the neat, 0.1%, and 0.2% reinforced samples were determined as 0.41, 0.38 and 0.33, respectively. The lowest and highest ε value was determined in 0.5%, and 0.3% reinforced composites as 0.27 and 0.43. When the literature was examined, it was seen that the results were compatible with similar studies [25, 29].

4. WEAR TEST RESULTS

The wear performance is a multifaceted phenomenon influenced by various factors including sliding distance, applied load, temperature, and contact conditions. In this section, the effects of different loads, sliding distance and graphene nanoplatelet content on COF, WR and wear volume are discussed.

Figure 4 illustrates the variation of the COF over time at 10 N load and 250 m sliding distance. It is obvious the COF curve of the neat specimen follows a more fluctuating course compared to the reinforced samples. A high number of such fluctuations illustrates that the neat sample surface is worn more, and the surface integrity deteriorates in a shorter time. It was observed that these fluctuations gradually decreased as the reinforcement ratio increased, resulting in a reduce in the COF. Kazemi et al. [30] stated that graphene reinforcement up to 0.3% in fiber-reinforced composite reduced the COF, and when this ratio is exceeded, it started to rise again.

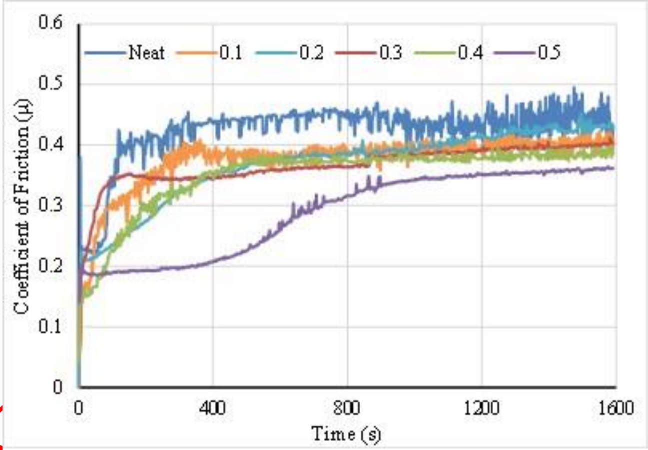

Figure 4. COF at 10 N load 250 m distance

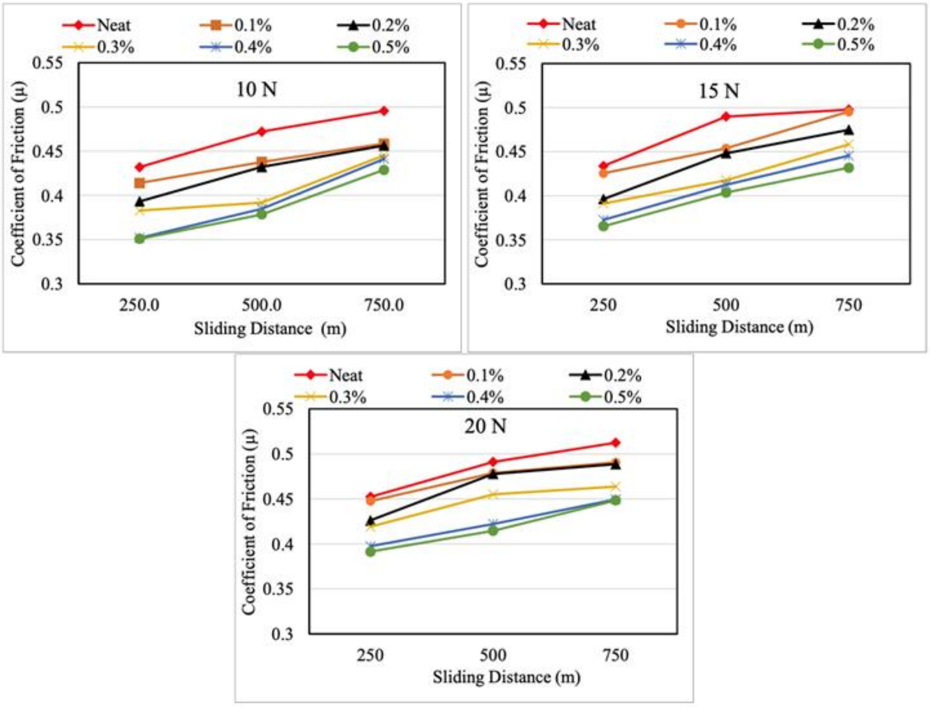

Figure 5. COF depending on the sliding distance

In Figure 5, COF graphs of reinforced and neat samples are given for each load, depending on the sliding distance. It is seen that the COF increase in all samples depending on the increasing sliding distance for all three applied loads. For 10 N load and 250 m sliding distance, the maximum and minimum COFs were obtained for the neat and 0.5% reinforced samples, and the COFs were measured as 0.43 and 0.35, respectively. Studies have revealed that the incorporation of 0.5% graphene nanoplatelet reinforcement provides an 18% reduction in the COF compared to the neat sample. Observations indicated that the COF reduced as the graphene nanoplatelet reinforcement ratio increased. Graphene nanoplatelet reinforcement seems to enhance the abrasion endurance of the epoxy. The homogeneous distribution of graphene nanoplatelet within the epoxy, which creates a robust network structure and establishes a favorable interface with the epoxy, emerges as the