

Original Article

Exploring the Tribological, Physiological, and Morphological Properties of Peanut Shell Reinforced Epoxy Bio-Composites

Rameshkumar H. Bhoi¹, Sumit Das Lala^{2*}, Payel Deb²

¹Faculty of Engineering and Technology, Parul University, Waghodia, Vadodara, Gujarat, India.

²Department of Mechanical Engineering, Faculty of Engineering and Technology, Parul University, Waghodia, Vadodara, Gujarat, India.

*Corresponding Author : sumit.daslala270126@paruluniversity.ac.in

Received: 04 August 2025

Revised: 05 September 2025

Accepted: 06 October 2025

Published: 31 October 2025

Abstract - Wear, friction, and lubrication are key components of surface interactions between moving parts. The study of these interactions is known as tribology. It plays a major role in reducing energy loss caused by friction in mechanical systems. A significant portion of energy is wasted due to friction at sliding interfaces, making it essential to develop innovative strategies to minimize both wear and friction in tribological systems. Advancements in this field are critical in fostering a more sustainable and eco-friendly future. This article presents extensive research on the tribological efficacy of peanut shell powder reinforced epoxy bio-composite. The composite samples were characterized using wear properties in dry conditions and surface roughness for different ratios of epoxy resin and peanut shell powder, such as 5% wt., 10% wt., 15% wt., and 20% wt. This developed composite material highlights its potential for enhancing efficiency and sustainability in various applications.

Keywords - Tribology, Peanut shell, Bio-composites, Natural filler, Epoxy resin.

1. Introduction

Polymer tribology is a critical determinant of the wear and friction characteristics of polymer materials and composites, having been extensively studied for over 30 years. Polymer tribology is mainly determined by friction-adhesion and deformation mechanisms [1, 2]. Further insight into tribological performance requires considering suitable material properties and operating conditions, including high temperatures, high pressures, and humidity. To deal with the increasing scarcity of metals, scientists are looking for alternatives from waste products. Bio-composites produced from natural byproducts and wastes like jute, rice husk, and oil palm shell are gaining importance in replacing conventional synthetic fibers. They are cheap, eco-friendly, and recyclable too. Unlike traditional synthetic composites, they are also non-toxic, renewable, and biodegradable [3-6]. Most of the reasons to use bio-composites are pegged to environmental hazards posed by synthetic fibers, issues in recycling, and their toxic byproducts. Hamid Essabir and his team [7] investigated the synthesis of a bio-composite with polypropylene as the matrix and agricultural natural fibres being the reinforcement. Kraton FG-1901X served as the coupling agent, comprising a styrene-ethylene-butadiene-styrene triblock copolymer modified with maleic anhydride. The average size of the ANS particles was 50 μm , yielding a μt of 1.29 g/ densitycm^3 . The composite was prepared by melt blending. The mechanical and thermal characteristics of the

composite specimens have been evaluated, revealing that ANS functions as a nucleating agent, consequently improving the crystallinity of a PP matrix at low concentrations (5-10 wt.%). Similarly, M. O. Jawaid et al. [8] discussed and compared the thermal as well as mechanical features of PP mixtures containing AS particles, both chemically treated and untreated, and with and without compatibilizer: PP-g-MA. AS particles were compounded into the polymer matrix within the extruder, with independent zones having a side feeder, used for heating. AS composites exhibited superior mechanical characteristics compared to the untreated counterparts, and absorbed more water than the untreated AS composites. Diene Ndiaye et al. [9] tried to improve the mechanical features of Wood Polymeric Composites (WPCs) by increasing the quantity of wood flour with coupling agents. Wood flour was dried and stockpiled to prevent absorption, and test samples were injection-molded. After testing, it was found that wood flour reduced the impact strength, tensile strength, and strain in the mixtures. The physical presence of wood in the composite further weakened the bonding between the components, meaning higher stress concentrations and shrinkage or swelling due to moisture content. S.M. Sapuan et al. [10] conducted an analysis to determine how coconut shell filler particles, along with epoxy pitch, impact the ductile as well as flexural characteristics of the mixtures. In a vessel, the epoxy and hardener were blended. The mixture was given to cure at



room temperature for 24 hours before being put into a mould. Upon curing, the composite was removed from the mould and subjected to a broiler for 12 hours at 40 degrees Celsius to complete the procedure. Their findings indicated that the filler in epoxy coconut combinations greatly influenced both ductile and flexural properties. With the increasing filler content, the composites' ductility and flexural strength increased. It is reported that the filler composites were found to have a relatively nonlinear response before significant failures in flexural tests. The materials showed improved strength when they contained a higher filler content, but resulted in reduced strains under ductile and flexural stress. Panyakaew S. et al [11] studied the possibility of using agricultural waste products for thermal insulation purposes and, at the same time, reduced consumption of resources as well as decreased energy consumption for cooling purposes as a means of countering the heat loss.. These resources possess low thermal conductivity and low embodied energy, though issues with combustibility and the potential for insect infestation and mold growth over long periods of time require further analysis.

