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Examine the Physical Properties of Rubber-Modified Unsaturated Polyester for Potential Wearable Technology Applications

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Abstract: This study examines the influence of incorporating natural rubber (NR) into unsaturated polyester resin (UP) on the thermal conductivity, friction coefficient, and wear rate. Three blend ratios (90/10, 60/40, and 50/50 UP/NR) were prepared to explore how varying NR content affects these properties. The results demonstrate that increasing the NR content leads to a significant rise in both the coefficient of friction and wear rate, particularly evident at the 50/50 composition. Specifically, the coefficient of friction increased by approximately 45–50%, while the wear rate nearly doubled compared with the 90/10 blend. Conversely, the thermal conductivity decreased progressively with higher NR ratios—by roughly 30% from the 90/10 to the 50/50 composition—due to the insulating nature of rubber. The 90/10 blend thus showed the highest heat transfer capability. Overall, the study confirms that blending UP with NR allows controlled tuning of material properties according to specific engineering needs. High NR content is advantageous for applications requiring impact absorption or vibration damping, whereas low NR content favors heat dissipation and wear resistance. In this context, UP reinforced with NR provides a balance of structural integrity and elasticity that can be valuable in wearable systems, including flexible housings, protective layers, vibration-damping elements, and thermal-insulating structures.

Keywords: polymer blends, wearable systems, coefficient of friction, wear resistance, thermal conductivity

1. Introduction

Polymeric materials are generally non-conductive, which is why they are widely used as insulators in various electronic and electrical applications. Their insulating properties help prevent the flow of electricity, protecting sensitive components in devices from potential electrical issues. However, despite these insulating qualities, polymers tend to accumulate electrostatic charge over time. This buildup of electrostatic discharge (ESD) can pose challenges, especially in high-precision electronic devices, where even a small discharge can cause malfunctions or permanent damage to the components. Therefore, managing ESD in polymeric materials becomes a crucial consideration when using them in electronic and electrical systems [1, 2]. The growing demand for materials that are not only cost-effective but also possess a range of desirable properties, such as chemical resistance, lightweight nature, and electrical conductivity, has driven significant innovation within this area of materials science. As industries across the globe continue to seek solutions that balance performance and cost, the need for advanced materials that can meet these criteria has become increasingly critical. This demand has spurred researchers and engineers to explore new ways of developing materials that are both efficient and versatile, capable of meeting the specific needs of various sectors, from electronics and automotive to healthcare and manufacturing [3]. Polymer blending has been an established practice in the polymer industry for a long time, and it involves the blending of two or more types of polymers to gain unique properties that are not obtainable through the use of one polymer. The applications of polymer blends vary from the automotive industry, coatings, biomedical engineering, aerospace industry, and civil engineering applications [4].

Polymers are an important class of materials that are commonly used in tribo-engineering applications due to their distinctive features. They are commonly used in a variety of mechanical components, including gaskets, vessel linings, pump chambers, gears, and other systems that require higher wear resistance. Polymers also play an important part in the development of wearable technology, which has special material requirements to suit the device's functional needs. These devices must have flexibility, the ability to absorb impacts, low weight, efficient heat management, and long-term mechanical stability in order to tolerate continuous body movement without failure. Combining various polymer types, polymer blends provide tunable and adaptable qualities that may be customized to meet these varied needs, guaranteeing optimal performance and durability in wearable applications. Polymer blends' adaptability makes it possible to create materials that are flexible and lightweight while also retaining their mechanical qualities over time [5], particularly due to the insufficient level of their tribotechnical characteristics, as polymers exhibit a low friction coefficient compared to metals due to their low interfacial adhesion energy [6, 7]. It should be

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noted that polymer tribology, as their friction and wear mechanisms, is more complex than for metal and less well understood. Polymer tribology differs from metal/ceramic tribology because polymer/metal or polymer/polymer contact is predominantly elastic, and well-established "laws of friction" for the tribology of metal and ceramic contacts in relative motion generally do not follow for polymer/metal friction contacts [8–10].