key factor contributing to the increased wear resistance. [31] Figure 6 presents the COF graphs for both reinforced and neat samples at all three sliding distances, depicting their variation as a function of load. It was apparent that the COFs increase for all materials depending on the increasing loads for each applied sliding distance. At low temperatures, the matrix material has a higher resistance to plastic deformation. Nevertheless, increasing the applied load, the surface temperature of the material escalates, leading to increased plastic deformation and surface degradation, ultimately causing a rise in the COF. Yazdani et al. [32] and Suresha et al. [33] underlined that the COF increases with higher loads which is well-suited with this study. The highest and lowest COFs were obtained for the neat epoxy, and 0.5% reinforced samples, and the COFs were measured as 0.51 and 0.44 for 750 m sliding distance and 20 N load, respectively. The increase in the graphene nanoplatelet content led to a decrease in the COF. Since graphene is a good lubricant and forms a transfer film layer, it contributes to reducing the COF [28].

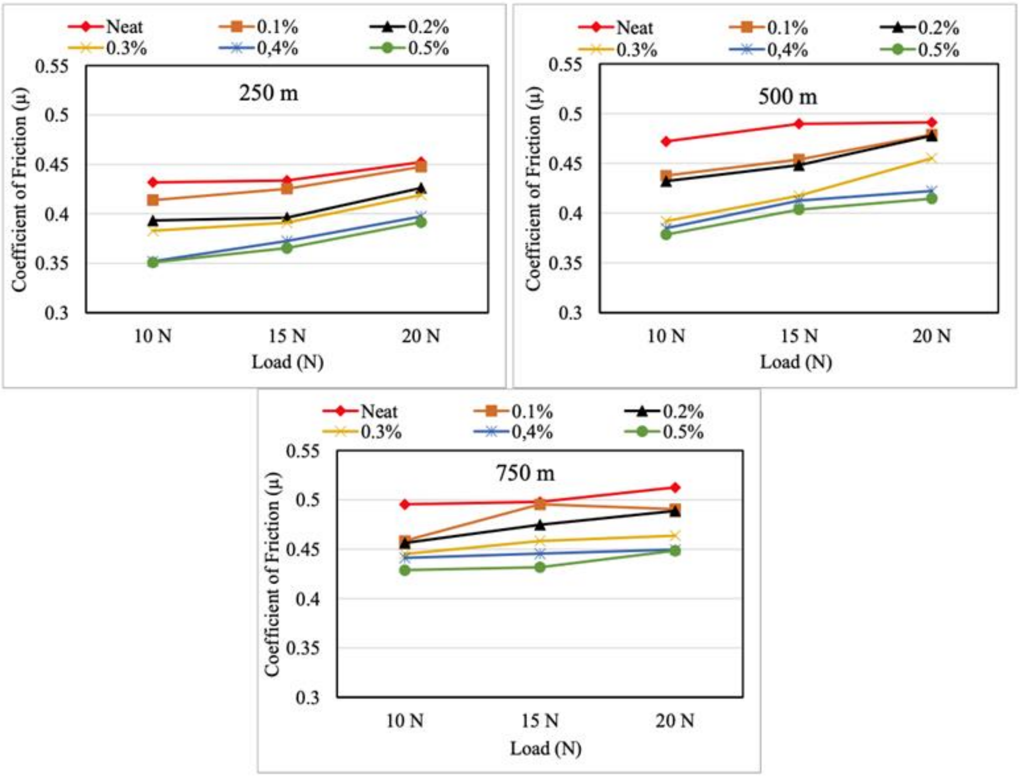

Figure 6. Coefficients of friction depending on load

In Figure 7, specific WR of reinforced and neat samples are given depending on the sliding distance. It was understood that the SWR reduced as the sliding distances increased. The maximum and minimum wear rates at 15 and 20 N loads were obtained in neat, and 0.5% graphene nanoplatelet reinforced composites, respectively. At these two applied loads, the wear rates at 250m distances differ significantly from 500 and 750 m distances. The wear rates for the neat and 0.5% reinforced composite were measured as $25.24*10^{-4}$ and $10.01*10^{-4}$, respectively, under the conditions of a 20 N load and 250 m sliding distance. It was observed that the WR exhibited a reduce with the increase in graphene nanoplatelet ratio. It is obvious that the graphene nanoplatelet reinforcement significantly increases the wear resistance. The reason for the enhancement in the wear endurance of the samples can be explained as the reduce in the COF and the improve the tensile strength. The decrease in the COF provides reduced lateral forces and lower wear loss. Furthermore, weak Van der Waals bonds between graphene layers enable interlayer shearing, which reveals the lubricating property of graphene [35].