S.O. Adeosun et al. [12] researched the physicochemical, alongwith mechanical features of unsaturated polyester reinforced with Sugarcane Bagasse (SB), palm nut shell, and pineapple waste. The research reported that at 10 and 20 vol% SB, an interfacial bond is strong enough to result in significant improvements of the flexural and tensile properties to be measured at 48, 38, and 218, 23 MPa, respectively. Increasing filler content resulted in improvement in the composite's impact strength, which is a favourable sign that the unsaturated polyester reinforced with superior sugarcane bagasse could work well. Khalil Ahmed et al [13] also stated that the tensile elongation, tear strength, hardness, oil resistance, and modulus of some suitable mixes surpass those of MW-filled PP/NBR hybrids. They added that thermal withering showed a decrease in elasticity; however, the value of modulus changed with age. H. Essabir et al. [14] concluded that the ductile characteristics of the aggregates enhance when the particle size diminishes. The mixtures based on polypropylene with the introduction of NA particles showed lower thermal stability than the polypropylene matrix upon heating. According to KaimengXua et al [15], the mechanical features of the composites with modified RSS superheated fumes were close to those of composites with unmodified RSS, which implies that the regulation of fumes at the extremely high temperatures might result in overrefining from the perspective of the size of RSS particles. Mounir El Achaby et al [16] mentioned that the thermoplastic HDPE had a density of around 0.959 g/cm³ with the melting temperature between 130 and 140°C. The ANS powder prepared for the present work was obtained from rural areas in the Souss Massa region of south-western Morocco. The obtained ANS is a byproduct following the removal of the almond core, which was extracted using a traditional hand-press process. These ANS residues were milled to very fine particles with an average size of 49 µm prior to use in the composites. The mechanical features of the mixtures

improved significantly as the Young's modulus increased by 58% compared with the neat polymer with the addition of the filler.

Tribological properties are key features that help identify the behaviour of the materials when applied to frictional forces. Natural fillers incorporated into polymer composites have shown outstanding tribological properties compared to their virgin form. Natural fiber polymer composites are increasingly preferred due to their ability to replace conventional materials while addressing fundamental environmental challenges. They offer a sustainable alternative to inorganic fillers and glass or carbon fibers. Emad suggests that fiber treatments are critical in enhancing the tribological characteristics of polymeric composites, which results in improved interfacial adhesion between fibres and the substrate. Such a statement implies that interfacial surface interactions are a main contributor to tribological performance. In addition, the orientation of fibers is another factor that has an effect on wear and friction behaviour; optimal tribological properties are achieved for perpendicular orientation of fibers to the sliding direction. The composition of natural fibres and matrix, the volume proportion of fibres, and the applied stress significantly influence friction and wear performance. Increased Load, in general, produces higher wear rates. The thermal analysis by E. Garcia et al. [17] showed that the addition of bio-fillers into polymers resulted in lower decomposition temperatures. Combined, HDPE and nutshells (PS) were used to make composite materials through extrusion and injection moulding. The amount of fiber did not significantly affect the tribological behaviour of HDPE, a significant advantage as the amount of HDPE used in the samples was reduced without negatively affecting its tribological properties. Raman spectra were not affected during tribological testing, which is a strong indication of high chemical stability at the surface. These results are important for polymer processing, as this research suggests the possible elimination of a compatibilizer without loss of key material properties, thus realizing savings.

Olga Musiukiewicz et al. [19] found that short-term water immersion at low temperature for WPCs changed their hardness characteristics and increased the friction coefficient. All these phenomena can be considered to be caused by the influence of moisture absorbed during immersion, which affects the interaction between filler and matrix, increasing the coefficient of friction and reducing the hardness. One of the key drawbacks of the conventional fillers and their hybrids is their high-water absorption rate [20, 21]. Water content in a material decreases its mechanical properties [22] and causes specimen swelling [23]. Naresh Kumar et al. [24] reported that hemp fiber content was reduced by 5 wt.% improved wear resistance, colour stability, and friction and reliability performance with minimum contact and variance coefficient variation. WANG Zhen-yu et al. [25] indicated that augmenting the banana fiber percentage resulted in decreasing physico-mechanical properties like thickness, debris content, and

