EFFECTS OF HYBRIDIZATION OF PALM KERNEL FIBRE AND SNAIL SHELL FILLER ON SOME END-USE PROPERTIES OF EPOXY-BASED COMPOSITES

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Abstract
This work studied the effects of hybridization of palm kernel shells fibre (PKF) and snail shells filler (SSF) on microstructural, mechanical, and water absorption properties of epoxy-based composites. Microstructure analysis of the composite samples was conducted using a digital optical microscope. Universal testing machine (UTM) was employed to evaluate the mechanical properties (tensile and compressive strengths) of the composite. Shore D hardness Durometer was used to evaluate the composite material's resistance to deformation, while Izod impact tester was deployed to determine the impact strength of the composites. The gravimetric technique was used to measure the water absorption by the composites. Results showed that the microstructures of the epoxy-based composite samples (8 – 10) with hybridized PKF and SSF fillers revealed improper mixing and non uniform distribution of the filler materials, particularly on samples 8 and 10, while sample 9 appear to be uniformly distributed. Further, sample 10 gave highest ultimate tensile strength of 12.721 MPa and impact strength of 0.211 J/mm^2, while sample 9 displayed highest value of Young's modulus of elasticity of 209.469 MPa, compared to the epoxy-based composites with mono fillers of PKF and SSF. The water absorption assessment showed that water absorption increased with increasing temperature.

Keywords: Composite, Hybridization, Impact strength, Palm kernel shell fibre, Snail shell fibre.

1. Introduction

Epoxy is a thermosetting polymer that has gained significant importance in various industries and applications (Sukanto et al., 2021). It is a versatile material known for its excellent mechanical strength and rigidity (Bello et al., 2015), adhesion and bonding (Xu et al., 2024), chemical resistance, easy processability, and long term durability and moisture resistance properties.

Despite the excellent properties of epoxy resin, reports have revealed that cured epoxies without modification can be brittle, exhibit poor impact resistance and toughness, and they are easy to crack due to stress concentration (Zhang et al., 2025; Kamo and Matsumotom 2025). Therefore, to address the observed demerits of epoxy resin, fillers are added to enhance the performance characteristics of epoxies. The fillers could be synthetic or natural. Synthetic fillers, in as much as they impact positively on the performance of composites, do not easily decompose, leading to long-term waste accumulation in landfills and the environment. Also, synthetic fillers agglomerate, causing uneven distribution within the matrix material. However, the use of natural fillers as reinforcements in epoxy composites offers potential benefits in terms of sustainability and reduced environmental impact compared to synthetic fillers.

Examples of natural fillers used for composite prearation include those derived from palm kernel shells and snail shells. Fillers from palm kernel shells are renewable, biodegradable, have lower carbon footprints, and generally comprised mainly of cellulose, hemicellulose and lignin which are known for their mechanical strength enhancement. Thus, the microstructure of palm kernel shell primarily consists of a fibrous husk which is rich in cellulose, hemicellulose, and lignin. On the other hand, snail shells possess a hierarchical microstructure with interesting mechanical properties. The combination of the prismatic and nacreous layers provides strength, toughness, and resilience to the snail shells. The prismatic layer contributes to hardness and stiffness, while the nacreous layer enhances the shells' fracture resistance and energy dissipation capabilities. Thus, snail shells are biodegradable and can contribute to sustainable material practices.

In view of the above, some research studies on the development of palm kernel shells and snail shells fillers-based composites have been conducted. Thus, Achukwu et al. (2015) investigated utilization of palm kernel shells (PKS) as a filler material for epoxy composite fabrication. Epoxy-PKS composites were fabricated by employing filler particle size of 150 μm and different loadings of 5%, 10%, 20%, 30% and 40% using hand mixing technique. The composites were tested for tensile, impact, hardness, morphological and water absorption properties. The obtained results showed good mechanical properties with 5-10% filler loadings attaining maximum values which improved

on alkali treatment. Similarly, Valášek, Habrová, and Müller (2019) studied degradation of composite made of epoxy resin and palm oil kernel shells (PKS) as filler. The filler was of irregular particle size up to 100 μm and the filler concentration in the matrix was 2.5, 5.0 and 10.0 wt.%. Results showed that the presence of organic particles in the matrix did not significantly affect the decrease of mechanical properties due to degradation in laboratory conditions.