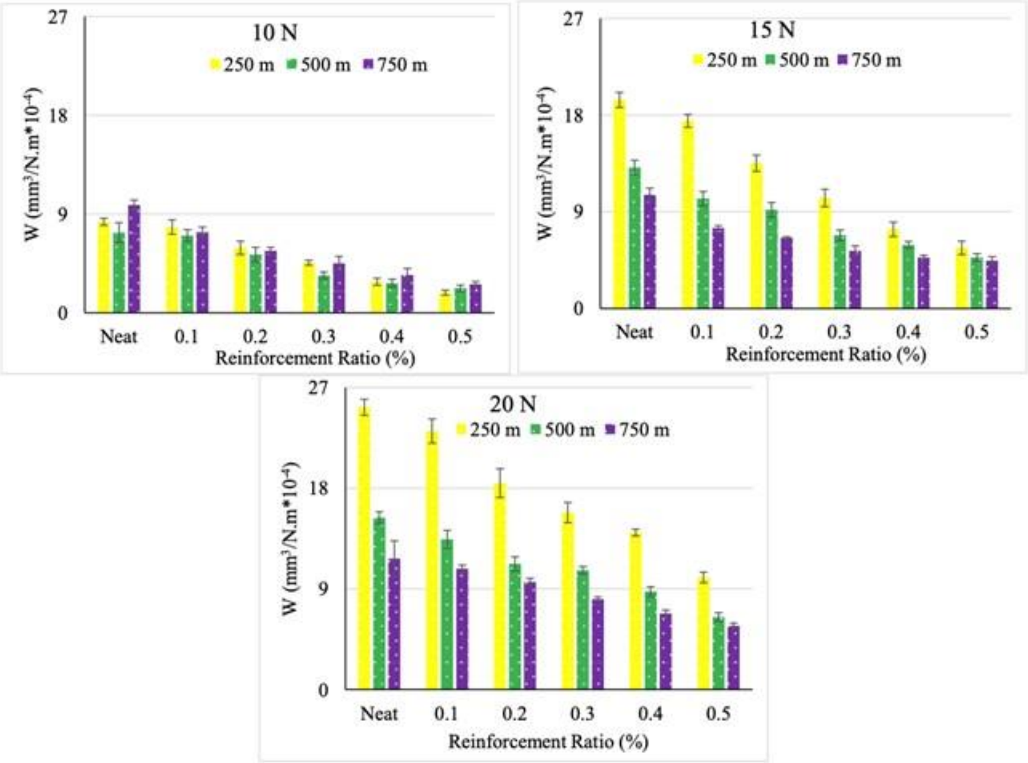

Figure 7. Specific wear rates depending on the sliding distance

Figure 8 illustrate the correlation between the load and wear rates of the neat and reinforced samples. It is evident that there is a gradual increase in the WR with an escalating the load. It has been determined that the difference between wear rates increased as the load increased at low sliding distances, while this difference decreased at high sliding distances. The wear volumes of the 0.2% graphene nanoplatelet reinforced composite at 20 N load at 250 m, 500 m and 750 m distances were measured as $18.46*10^{-4}$, $11.23*10^{-4}$ and $9.66*10^{-4}$ $mm^3/N.m$, respectively. Increasing the load from 10 N to 15 N for the same distance increased the wear volume at least twice. It is understood that the wear volume didn't change much after a certain sliding distance. The results are consistent with similar studies [36,37].

The change of wear volume with increasing load is illustrated in Figure 9. It was observed that the wear volume get higher with increasing the load. For neat epoxy, increasing the load from 10 N to 20 N increased the wear volume from 2.07 mm^3 to 12.62 mm^3 at a 250 m distance. This shows that there is a parabolic relationship between the applied load and the wear volume. At 20 N and 500 m distance, the wear volume of 0.5% graphene nanoplatelet reinforced composite was reduced by approximately 58%, compared to neat epoxy, down to 6.48 mm^3. Kumar et al. [38] also yielded similar results, demonstrating an increase in wear volume with escalating the applied load.

The graphs of wear volumes at constant load and variable sliding distances are shown in Figure 10. It is obvious that the wear volume at 10 N loads is quite low compared to the wear volume at 15 N and 20 N loads. The difference between wear volumes decreased with increasing sliding distances as the graphene nanoplatelet content increased. The two-dimensional planar geometry of graphene nanoplatelet helped to restrain crack propagation, thereby reducing the size of the debris and the wear rate. For neat epoxy, increasing the load from 10 N to 20 N at a constant sliding distance increased the wear volume from 2.07 mm^3 to 12.06 mm^3 while increasing it from 250 m to 750 m at a constant load from 2.07 mm^3 to 0.46 mm^3. The effect of the load on the wear volume is more dominant compared to the sliding distance.