hardness, but porosity, compressibility, and water absorption showed a positive trend. In erosion-resistant composites with less than 10% banana fiber, friction performance improved with only 0.522 ± 0.004 , and modifications were reduced at 0.221 ± 0.034 . The wear of the mixtures increased due to higher banana fiber composition. The least wear was recorded in composites containing less than 10% banana fiber, at a range of 1.32 to 1.41 g. Preliminary results showed that a lower concentration of banana fiber (10 wt.%) improved the friction as well as wear performance of the mixtures and related better retention of color, along with less variability in friction. Yunhai Ma et al. [26] added cow manure fibers and corn stalk fibers to enhance the friction coefficients of erosion-resistant mixtures. The increases in friction coefficient were more significant with lower fibre content of cow manure fibres at 2 wt.% and 4 wt.%, while the results were reversed with higher fibre content of 6 wt.% and 8 wt.% M. Chegani et al. [27] proved that higher wear load conditions have resulted in a considerable increase of volume wear in the composites, which could be caused by the various wear mechanisms activated under increased wear stress. At lower loading conditions, cutting and scoring wear were dominating, with minimal subsurface damage. However, under high load conditions, wear mechanisms shift to include elements of deformation, adhesion, and friction components, which are third-body friction elements.

Atuanya et al. [28] reported that in the absence of compatibilizers or coupling agents, the tensile strength of HDPE composites remained comparable to pure neat HDPE. Specifically, HDPE composites showed a 2.78% decrease in tensile stress and a 54.97% improvement in elastic modulus, especially for composites with 10% nut shell content, accompanied by results similar to those of pure HDPE. The above studies conclude that natural fillers can be suitably used to develop polymer bio-composites with enhanced properties compared to neat polymer. It is also observed from the literature that wear properties improve with the incorporation of natural filler in the polymer bio-composites. Moreover, limited work has been carried out on peanut shell reinforced polymer composites in the field of tribology. Hence, the present work focuses on developing peanut shell reinforced epoxy bio-composite at different weight percentages and studying their tribological and morphological behaviour. The designed composite may supplant conventional materials across several sectors.

2. Materials and Methods

2.1. Sample Preparation

The natural filler, peanut shell, was used in the present study. The shells contain hemicellulose, cellulose, and lignin as inherent constituents. Furthermore, the LapoxPowergrip high-strength epoxy resin and hardener are used to bond the peanut shell powder and develop the composite material. This material offered excellent mechanical strength, electrical insulation, resistance to water and heat, and non-corrosiveness. The weight ratio recommended for the resin and hardener was 1:10. The density of the epoxy resin system was 1.28 g/cm^3 . The shells

were first soaked in a 10% NaOH solution, kept in a hot air oven for 24 hr, and then washed with acetic acid and water to remove the adhered Na. Thereafter, the shells are dried using a hot air oven to eliminate excess moisture and grinded into the form of fine powder.

2.2. Composite Development

The composite samples were prepared using the casting technique. The epoxy resin was first heated at 100°C in a hot plate magnetic stirrer with continuous stirring at 500 rpm to reduce the viscosity. Thereafter, the powdered treated peanut shells are introduced into the epoxy resin and stirred for 1 hour to have uniform mixing. The temperature was then reduced, and the hardener was added to the composite slurry for hardening. The slurry was then poured into ASTM standard moulds to conduct the wear test of the composites. The composite specimens were then cured using a hot air oven at a temperature of around 100°C . Figure 1 shows the overall process for composite development.



Fig. 1 Overall process of composite development

2.3. Characterization of Composite Specimens

The developed composite samples were tested for wear resistance and surface roughness properties toward the effect of the process to check whether there is any variation in bio-composites' behaviour. Those analyses reflect the influence of natural fillers with the epoxy matrix on the global performance of bio-composites in durability and surface quality aspects, consequently affecting optimization of material properties for specific applications. This is done by a Tribometer (TR-20LE-PHM 200). It is a sophisticated instrument designed specifically to measure the key tribological properties of friction, wear, and lubrication between two contacting surfaces. It tests the components under controlled environment conditions, simulating actual friction and wear conditions so that material behaviour under different loads and sliding conditions can be studied with precision.

Surface roughness plays a significant role in determining the material's frictional behaviour, wear resistance, and overall durability under operational conditions. Surface roughness testing provides valuable data to optimize the performance and lifespan of bio-composites in practical applications. The SurfTest SJ-210 is a user-friendly surface roughness measurement instrument designed as a handheld tool for the measurement of surface roughness of the developed composite. A water absorption test was performed on the composite samples for a period of 28 days. The samples were dipped in regular water for 7, 14,

21, and 28 days, and the corresponding water absorption by the composite specimens was investigated. The morphology of the samples at 5% and 20% wt. of peanut shell composite was examined using Scanning Electron Microscopy analysis. Hitachi SU3800 SEM was used to investigate the morphology of the developed composite.

3. Result & Discussion

3.1. Analysis of Wear Testing

The wear test analysis was conducted for the developed composites at 4 different weight percentages. Two different variations of loads of 5N and 10N were considered for the analysis. Table 1 represents data on load measurements (5N and 10N) across four different weight percentages (5%, 10%, 15%, and 20%). Each of the readings was taken thrice to ascertain the accuracy of the test results. The data provides insight into the effect of different loads and weight percentages on a given material or system.