The primary aim of this study is to explore and understand the impact of incorporating natural rubber (NR) into unsaturated polyester resin (UP) on the thermal and tribological properties of the resulting polymer blends. By examining these effects, the study seeks to determine how the combination of NR and UP influences the material's performance in key areas such as heat resistance, friction, wear, and durability. These properties are critical for applications in both engineering and wearable technology, where materials are expected to not only withstand mechanical stress but also operate efficiently under varying thermal conditions. Through this investigation, the study aims to provide valuable insights into how polymer blends can be optimized for specific functional requirements, particularly in industries that demand both lightweight and high-performance materials.

2. Literature Review

The researcher investigated the tribological properties of 3D printed polymers (ABS, PLA, co-polyester, and PCL) for various applications, including medical and automotive. Using Fused Deposition Modeling, the researcher printed specimens and assessed their tribological characteristics with a pin-on-disc tester and Vickers hardness testing. The study found that 3D printing improved the bonding strength and wear resistance of the polymers. The friction coefficients varied, with PLA and co-polyester showing the lowest values (0.3), while ABS and PCL had higher values (0.4 and 0.39). Surface roughness and hardness were key factors in controlling friction and wear, demonstrating the suitability of these 3D printed materials for diverse applications [11].

Ibrahim et al. [12] conducted an in-depth study to investigate the effects of incorporating graphite microparticles into epoxy matrix composites, focusing on their impact on both the mechanical and tribological properties of the resulting materials. Through a series of controlled experiments, they observed that increasing the graphite content led to a noticeable reduction in the tensile strength of the composites. However, the study also highlighted significant improvements in other mechanical properties, such as flexural strength, hardness, and impact strength. These findings suggest that while the addition of graphite may compromise the tensile strength, it has the potential to enhance other critical properties that contribute to the overall performance of the composite materials. The results particularly emphasize the role of graphite as an effective filler material, offering enhanced wear resistance and improved frictional characteristics, which are crucial for applications that require durable and high-performance composite materials. The research suggests that optimizing the amount of graphite used in these composites could lead to a balance between different mechanical properties, making it a valuable approach for developing advanced materials in various engineering applications.

Chen et al. [13] conducted a comprehensive experimental study to investigate the mechanical and tribological properties of composite materials, focusing on phenolic-resin-based fiber-reinforced composites. The study provides valuable insights into the behavior of composite-metallic friction interfaces, which are critical in friction-based structural components for earthquake engineering. These components must withstand repetitive stresses, high frictional forces, and extreme conditions to ensure the reliability and longevity of structures under seismic activity. By analyzing the interaction between composite and metallic interfaces under various conditions, the study offers important information for optimizing materials used in earthquake-resistant structures, improving their durability and effectiveness in mitigating seismic risks.

3. Experiment and Method

3.1. Materials

UP and NR were supplied by Saudi Industrial Resins Limited Company (SIR)™.

3.2. Preparation of polymer blends

Initially, 90% UP was carefully mixed with 1% hardener using a magnetic stirrer to ensure a homogeneous blend. Following this, 10% NR was gradually added to the mixture and thoroughly combined to achieve uniform dispersion of the rubber particles within the polyester matrix. The resulting mixture was then carefully poured into molds that had been pre-coated with a thin layer of oil to prevent sticking. The molds were left undisturbed for a period of two days to allow the material to fully cure and harden at room temperature. Once the material had solidified, the sample was carefully removed from the mold and placed in a drying oven, where it was heated at 60 °C for one hour to remove any residual moisture. This process was repeated for the remaining proportions of the UP and NR blend, ensuring that each sample was processed under identical conditions for consistency and accuracy in the final product properties.

3.3. Wear test

The wear test was performed using the wear method according to ASTM G99-17. Samples were cut with dimensions of 10 × 10 mm (length and width) and 20 mm (height), and the sample weight was measured after a specified time period (30 min in this study). The applied loads were 1 and 2.5 kg. The abrasion rate was calculated using the following equation:

$$Wear\ rate = \frac{\Delta W}{S_D} \quad (1)$$

where DW represents the change in sample weight before and after wear and SD is the wear distance (cm), which can be calculated using the following equation:

$$S_D = 2\pi rnt \quad (2)$$

where (r) is the radius of rotation, (n) is the number of revolutions per minute (rpm) (400 rpm in this test), and t is the rotation time (in min) [14].