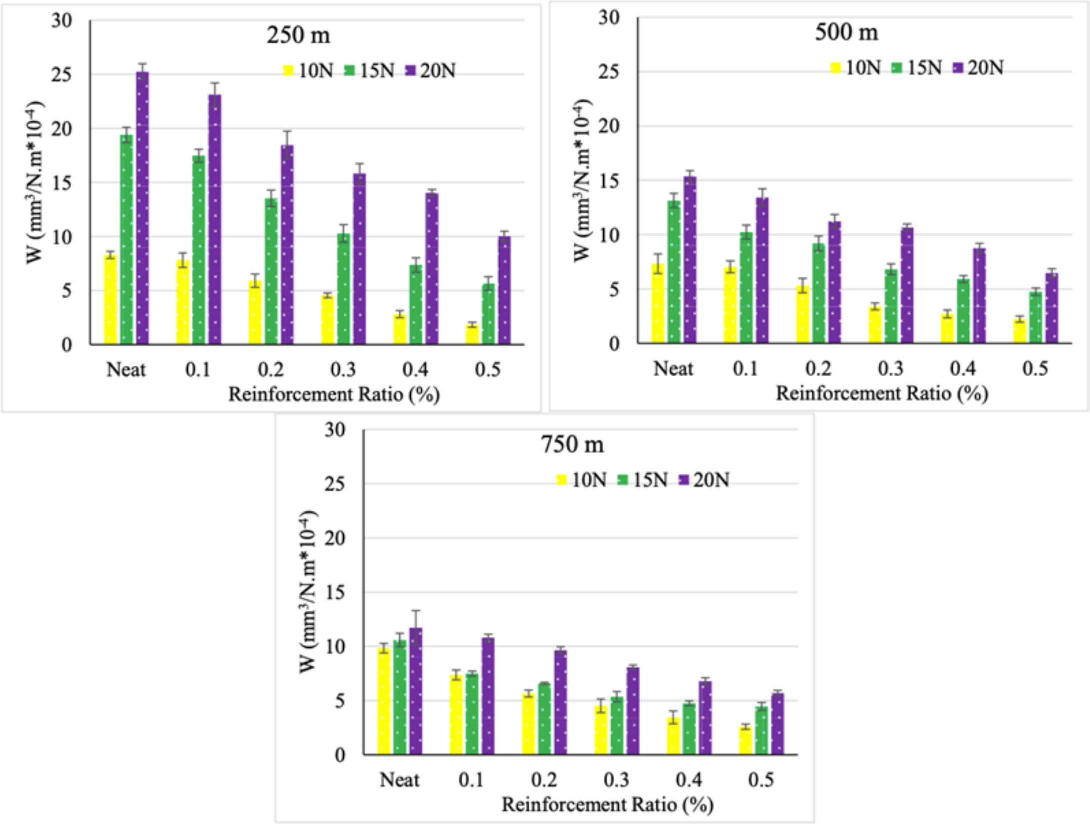

Figure 8. Load-dependent specific wear rates

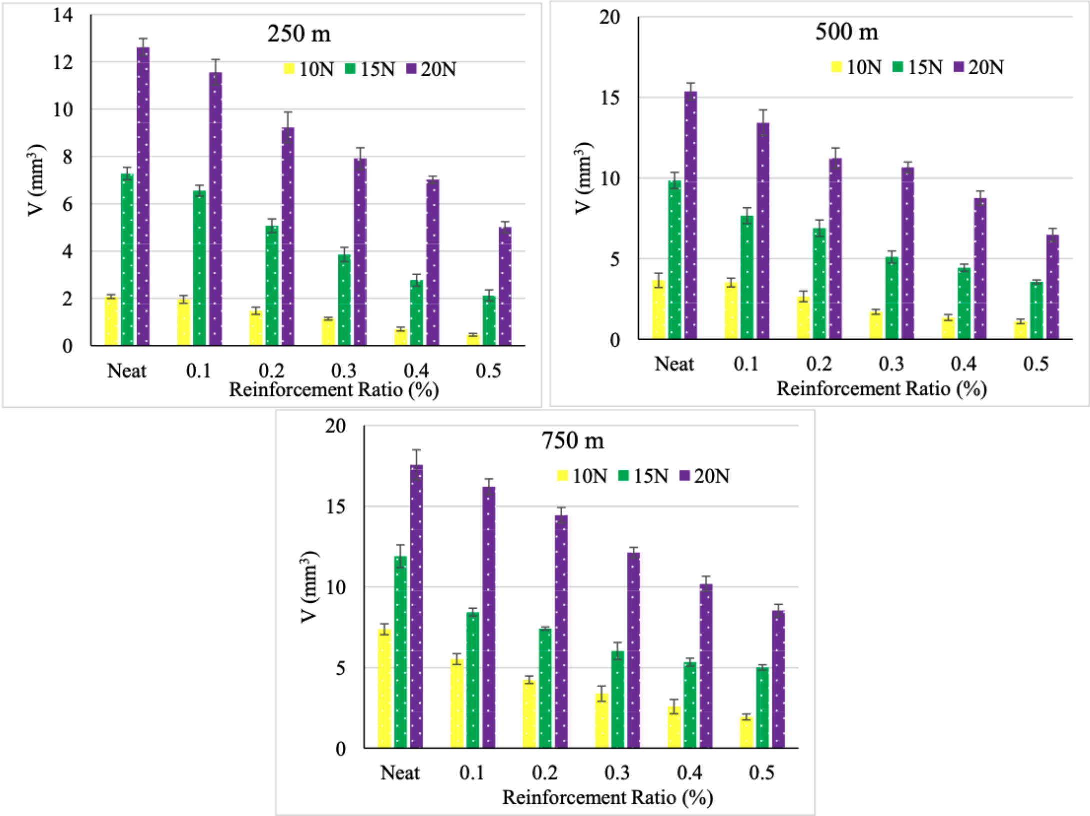

Figure 9. Load-dependent wear volumes

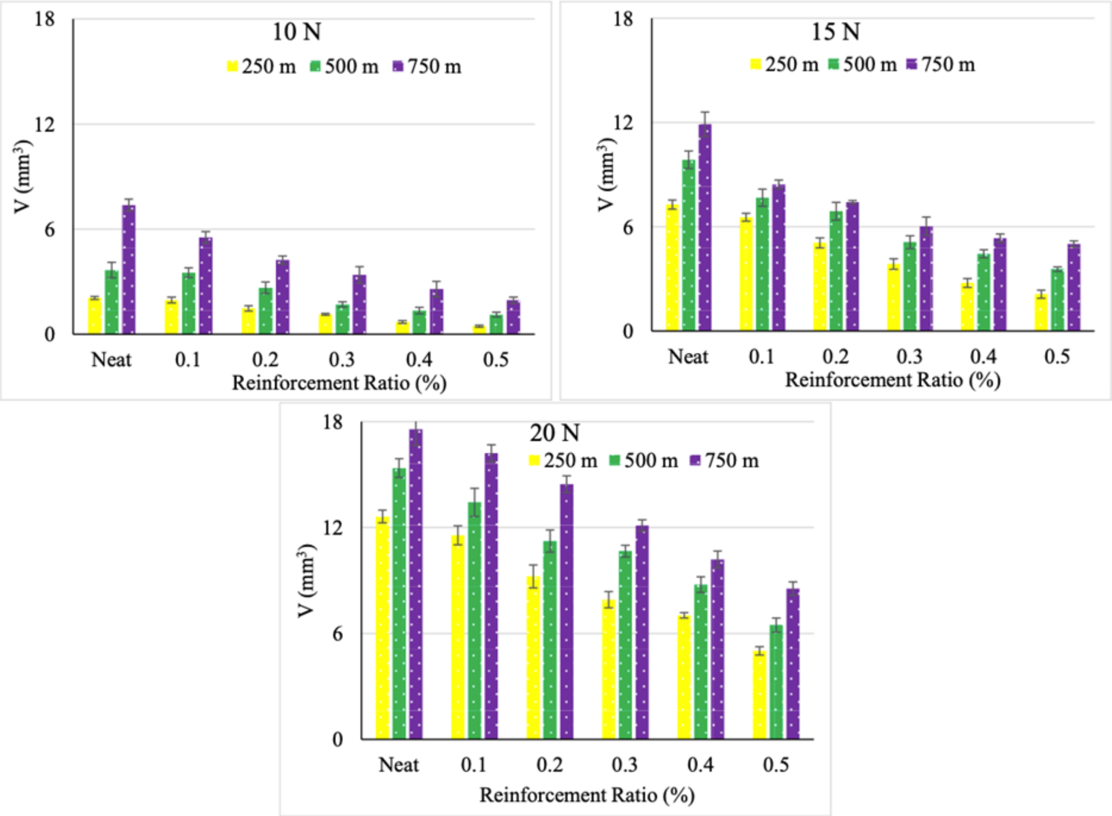

Figure 10. Wear volumes depending on the sliding distance

5. WEAR SURFACE MORPHOLOGY

In Figure 11, the surface morphologies of the neat and reinforced worn specimens under different loads are given. Upon examining Figures 13a and 13c, it is evident that the wear trace width of the neat sample under a 10 N load is narrower compared to the 20 N load. Additionally, it was seen that the cavities within the matrix became larger, deeper, and more prevalent in the wear zone with increasing load. This indicates that the surface of a sample subjected to a 10 N load is smoother than those subjected to higher loads. Upon comparing the wear areas of the 0.2% graphene nanoplatelet-reinforced composite in Figure 13e and Figure 13f, it is observed that the wear trace expands in the region where the load is increased.It is understood that the wear trace of 0.2% graphene nanoplatelet reinforced composite is lower compared to the neat sample, and the matrix deformation is reduced. It has also been observed that the wear debris is smaller and has a cleaner surface.

The lubricating property of graphene nanoplatelet formed a film layer between the pin and the counter surface, reducing the contact area and resulting in increasing wear resistance. In Figure 13g and Figure 13h, it is seen that the trace width of 0.5% graphene nanoplatelet reinforced composite is lower than neat and 0.2% graphene nanoplatelet reinforced composite. It is

clear that both the amount of debris, pits, and size of scratches were observed less in the wear zone in Figure 13g and Figure 13h. It was noted that the amount of wear increased as the load was increased in all three materials that underwent surface morphology examination. Increasing the graphene nanoplatelet reinforcement ratio improved the tribological properties of the sample.