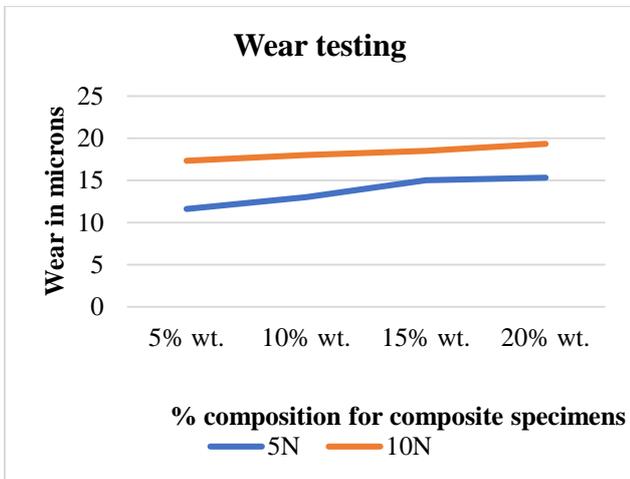


Fig. 2 Wear test results for the composite specimens at different weight percentages of filler

It is evident from Figure 2 that for a 5N Load and 5% wt. of composite specimen, the wear values are 11, 12, and 12. These values show that, under 5N Load, the weight percentage of 5% results is rather stable measurements of 11 to 12 units. At 10% wt., the numbers actually creep up to 13, 13, and 13; therefore, with a 5N load, there is a slight increase in wear, which might be due to the added weight. At 15% wt., the values increase even more to 15, 15, and 15. The pattern continued here: as the weight percent increased, the material or system responded with that higher value, at 20% wt. The values remain steady at 15, 15, and 16. This reveals that despite some slight increases, the system tends

To stabilize at around 15, with the slight variation seen at 20% wt. For 10N Load, at 5% wt. of composite specimens, the values are 18, 17, and 17. The values show that the system will respond by giving a little higher value than the case of 5N Load due to the applied force. The values tend to be stable with little variation at this weight percentage. At 10% wt. Values remain at 18, 18, and 18. That is to say, at 10 %wt, and a Load of 10N, the system does not exhibit any drastic variation in the measurement of

wear with a constant response. At 15% wt., the values are also constant at 18, 18, and 18. It has been seen that even at high weight percentages, the system retains stability under the Load of 10N, at 20% wt. The values increase slightly to 20, 19, and 19, showing that, at the increase in weight percentage up to 20%, the system starts responding with a higher measurement.

Hence, there appears to be a relationship between increased weight and increased system response under the 10N Load. It noted that as the wt. The percentage increases from 5% to 20%, and the response of the system kept increasing steadily in arbitrary units. For each wt.%, the values were consistent between the three runs, but variations were noticeable in the higher wt.% of composites.

It shows a weak increase at 20% wt. But stabilizes between 15 and 16 units. The system shows the same trend for the higher Load of 10N; the measured values increase with a higher weight percentage. At lower weight percentages (5% and 10%), the values are quite stable, but at 20% wt., it show an increase in response, though not very significant. The values remained the same across trials for this higher Load.

An improvement in the coefficient of friction is observed for the developed composites. For 5% wt. Composing the coefficient of friction was observed to be 0.23, 10% wt. is 0.28, 15% wt. is 0.31, and 20% wt. is 0.42 for a 5N Load applied. However, for 10N Load, the values were 0.25, 0.36, 0.41, and 0.52 for 5, 10, 15, and 20% wt. Composite specimens. These results are comparatively better than the work conducted by Tasgin et al. [29].

Table 1. Detailed analysis of surface roughness for 5% and 10% wt. composite (all values are in micron)

| Value | 5 % wt | | | 10 % wt | | |
|-------|--------|-------|-------|---------|-------|-------|
| Ra | 0.936 | 0.936 | 0.937 | 0.941 | 0.942 | 0.941 |
| Rq | 1.512 | 1.512 | 1.512 | 1.515 | 1.515 | 1.513 |
| Rz | 8.009 | 8.007 | 8.009 | 8.009 | 8.011 | 8.011 |

Table 2. Detailed analysis of surface roughness for 15% and 20% wt. composite (all values are in micron)

| Value | 15 % wt | | | 20 % wt | | |
|-------|---------|-------|-------|---------|-------|-------|
| Ra | 0.942 | 0.943 | 0.943 | 0.947 | 0.947 | 0.947 |
| Rq | 1.517 | 1.515 | 1.518 | 1.519 | 1.518 | 1.519 |
| Rz | 8.012 | 8.016 | 8.015 | 8.016 | 8.018 | 8.018 |

3.2. Analysis of Surface Roughness

A roughness test was conducted for all 4 different weight percentages of the composite specimens. Table 2 provides a detailed analysis of surface roughness characteristics (Ra, Rq, and Rz) at different weight percentages (5%, 10%, 15%, and 20%). Each of the values was calculated three times to maintain the accuracy of the test results. These values give insight into the surface texture and its variation with increasing weight percentage.