3.4. Coefficient of friction

The coefficient of friction for the prepared samples was calculated using a friction coefficient device. It consists of a rectangular parallelepiped object called a slide, on which the sample is placed. The slide is placed on a horizontal surface and contains a hook to which a string is attached, passing over a pulley. A balance pan hangs from the other side. Initially, the slide and the balance pan are separated, and the string pulling the slide must be horizontal. The slide is placed on the board, and the position of its edge is marked with a pencil. Weights are then gradually placed on the pan until the object begins to move. The coefficient of friction is then derived from the following law [15]:

$$\varsigma = \frac{M}{m} \tag{3}$$

M: Weight of weights
m: Weight of sample with base (slide)

3.5. Thermal conductivity

A Lee Disk device (George and Griffin™) can be used to calculate the thermal conductivity coefficients of the tested materials. The thermal conductivity is determined using the following equation:

$$K\left[\frac{T_B - T_A}{d_s}\right] = e\left[T_A + \frac{2}{r}\left(d_A + \frac{1}{4}d_s\right)T_A + \frac{1}{2r}d_sT_B\right] \tag{4}$$

where e represents the amount of thermal energy passing through a unit area of the disk material per second (W/m²·K) and is estimated from the following equation:

$$\begin{aligned} IV = \pi r^2 e\,(T_A + T_B) + 2\pi re\,[d_AT_A] \\ + d_s\frac{1}{2}(T_A + T_B) + d_BT_{Bd} + d_cT_C \end{aligned} \tag{5}$$

IV is the thermal energy that passes through the heating coil per unit time; T_A, T_B, and T_C represent the respective disk temperatures; and d and r are the thickness and radius of the disk (mm). According to ASTM-D150, the specifications for measuring thermal conductivity were a thickness of 6.73 mm and a diameter of 40 mm [16].

4. Results and Discussions

4.1. Coefficient of friction

Figure 1 shows a comparison of friction coefficients for a polymeric material made from a blend of UP and NR in various ratios of 90/10, 60/40, and 50/50. After close inspection of the data presented, it is clear that the material's precise composition has a significant impact on its frictional behavior.

In the 90/10 ratio, where polyester resin is the major component, the material has a lower friction coefficient than the other ratios. This reduced friction is most likely due to the predominant presence of polyester resin, which adds to a smoother surface with less resistance to motion. The natural properties of polyester resin, such as its molecular structure and comparatively low surface roughness, enable smoother sliding and less interaction between the material surfaces, which lowers friction.

In applications where low friction is required, this specific 90/10 composition may be beneficial. These applications could include low-resistance surfaces, sliding contacts, or systems where wear reduction and energy economy are critical. For instance, this reduced friction may assist in prolonging the life of elements like bearings, seals, or other mechanical parts that move constantly, assuring smoother and more effective functioning. Therefore, the 90/10 composition could be specially designed for applications where friction control is critical to the system's overall functioning and performance [11]. A discernible increase in the friction coefficient is seen in the 60/40 ratio, which increases the amount of NR in relation to the UP. The increased amount of NR, which has an innate propensity to interact more thoroughly with the opposing surface upon contact, is the main cause of this increase in friction. Rubber has a higher resistance to motion due to its increased surface interaction and capacity to deform under pressure, which raises the total friction between surfaces.

The increased rubber component also helps to improve the material's resilience to wear. Because of its elasticity and capacity to absorb energy, NR increases the material's longevity in situations involving stress or frequent contact.