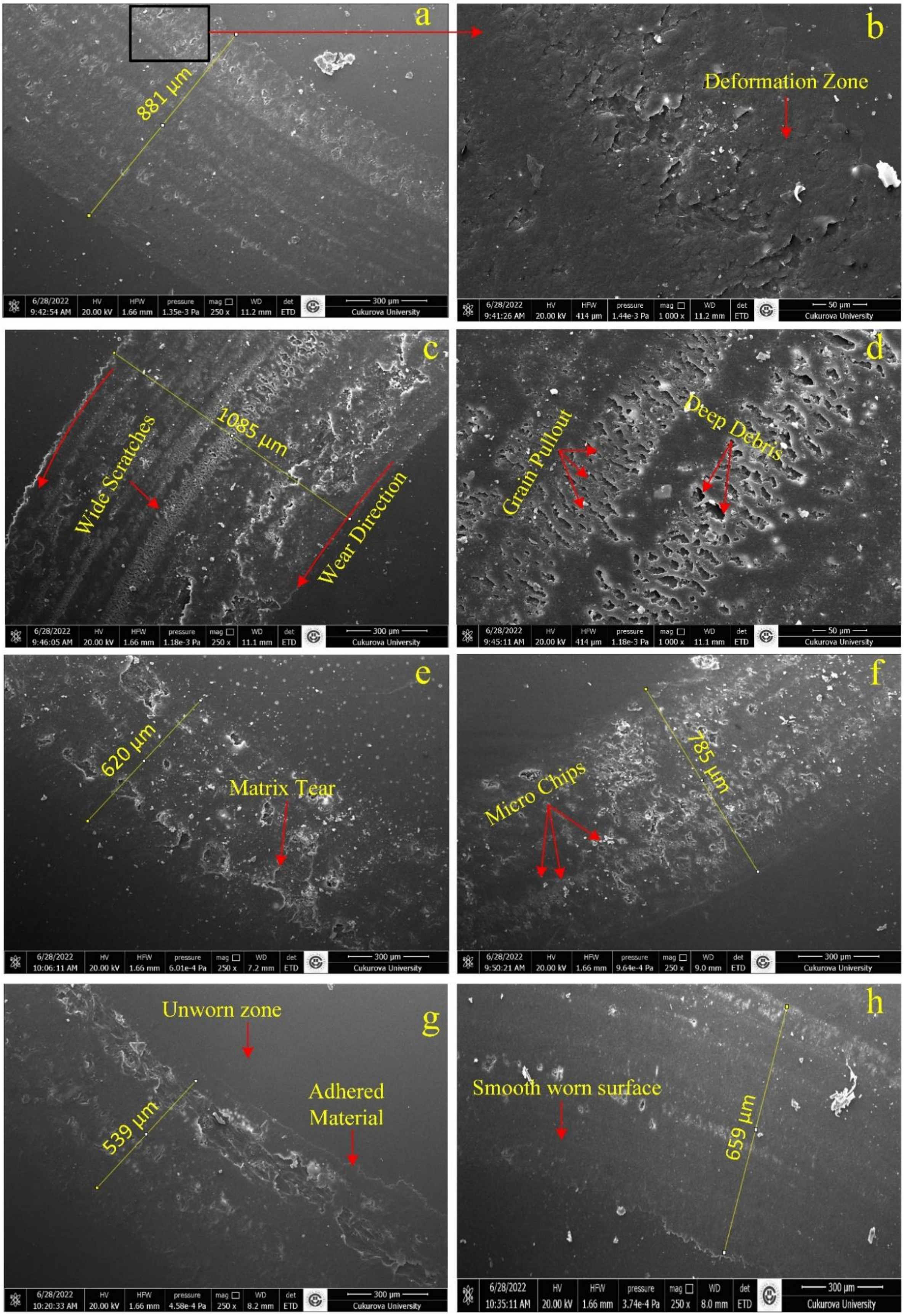

Figure 11. SEM images of worn samples; a) Neat 10 N, b) Magnification of image a at 1000x c) Neat 20 N, d) Magnification of image c at 1000x e) 0.2%Gr 10 N, f) 0.2% Gr 20 N, g)0.5%Gr 10 N, h) 0.5%Gr 20 N

3. CONCLUSIONS

The effects of graphene nanoplatelet reinforcement to epoxy material and different reinforcement ratios on the tensile force and wear properties of the produced composites are as follows;

- The test results revealed a significant impact of incorporating graphene nanoplatelet into the epoxy matrix material on the mechanical properties. The Young's Modulus, which is an expression of the amount of strain of the materials against the applied load, was higher than that of pure epoxy in all samples with graphene nanoplatelets.
- The most significant effect of graphene nanoplatelets on the Young's Modulus was seen in the sample with 0.2% nanoparticles. An 86% increase was achieved in the modulus of elasticity of this sample. Although a slight decrease was observed in the sample strength and Young's Moduluswith the added nanoparticle amount exceeding 0.2%, this decrease did not go below the neat epoxy values.
- There was an increase in the COF across all material types as the load and sliding distance were increased. However, compared to the neat epoxy, the graphene nanoplatelet-reinforced composites exhibited a lower COF. Moreover, both the addition of graphene nanoplatelet and an increase in graphene nanoplatelet content contributed to enhanced wear resistance in the samples.
- Increasing the sliding distance and load resulted in an increase in wear volume. It was comprehended that the WR elevated with a rise in the load, whereas the WR declined with an increase in the sliding distance.
- Upon examining the SEM pictures, it was evident that the wear tracks were wider, the surface deformation was more, and the cavities were deeper for higher load levels. It was observed that the deformation, microcracks and chip formation in the worn region of the composite were reduced with graphene nanoplatelet reinforcement. Sem images support the obtained mechanical and tribological results.

DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission

AUTHOR'S CONTRIBUTIONS

Mehmet Emin DEMİR: Wrote the manuscript and analyse the results.