3.2.1. Ra (Arithmetic Average Roughness)

Ra is the arithmetic mean of surface roughness profile deviations over a specified length. The value shows how smooth or rough a surface will be at different weight percentages. At 5% wt. An average value of Ra is observed as 0.936, 0.936, and 0.937. This indicates that at 5% wt., the surface roughness remains stable with the least amount of variation in the values, at 10% wt. There is an increase in the average value of Ra, i.e., 0.941, 0.942, and 0.941, but values are fairly consistent across the readings. At 15% wt. of composite samples, values are 0.942, 0.943, and 0.943, which are relatively higher when compared with 10% wt. Composite samples. In other words, it would be marginally rougher. However, the Ra values are very stable across 20% wt. Composite samples. Values continue to grow significantly to 0.947 for all columns of Ra. This shows a clear but minimal rise in surface roughness as the weight percentage increases.

3.2.2. Rq (Root mean Square Roughness)

Rq is the root mean square of the surface height deviations, which is more sensitive to large deviations than Ra, at 5% wt. The values are constant at 1.512, indicating a steady surface texture for all measurements, at 10% wt. The values increase moderately by 1.515, 1.515, and 1.513. Even though the values are quite close to those obtained for 5% wt., this increase indicates that the surfaces are slightly rougher at 15% wt. Rq values turn out to be 1.517, 1.515, and 1.518. The trend still continues with a slightly increasing roughness due to the rise in weight percentage, but it is not very significant at 20% wt. The values seem to have increased further to 1.519, 1.518, and 1.519. Generally, the increase in Rq follows the weight percent increment, though changes are small; this indicates how surface roughness is only slightly rougher as the weight percentage increases.

3.2.3. Rz (Average Maximum Height of the Profile)

This gives weight to extreme deviations in surface texture and measures the average maximum peak-to-valley height at 5% wt. The values are 8.009, 8.007, and 8.009, which are expected to be highly consistent with a negligibly minor variation in surface profile, at 10% wt. Values obtained are 8.009, 8.011, and 8.012, showing a small increase compared to 5% wt, but variation remains minor, and the surface profile is mostly unchanged at 15% wt.

Values for Rz show slight increases and reach values of 8.012, 8.016, and 8.016. The slight upshift indicates the beginning of more pronounced peaks and valleys on the surface with an increase in the weight percentage of filler, at 20% wt. Values increase to 8.016, 8.018, and 8.018, showing a continued stable increase in surface texture deviations. However, consistency across readings shows that the profile is stable even as the weight percentage increases.

3.3. Scanning Electron Microscopy (SEM)

The surface morphology of the composite specimens at 5% wt and 10% wt. of the peanut shell filler is investigated

using SEM micrographs. The composite specimen at 5% wt of filler shows a smooth surface with almost no agglomeration. This shows that the composite at 5% wt. The filler had uniform dispersion of the peanut shell filler in the epoxy matrix. However, for 20% wt. filler composite, the surface morphology is rough, and agglomeration of particles is observed in different portions.

There is also the formation of cracks and pores at various parts of the developed composite surface. This indicates that the particles are not properly dispersed in the matrix. This may be due to the lower amount of resin, which is not enough to wet the filler particles properly [9, 30]. Figure 3 shows the SEM images of the 5% wt and 20% composite samples.