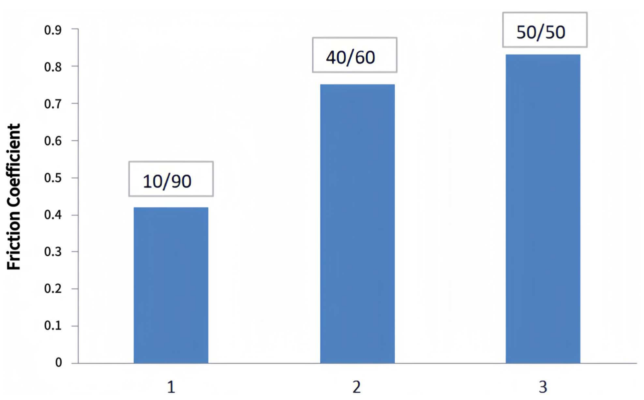
The 60/40 blend is better suited for applications requiring a higher level of friction, including high-traction parts or systems that must withstand increased mechanical stress and wear over time, because of its enhanced wear resistance.

Seals, gaskets, and friction-based components in machinery are examples of such applications, where endurance and a modest amount of friction are essential for preserving performance and averting early failure. The 60/40 composition finds a balance between retaining some flexibility for functional adaptability and offering enough friction for wear resistance and traction. As a result, this material combination is perfect for situations where the lifetime and effectiveness of the components depend on both durability and a controlled rise in friction [17, 18].

The 50/50 ratio, which is an equal blend of UP and NR, has the highest friction coefficient of the three compositions examined. This large increase in friction indicates that the balanced combination of the two materials generates an optimal interaction between the components, resulting in a greater ability to generate friction when in contact with an opposing surface. The even distribution of resin and rubber most likely adds to a synergistic effect, in which the properties of each material complement each other in a way that improves surface engagement, resulting in increased resistance to movement. The increased friction coefficient reported in this 50/50 ratio composition may be useful in applications that need a greater amount of grip or frictional force.

For instance, this formulation might be advantageous for parts like brake pads, traction devices, or other mechanical systems that depend on greater friction to function well. A material that may provide the required frictional resistance for such high-grip applications is produced by striking a compromise between the energy-absorbing qualities of rubber and the smooth surface

Figure 1
Friction coefficients of all samples



of resin. It should be noted, nonetheless, that this composition might not be the best choice for applications where minimal friction is essential.

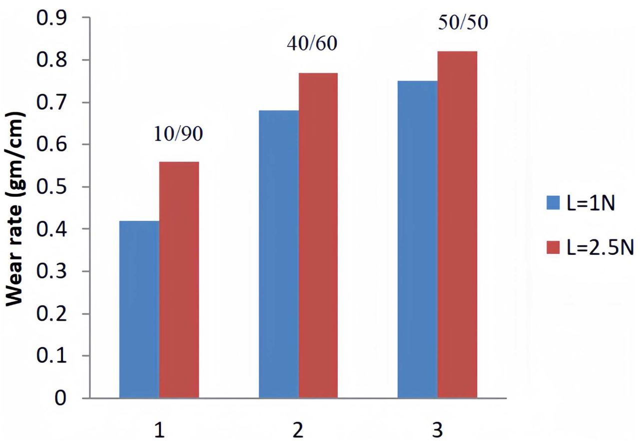
The 50/50 ratio may cause excessive friction and early wear in systems where smooth motion, energy efficiency, or decreased wear are crucial, like sliding contacts or low-resistance machinery. Therefore, this mix may not be the ideal option for applications that require little friction for optimal performance, even though it is well suited for high-friction settings. Therefore, when choosing the right mixture, careful consideration of the intended use and desired frictional qualities is required [19].