Hüsna TOPKAYA: Perofrmed the experiments and analyse the results.

Yahya Hışman ÇELİK: Performed the experiments and analyse the results.

Tuba BAĞATIR: Performed the experiments analyse the results.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

REFERENCES

[1] Hull, D., Clyne, T., "An Introduction to Composite Materials", Cambridge University Press, (2012).

[2] Hsissou, R., Seghiri, R., Benzekri, Z., Hilali, M., Ra, M., and Elhar, A. (2021). "Polymer composite materials : A comprehensive review" ***Composite Structures,*** 262: 113640, (2021).

[3] Jain, V., Bisht, A., Jaiswal, S., Dasgupta, K., and Lahiri, D. "Assessment of Interfacial Interaction in Graphene Nanoplatelets and Carbon Fiber-Reinforced Epoxy Matrix Multiscale Composites and Its Effect on Mechanical Behavior" ***Journal of Materials Engineering and Performance,*** 30, 8913–8925: (2021).

[4] Kamaraj, M., Manimaran, R., & Datta, S. "Optimization of Dry Sliding Wear Parameters of Graphene-Filled Flax Fiber-Reinforced Epoxy Composites using Taguchi Grey Relational Analysis" ***Journal of The Institution of Engineers (India): Series D.***, (2022).

[5] Prolongo, M. G., Salom, C., Arribas, C., and Sa, M. "Influence of graphene nanoplatelets on curing and mechanical properties of graphene/epoxy nanocomposites", ***Journal of Thermal Analysis and Calorimetry,*** (2015).

[6] Hou, L., Gao, J., Ruan, H., Xu, X., and Lu, S. "Mechanical and thermal properties of hyperbranched poly(ε-caprolactone) modified graphene/epoxy composites" ***Journal of Polymer Research***, 27(2): (2020).

[7] Kalin, M., Zalaznik, M., & Novak, S. "Wear and friction behaviour of poly-ether-ether-ketone (PEEK) filled with graphene , WS2 and CNT nanoparticles", ***Wear,*** 1–8, (2015).

[8] Mittal, G., Dhand, V., Yop, K., Park, S., and Ro, W. "Journal of Industrial and Engineering Chemistry A review on carbon nanotubes and graphene as fillers in reinforced polymer nanocomposites", ***Journal of Industrial and Engineering Chemistry,*** 21: 11–25, (2015).

[9] Kuilla, T., Bhadra, S., Yao, D., Hoon, N., Bose, S., and Hee, J. "Progress in Polymer Science Recent advances in graphene based polymer composites", ***Progress in Polymer Science***, 35(11): 1350–1375, (2010).

[10] Potts, J. R., Dreyer, D. R., Bielawski, C. W., and Ruoff, R.S., Graphene-based polymer nanocomposites. ***Polymer,*** 52(1): 5–25, (2011).

[11] Avinc, I., Akpinar, S., Akbulut, H., & Ozel, A. "Experimental analysis on the single-lap joints bonded by a nanocomposite adhesives which obtained by adding nanostructures", ***Composites Part B***, 110: 420–428, (2017).

[12] Gnanakkan, V., Veerakumar, S., Shanmugavel, B. P., Paskaramoorthy, R., and Harish, S. "The Influence of Graphene Nanoplatelets on the Tensile and Impact Behavior of Glass-Fiber-Reinforced Polymer Composites" ***Journal of Materials Engineering and Performance,*** 596–609, (2021).

[13] Doagou-rad, S., Islam, A., Jensen, J. S., and Alnasser, A. "Interaction of nanofillers in injection-molded graphene /carbon nanotube reinforced PA66 hybrid nanocomposites" ***Journal of Polymer Engineering***, 38(10): 971–981, (2018).

[14] Wan, Y., Tang, L., Gong, L., Yan, D., and Li, Y. "Grafting of epoxy chains onto graphene oxide for epoxy composites with improved mechanical and thermal properties" ***Carbon,*** 69: 467–480, (2013).

[15] Chatterjee, S., Wang, J. W., Kuo, W. S., Tai, N. H., Salzmann, C., Li, W. L., Hollertz, R., Nüesch, F. A., and Chu, B. T. T. "Mechanical reinforcement and thermal conductivity in expanded graphene nanoplatelets reinforced epoxy composites" ***Chemical Physics Letters,*** 531: 6–10, (2012).

[16] Polat, S., Avc, A., and Ekrem, M. "Fatigue behavior of composite to aluminum single lap joints reinforced with graphene doped nylon 66 nano fibers", ***Composite Structures Journal***, 194: 624–632, (2018).

[17] Chandrasekaran, S., Sato, N., Tölle, F., Mülhaupt, R., Fiedler, B., and Schulte, K. "Fracture toughness and failure mechanism of graphene based epoxy composites", ***Composıtes Scıence And Technology***, 97: 90–99, (2014).

[18] Boumaza, M., Khan, R., & Zahrani, S. "An experimental investigation of the effects of nanoparticles on the mechanical properties of epoxy coating" ***Thin Solid Films***, 620: 160–164, (2016).