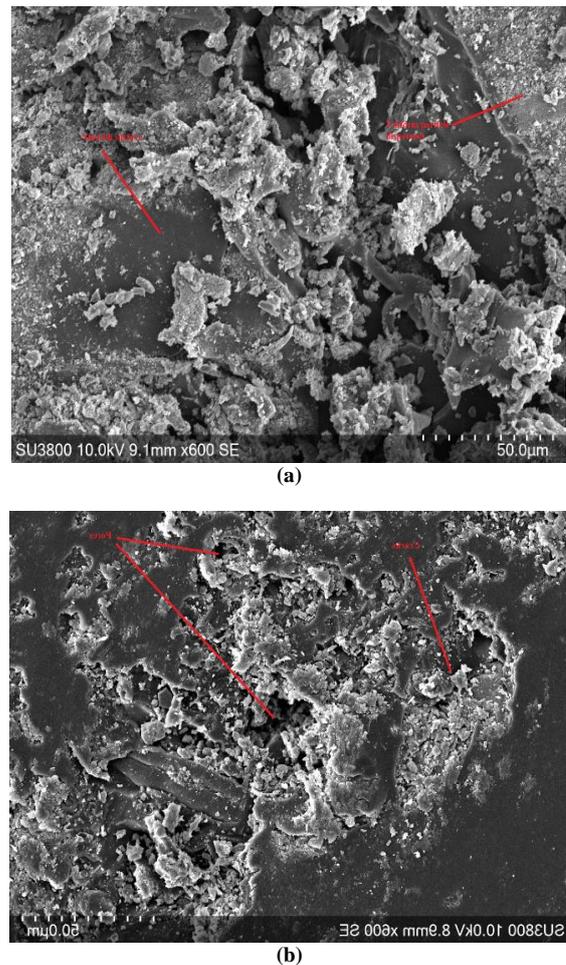


Fig. 3 SEM images of the (a) 5% wt. and (b) 20%wt. composite samples

3.4. Water Absorption Test

A water absorption test pertaining to both regular water and saline water was used in the present study to investigate the absorbance of liquid in the developed composite specimens. The test results are illustrated in Figure 4. It is observed that water absorption increases with increasing filler content for the composite specimens. This is due to the moisture-absorbing property of natural filler [7, 31]. The lowest water absorption of 5.5% is observed for 5% wt. of filler composite specimen.

The highest water absorption by the neat epoxy was 3.3%. It is further interesting to know that after 28 days, there was a significant decrease in water absorption by all the composite specimens. Water absorption of only 0.1% was observed for 5, 10, and 15% wt. of filler. For 20% wt. of filler, it was found to be 0.2%. This may be due to the saturation of the composite specimens, which further restricts absorption of liquid by the composite [32, 33]. However, for neat epoxy, the water absorption after 28 days of immersion was 0.9%.

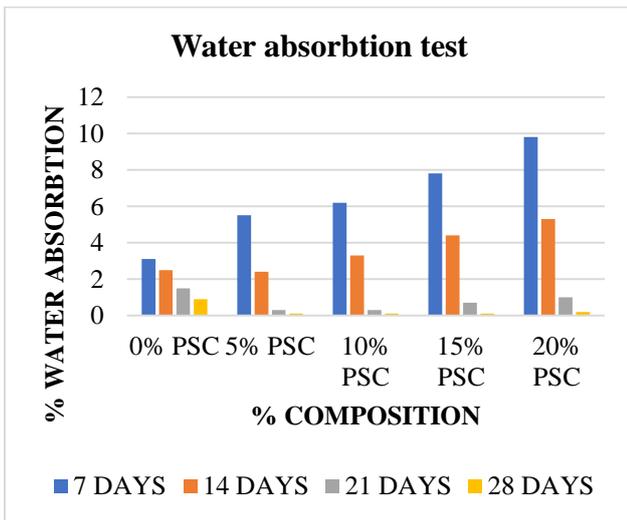


Fig. 4 Water absorption test for the composite specimens

4. Conclusion

The present study aims towards the development of epoxy reinforced peanut shell composite at 4 different weight percentages. Composite specimens are prepared using the stir casting process. The surface roughness parameters show an evident trend of slightly heightened roughness along the 5% to 20% weight percentage range. However, changes are relatively small, and even at higher weight percent, surface texture is maintained consistently with minor increases in roughness. It can be further concluded that Ra (average roughness) increases with some trivial value percent weight from 5% up to 20%. This indicates that the surface is becoming marginally rougher

but remains pretty smooth. Rq (RMS roughness) exhibits similar behaviour but provides slightly larger deviations than the mean value from the Ra. With this, the increase in Rq shows that there will be a larger deviation in surface texture as the weight percentage increases. Rz or peak-to-valley height increases a little as the weight percentage increases; hence, the surface profile is becoming uneven with higher peaks and deeper valleys as the weight percentage increases. Consistency of data in readings also suggests the process or material that is analysed sustains a controlled surface texture regardless of all the weight percentage changes. The data pertaining to the wear test indicates that the response of the system is increased irrespective of whether the applied loads are 5N or 10N due to an increase in the percentage weight from 5% to 20%. In the case of 5N Load, the system stabilizes around 15 to 16 units at higher percentages of weight. In the case of a 10N load, the system is steady at around 18 units, up to a weightage of 15% wt. But a slight rise at 20% wt.

Hence, measurements are quite reliable, and a controlled system response to various load conditions and percentage weight is obtained. SEM micrographs reveal that composite specimens developed at a lower filler percentage of 5% wt. Shows comparatively better surface morphology and allows uniform dispersion of filler into the matrix. Nevertheless, with a larger filler content of 20% wt., the dispersion of particles is non-uniform, resulting in cracks and pores in the composite surface. The water absorption test indicates that water absorption escalates with more filler content in the mixture. However, the highest water absorption of 9.8% was observed for 20% wt. Filler composite, which reduces to 0.1% after 28 days of immersion. The developed composite can be suitably used as a resistant substance.