4.2. Wear rate

Figure 2 shows a detailed comparison of the wear rate for a polymeric material composed of a blend of UP and NR at various ratios—90/10, 60/40, and 50/50—under variable applied loads of 1N and 2.5N. The wear rate is measured in grams per centimeter (gm/cm), which gives a clear picture of how the material's composition influences its wear resistance under various loading circumstances. The results are graphically depicted by two distinct lines: the blue line corresponds to the wear rate under a 1N load, while the red line reflects the wear rate under a 2.5N load. The statistics show the link between material composition and wear characteristics as affected by applied load. For all three material compositions, the wear rate normally rises as the load increases from 1N to 2.5N. This is to be expected since larger loads usually lead to increased friction and more severe wear. A comprehensive comprehension of the material's performance under various stress circumstances is made possible by the blue and red lines, which provide a visual comparison of how the wear rate changes with load. The wear rate variance across the three ratios—90/10, 60/40, and 50/50—shows that the ratio of UP to NR has a major impact on the material's wear resistance and durability. Because rubber can absorb energy and deform under stress, it generally offers superior wear resistance to polyester resin, which tends to be more rigid and may wear more quickly under higher pressures. The suitability of each composition for certain applications where wear resistance under variable loads is a crucial aspect can be assessed with the aid of this graphical representation of wear rates.

Scientific Discussion:

Figure 2
Wear rate of all samples



1) Effect of load on wear rate:

The graph shows a clear trend that as the applied load increases from 1N to 2.5N, the wear rate also increases for all blends. This is a typical behavior in tribology, where higher loads tend to increase the contact pressure between the surfaces, leading to higher friction and, consequently, an increased rate of material loss (wear). This relationship is consistent with the general understanding that wear rate is load-dependent, and higher forces accelerate material degradation [20, 21].

2) Comparison between different ratios:

a. 90/10 (Resin/Rubber): The wear rate is the lowest under both loads (1N and 2.5N). This suggests that the material with a higher proportion of UP and a lower proportion of NR performs better in terms of resistance to wear. The polyester resin likely provides a smoother surface with lower resistance to wear under the given loads.
b. 60/40 (Resin/Rubber): This composition shows a moderate wear rate. As the rubber content increases, the material's ability to resist wear decreases, likely due to the increased friction and reduced hardness compared to the 90/10 composition.
c. 50/50 (Resin/Rubber): This composition exhibits the highest wear rate for both applied loads. The 50% rubber content increases the material's flexibility, which may result in higher deformation under load, leading to greater wear. Additionally, higher rubber content typically contributes to increased friction, which accelerates material degradation [17].

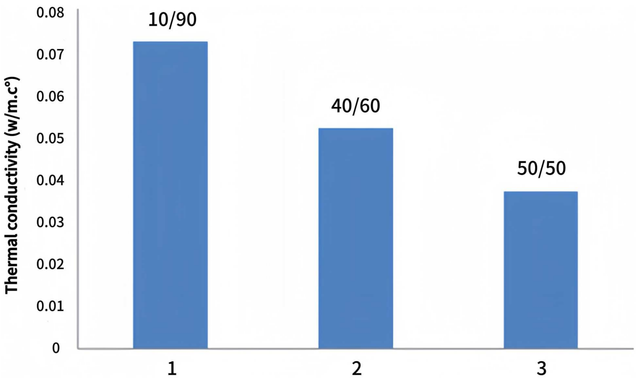
Based on these comparisons, the results presented in the graph align well with a study by Daway, which investigated a blend of UP and NR at varying NR contents of 0%, 5%, 10%, and 15%. The study by Daway demonstrated that increasing the proportion of NR in the blend leads to an increase in the wear rate. This result is in line with recent studies, which showed that the wear rate tends to increase as the blend's NR content rises. Because natural rubber can cause more material deformation under stress even while it has advantageous qualities like flexibility and impact resistance, the higher rubber component probably adds to the material's increased propensity to experience wear. Because of improved surface contacts and greater frictional resistance, which are directly linked to the wear process, the material becomes more prone to wear as the rubber content rises.

The idea that the wear behavior of polymeric blends is significantly influenced by the presence of NR is further supported by these similar results. The conclusion that the material composition, particularly the proportion of UP to NR, has a significant impact on wear rate is reinforced by the comparison with Daway's findings [22].