[19] Sepetcioglu, H., & Tarakcioglu, N. "Effect of Graphene Nanoplatelets on Progressive Failure Behavior under Internal Pressure of Composite Cylindrical Pressure Vessels" ***Journal of Materials Engineering and Performance,*** 31(3): 2225–2239, (2022).

[20] Du, X., Zhou, H., Sun, W., Liu, H., & Zhou, G. "Graphene / epoxy interleaves for delamination toughening and monitoring of crack damage in carbon fibre / epoxy composite laminates" ***Composites Science and Technology,*** 140: 123–133, (2017).

[21] Upadhyay, R. K., and Kumar, A. "Effect of humidity on the synergy of friction and wear properties in ternary epoxy-graphene-MoS2 composites" ***Carbon,*** 146: 717–727, (2019).

[22] Wang, H., Xie, G., Zhu, Z., Ying, Z., and Zeng, Y. "Enhanced tribological performance of the multi-layer graphene filled poly (vinyl chloride) composites", ***Composıtes Part A,*** 67: 268–273, (2014).

[23] Akbulut, H., Keskin, Z., and Özel, A. "The effects of graphene nanostructure reinforcement on the adhesive method and the graphene reinforcement ratio on the failure load in adhesively bonded joints", ***Composites Part B***, 98: 362–369, (2016).

[24] Xiao, W., Lu, S., Wang, Y., & Shi, J. "Mechanical and tribological behaviors of graphene / Inconel 718 composites", ***Transactions of Nonferrous Metals Society of China,*** 28(10): 1958–1969, (2018).

[25] Alexopoulos, N. D., Paragkamian, Z., Poulin, P., and Kourkoulis, S. K. "Fracture related mechanical properties of low and high graphene reinforcement of epoxy nanocomposites", ***Composites Science and Technology***, 150: 194–204, (2017).

[26] Li, S., Zhang, J., Liu, M., Wang, R., and Wu, L. "Influence of polyethyleneimine functionalized graphene on tribological behavior of epoxy composite", ***Polymer Bulletin,*** 78: 6493–6515, (2021).

[27] Eayal Awwad, K. Y., Yousif, B. F., Fallahnezhad, K., Saleh, K., & Zeng, X. "Influence of graphene nanoplatelets on mechanical properties and adhesive wear performance of epoxy-based composites", ***Friction,*** 9(4): 856–875, (2021)

[28] Jia, Z., Feng, X., & Zou, Y. "Graphene Reinforced Epoxy Adhesive For Fracture Resistance", ***Composites Part B,*** 155: 457–462, (2018).

[29] Shokrieh, M. M., Esmkhani, M., Shahverdi, H. R., and Vahedi, F. "Effect of Graphene Nanosheets (GNS) and Graphite Nanoplatelets (GNP) on the Mechanical Properties of Epoxy Nanocomposites", ***Science of Advanced Materials***, 5(3): 1–7. (2013).

[30] Kazemi-khasragh, E., Bahari-sambran, F., Eslami-farsani, R., Chirani, S. A., Mohammad, S., and Siadati, H. "The effects of surface-modified graphene nanoplatelets on the sliding wear properties of basalt fibers-reinforced epoxy composites", ***Journal of Polymer Applied Science,*** 47986: 1–9, (2019).

[31] Sun, W., Yu, S., Tang, M., and Wang, X. "Friction and Wear Properties of Graphene / Epoxy Composites", ***Earth and Environmental Science,*** 706: 012032021, (2021).

[32] Yazdani, B., Xu, F., Ahmad, I., Hou, X., Xia, Y., and Zhu, Y. "Tribological performance of Graphene /Carbon nanotube hybrid reinforced Al2O3 composites", ***Nature Publishing Group***, 1–11, (2015).

[33] Suresha, B. Chandramohan, G. Samapthkumaran, P. Seetharamu, S. and Vynatheya, S. "Friction And Wear Characteristics Of Carbon-Epoxy And Glass-Epoxy Woven Roving Fiber Composites", ***Journal of Reinforced Plastics and Composites,*** 25: 771, (2006).

[34] Zakaria, M. R., and Kudus, M. H. A. "Study on Two Body Abrasive Wear behaviour of Carboxyl- Graphene Reinforced Epoxy Nano-composites", 376: 012058, (2018).

[35] Lahiri, D., Hec, F., Thiesse, M., and Durygin, A. "Nanotribological behavior of graphene nanoplatelet reinforced ultra high molecular weight polyethylene composites", ***Tribology International,*** 70: 165–169, (2014).

[36] Surya Rajan, B., Sai Balaji, M.A, Mohamed Aslam Noorani, A.B. "Tribological performance of graphene/ graphite filled phenolic composites-A comparative study", ***Composites Communications***, 15: 34–39, (2019).

[37] Du, Y., Zhang, Z., Wang, D., Zhang, L., Cui, J., Chen, Y., Wu, M., Kang, R., Lu, Y., Yu, J., & Jiang, N. "Enhanced tribological properties of aligned graphene – epoxy composites", ***Tribology,*** 10: 854–865, (2022).

[38] Kumar, S., Singh, K.K., Ramkumar, J., "Comparative study of the influence of graphene nanoplatelets filler on the mechanical and tribological behavior of glass fabric-reinforced epoxy composites",***Polymer Composites***, 1–15, (2020).