Acknowledgement

The authors hereby acknowledge the Micro Nano R&D centre, Parul University, for SEM analysis. The authors would also like to thank the Materials Engineering laboratory, Department of Mechanical Engineering, PIET, Parul University, for providing the facilities to conduct the experiments.

References

- [1] J. Rout, "The Influence of Fibre Treatment on the Performance of Coir-Polyester Composites," *Composites Science and Technology*, vol. 61, no. 9, pp. 1303-1310, 2001. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [2] A.K. Rana, A. Mandal, and S. Bandyopadhyay, "Short Jute Fiber Reinforced Polypropylene Composites: Effect of Compatibiliser, Impact Modifier and Fiber Loading," *Composites Science and Technology*, vol. 63, no. 6, pp. 801-806, 2003. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [3] S.V. Joshi et al., "Are Natural Fiber Composites Environmentally Superior to Glass Fiber Reinforced Composites?," *Composites Part A: Applied Science and Manufacturing*, vol. 35, no. 3, pp. 371-376, 2004. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [4] Sanjay K. Nayak, Smita Mohanty, and Sushanta K. Samal, "Influence of Short Bamboo / Glass Fiber on the Thermal, Dynamic Mechanical and Rheological Properties of Polypropylene Hybrid Composites," *Materials Science and Engineering: A*, vol. 523, no. 1-2, pp. 32-38, 2009. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [5] V.A. Bely, A.I. Sviridenok, and M.I. Petrokovets, *Friction and Wear in Polymer-Based Materials*, Pergamon, pp. 1-426, 2013. [[Google Scholar](#)] [[Publisher Link](#)]
- [6] I.V. Kragelsky, and V.V. Alisin, *Tribology-Lubrication, Friction and Wear*, Tribology, Willey, pp. 1-948, 2001. [[Google Scholar](#)] [[Publisher Link](#)]