4.3. Thermal conductivity

Figure 3 shows the thermal conductivity of a polymeric material composed of UP and NR in different ratios (90/10, 60/40, and 50/50). The highest thermal conductivity is observed in the 90/10 composition, indicating that the higher resin content allows for better heat transfer. As the rubber content increases, particularly in the 60/40 and 50/50 ratios, the thermal conductivity decreases due to the insulating properties of NR [23]. This suggests that the balance between resin and rubber affects the material's ability to conduct heat. Materials with higher resin content, such as the 90/10 composition, are suitable for heat dissipation applications, while higher rubber content, like in the 50/50 composition, is ideal for insulation purposes [24].

Figure 3
Thermal conductivity of all samples



4.4. Scanning electron microscope (SEM)

The morphology of the sample was analyzed utilizing a scanning electron microscope (SEM) with code (90129000) manufactured by FEI Company, United States.The SEM micrograph in Figure 4 illustrates the surface morphology of a polymer blend composed of 90 wt% UP and 10 wt% NR, examined at a magnification of 4000× and an accelerating voltage of 2.00 kV. The image reveals a heterogeneous morphology, indicating clear phase separation between the polyester matrix and the dispersed rubber phase. The smooth and continuous regions correspond to the UP matrix, whereas the darker, more irregular domains are attributed to the dispersed NR phase. This distinct two-phase structure reflects the inherently poor compatibility between the polar thermosetting UP and the non-polar elastomeric NR.

Several microvoids and interfacial gaps are visible, suggesting weak interfacial adhesion and limited stress transfer between the two phases. Such morphology is typical for uncompatibilized polymer blends and can result in reduced tensile strength but improved toughness or impact resistance. The elongated surface striations and flow patterns may arise from differential shrinkage during curing or from residual stresses generated during processing.

Figure 5 shows the SEM micrograph of the 60/40 UP/NR blend that reveals a more homogeneous surface morphology compared to the 90/10 composition. The image shows fewer distinct phase boundaries, suggesting partial compatibility between the polyester and rubber phases at higher NR content. The smoother surface and reduced void formation indicate improved interfacial adhesion and better dispersion of the rubber phase within the polymer matrix.

Figure 6 shows the SEM micrograph of the 50/50 UP/NR blend. A highly irregular and rough surface, indicating significant interaction and mixing between the polyester and rubber phases. The morphology appears more homogeneous compared to lower