- [7] Hamid Essabir et al., “Biocomposites Based on Argan Nut Shell and a Polymer Matrix: Effect of Filler Content and Coupling Agent,” *Carbohydrate Polymers*, vol. 143, pp. 70-83, 2016. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [8] Fatima Zahra El Mechtali et al., “Mechanical and Thermal Properties of Polypropylene Reinforced with Almond Shells Particles: Impact of Chemical Treatments,” *Journal of Bionic Engineering*, vol. 12, pp. 483-494, 2015. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [9] Diène Ndiaye, Mamadou Gueye, and Bouya Diop, “Characterization, Physical and Mechanical Properties of Polypropylene/Wood-Flour Composites,” *Arabian Journal for Science and Engineering*, vol. 38, pp. 59-68, 2013. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [10] S.M. Sapuan, M. Harimiand, and M.A. Maleque, “Mechanical Properties of Epoxy/Coconut Shell Filler Particle Composites,” *Arabian Journal for Science and Engineering*, vol. 28, no. 2, pp. 171-182, 2003. [[Google Scholar](#)]
- [11] Satta Panyakaew, and Steve Fotios, “321: Agricultural Waste Materials as Thermal Insulation for Dwellings in Thailand: Preliminary Results,” *Proceedings of the 25th Conference on Passive and Low Energy Architecture*, Dublin, Ireland, pp. 22-24, 2008. [[Google Scholar](#)]
- [12] S.O. Adeosun et al., “Influence of Organic Fillers on Physicochemical and Mechanical Properties of Unsaturated Polyester Composites,” *Arabian Journal for Science and Engineering*, vol. 41, pp. 4153-4159, 2016. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [13] Khalil Ahmed, “Eco-Thermoplastic Elastomer Blends Developed by Compatibilizing Chlorinated Polyethylene into Industrial-Waste-Filled Polypropylene/Acrylonitrile Butadiene Rubber System,” *Arabian Journal for Science and Engineering*, vol. 40, pp. 2929-2936, 2015. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [14] H. Essabir et al., “Mechanical and Thermal Properties of Bio-Composites Based on Polypropylene Reinforced with Nut-Shells of Argan Particles,” *Materials & Design*, vol. 49, pp. 442-448, 2013. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [15] Kaimeng Xu et al., “Effects of Environmental-Friendly Modified Rubber Seed Shell on the Comprehensive Properties of High Density Polyethylene/Rubber Seed Shell Composites,” *Industrial Crops and Products*, vol. 91, pp. 132-141, 2016. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [16] Hamid Essabir et al., “Morphological, Structural, Thermal and Tensile Properties of High Density Polyethylene Composites Reinforced with Treated Argan Nut Shell Particles,” *Journal of Bionic Engineering*, vol. 12, pp. 129-141, 2015. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [17] E. García et al., “Mechanical, Dynamic and Tribological Characterization of HDPE / Peanut Shell Composites,” *Polymer Testing*, vol. 98, pp. 1-13, 2021. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [18] Emad Omrani et al., “State of the Art on Tribological Behavior of Polymer Matrix Composites Reinforced with Natural Fibers in the Green Materials World,” *Engineering Science and Technology, an International Journal*, vol. 19, no. 2, pp. 717-736, 2016. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [19] Olga Mysiukiewicz, and Tomasz Sterzyński, “Influence of Water on Tribological Properties of Wood-Polymer Composites,” *Archives of Mechanical Technology and Materials*, vol. 37, pp. 79-84, 2017. [[Google Scholar](#)] [[Publisher Link](#)]
- [20] Narish Singh, B.F. Yousif, and Dirk Rilling, “Tribological Characteristics of Sustainable Fiber-Reinforced Thermoplastic Composites under Wet Adhesive Wear,” *Tribology Transactions*, vol. 54, no. 5, pp. 736-748, 2011. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [21] L. Sobczak, O. Brüggemann, and R.F. Putz, “Polyolefin Composites with Natural Fibers and Wood-Modification of the Fiber/Filler-Matrix Interaction,” *Journal of Applied Polymer Science*, vol. 127, no. 1, pp. 1-17, 2013. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [22] Kamal B. Adhikary, Shusheng Pang, and Mark P. Staiger, “Dimensional Stability and Mechanical Behaviour of Wood-Plastic Composites Based on Recycled and Virgin High-Density Polyethylene (HDPE),” *Composites Part B: Engineering*, vol. 39, no. 5, pp. 807-815, 2008. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [23] Sławomir Borysiak, “Fundamental Studies on Lignocellulose / Polypropylene Composites: Effects of Wood Treatment on the Transcrystalline Morphology and Mechanical Properties,” *Journal of Applied Polymer Science*, vol. 127, no. 2, pp. 1309-1322, 2013. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [24] Naresh Kumar et al., “Experimental Investigation on the Physical, Mechanical and Tribological Properties of Hemp Fiber-Based Non-Asbestos Organic Brake Friction Composites,” *Materials Research Express*, vol. 6, no. 8, 2019. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [25] Wang Zhen-Yu et al., “Influence of Banana Fiber on Physicomechanical and Tribological Properties of Phenolic Based Friction Composites,” *Materials Research Express*, vol. 6, no. 7, 2019. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [26] Yunhai Ma et al., “Tribological and Physio-Mechanical Characterization of Cow Dung Fibers Reinforced Friction Composites: An Effective Utilization of Cow Dung Waste,” *Tribology International*, vol. 131, pp. 200-211, 2019. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [27] Faissal Chegdani, Satish T.S. Bukkapatnam, and Mohamed El Mansori, “Thermo-Mechanical Effects in Mechanical Polishing of Natural Fiber Composites,” *Procedia Manufacturing*, vol. 26, pp. 294-304, 2018. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [28] C.U. Atuanya et al., “Empirical Models for Estimating the Mechanical and Morphological Properties of Recycled Low Density Polyethylene/snail Shell Bio-Composites,” *Journal of the Association of Arab Universities for Basic and Applied Sciences*, vol. 21, pp. 45-52, 2016. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]

- [29] Yahya Tasgin et al., "Mechanical, Wear and Thermal Properties of Natural Fiber-Reinforced Epoxy Composite: Cotton, Sisal, Coir and Wool Fibers," *Journal of Material Science*, vol. 59, pp. 10844-10857, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [30] C. Girisha et al., "Mechanical Performance of Natural Fiber-Reinforced EpoxyHybrid Composites," *International Journal of Engineering Research and Applications (IJERA)*, vol. 2, no. 5, pp. 615-619, 2012. [[Google Scholar](#)] [[Publisher Link](#)]
- [31] K. Begum, and A.M. Islam, "Natural Fiber as a substitute to Synthetic Fiber in Polymer Composites: A Review," *Research Journal of Engineering Sciences*, vol. 2, no. 3, pp. 46-53, 2013. [[Google Scholar](#)] [[Publisher Link](#)]
- [32] Ojha Shakuntala, Gujjala Raghavendra, and Acharya Samir Kumar, "Effect of Filler Loading on Mechanical and Tribological Properties of Wood Apple Shell Reinforced Epoxy Composite," *Advances in Materials Science and Engineering*, vol. 2014, no. 1, pp. 1-9, 2014. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [33] Hanafi Ismail, M.R. Edyham, and B. Wirjosentono, "Bamboo Fibre Filled Natural Rubber Composites: The Effects of Filler Loading and Bonding Agent," *Polymer Testing*, vol. 21, no. 2, pp. 139-144, 2002. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]