Figure 4
SEM micrograph of the 90/10 UP/NR

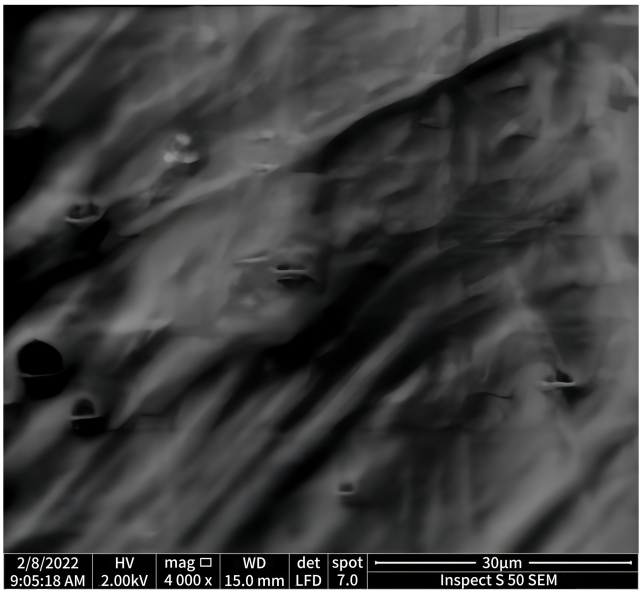


Figure 5
SEM micrograph of the 60/40 UP/NR

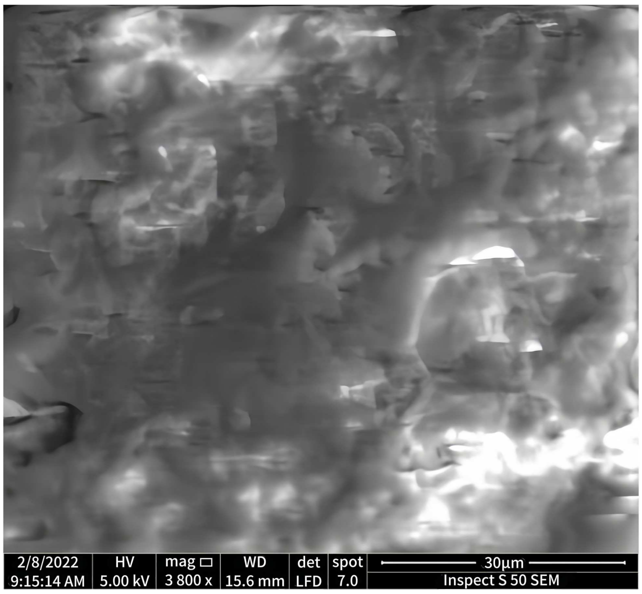
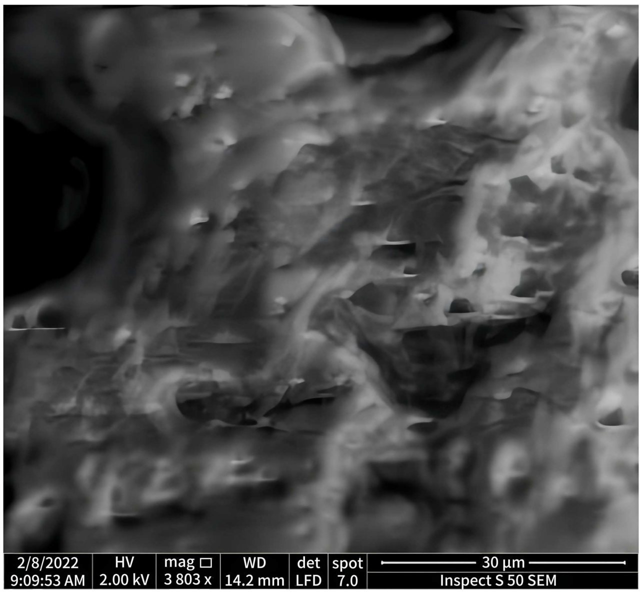


Figure 6
SEM micrograph of the 50/50 UP/NR



NR ratios, with reduced evidence of distinct phase separation. This suggests improved interfacial contact and dispersion of the two components.

However, some voids and microcracks are still visible, reflecting incomplete compatibility at the molecular level. The increased NR content contributes to a more ductile and flexible morphology, as evidenced by the deformed and continuous surface structure. Overall, the image suggests that the 50/50 blend achieves better phase integration, enhancing toughness and flexibility while reducing brittleness relative to the neat polyester resin.

5. Conclusion

The blending of UP with NR significantly affects the physical and tribological properties of the resulting composites. The variation in composition allows for tailoring material performance to specific engineering applications. Increasing the NR content led to a noticeable rise in both the coefficient of friction and wear rate, particularly at the 50/50 composition. This trend is attributed to the elastomeric nature of NR, which increases surface interaction and deformation under load. Conversely, thermal conductivity decreased with increasing NR proportion due to the inherently insulating characteristics of the rubber phase. The 90/10 UP/NR blend exhibited the highest thermal conductivity, making it more suitable for applications requiring efficient heat dissipation. SEM micrographs revealed a gradual transition from a distinct two-phase structure at low NR content (90/10) to a more homogeneous and ductile morphology at higher NR levels (60/40 and 50/50). This indicates partial improvement in phase compatibility and dispersion as rubber content increases. The 50/50 blend showed the most integrated and flexible morphology, suggesting enhanced toughness and energy absorption but reduced stiffness and wear resistance. Such a balance may be beneficial in impact-absorbing or vibration-damping applications. These findings highlight the potential applicability of UP/NR blends in next-generation wearable technologies where customizable material behavior is essential.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

Author Contribution Statement

Rafah Alwan Nassif: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Raghad Hamid Hilal:** Software, Validation, Investigation, Resources, Data curation, Supervision, Project administration.

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