In a related study, Kolawole et al. (2020), researched on the influence of calcined snail shell particles on mechanical properties of recycled aluminum alloy for automotive application. Different weight proportions i.e. (0 - 7.5) wt% of calcined snail shell particles at an interval of 1.5 wt% were successfully incorporated into Al-Si alloy matrix melted at 750 °C using stir-casting route. The microstructure, physical and mechanical properties of the resulting composites were examined and presented. Microstructural examination shows fairly uniform dispersion of snail shell particles in the aluminum alloy matrix intermingled with aluminum-silicon dendrites. Mechanical properties such as hardness, impact, compressive and tensile strengths increased with increasing addition of calcined snail shell particulate up to 6 wt% while density and elongation decreases. The total equivalent density reduction of 5.4% in composites compared to unreinforced alloy was obtained at 7.5 wt% snail shell addition. The maximum hardness, impact, compressive and tensile strengths obtained are 118±4 HV, 88 J, 552±20 MPa and 211 ± 4.8 MPa equivalent to 21, 25, 19 and 36 percent increase respectively relative to un-reinforced aluminium-silicon alloy.

Despite the observed good performance of the composites made with mono fillers, reports have shown that the use of more than one fillers in composite preparation (otherwise known as hybridization) overs better performance. Thus, the effect of glass fiber combined with treated banana-hemp fibers was studied by Ramasamy et al. (2017). The alkaline solution was used to treat the fibers with the aim to increase their mechanical strength. The experimental result showed that the glass/banana/hemp fiber composite exhibited the maximum tensile strength than other two combinations. Demir, Yar, Eskizeybek, Avcı (2023), evaluated the influence of simultaneous fiber hybridization and matrix modification on polymer composites' tensile, flexural, and low-velocity impact properties. Hybrid glass/carbon epoxy composites and hybrid glass/carbon/multi-walled carbon nanotube (MWCNT) multiscale polymer composites of stacking sequences $[GCGCGC]_S$, $[CGCGCG]_S$, and $[G_6C_6]$ were manufactured. Depending on the stacking sequence, the flexural strength of the hybrid composites was improved between 10% and 16% concerning carbon fiber composite. With the introduction of MWCNTs, a slight increase in the tensile strength for unsymmetrical hybrid composites by around 5% and decrease by 7% for symmetrical ones were observed.

On the other hand, Oladele et al. (2020) investigated the influence of chemically treated palm kernel shell fiber (PKSF) and particulate cassava peel (PCP) as hybrid reinforcements on some selected mechanical properties and wear behavior of PKSF/PCP hybrid reinforced epoxy composites. From the results, it was discovered that chemically treated PKSF/PCP hybrid reinforced samples performed better than the untreated PKSF/PCP hybrid reinforced counterparts in most of the properties considered. Further, the tensile strength, flexural strength, impact strength, and hardness properties of PKS-PKF-Epoxy hybrid composites were reported by Olaitan et al. (2017). The study concentrated on the effect of PKS content on the composite and their mechanical properties, as indicated at the onset. Generally, the composite with 6% PKS and 4% PKF offered the highest impact strength and therefore fit for the purpose. Furthermore, the composites of palm kernel shell phosphorus alcohol (PKS/Epoxy/PVA) were characterized concerning tensile properties, impact, flexural, hardness strengths, and density (Baffour-Awuah et al., 2021). The results showed an enhancement of hardness and Young's modulus when fiber volume fraction increased.

Considering the above literatures, there is no reported work on the effects of hybridization of palm kernel fibre and snail shell powder on microstructural, mechanical and water absorption properties of epoxy-based composites, to the best of our knowledge. Thus, this study aims to evaluate the effects of hybridization of palm kernel fibre and snail shell powder on microstructural, mechanical and water absorption properties of epoxy-based composites.

2. Materials and Method

2.1 Materials

The matrix used was epoxy resin and its hardener. Palm kernel shells were locally procured from oil palm milling sites in Obosima Ohaji in Imo State. Snail shells were procured from dumpsites close to seafoods section at Worldbank market Owerri. Both palm kernel shells and snail shells were used as sources of natural fillers. Aluminium oxide was used as synthetic filler while aminopropyl trimethoxy silane was used as coupling agent.

2.2 Method

2.2.1 Preparation of the palm kernel and snail shells

Palm kernel shells were pulverized using locally fabricated crushing machine and sieved. The obtained particles were further pulverized using a ball milling machine and then sieved to obtain fine powdered palm kernel shell particles. The resulting palm kernel fibres were mixed with 2 wt.% of aminopropyl trimethoxy silane, oven-dried for 2 hours, retrieved and then stored in a dessicator before use. Similarly, the snail shells were washed, dried and pulverized into fine powder using locally fabricated crushing machine. Subsequently, the pulverized snail shells were oven-dried at 70 °C for 2 hs. Thereafter, they were further pulverized using a ball milling machine and sieved to obtain free-flowing snail shell powder. The resulting snail shell filler was mixed with 2 wt.% of aminopropyl trimethoxy silane, oven-dried for 2 hours, retrieved and then stored in a dessicator prior to use.

2.2.2 Composite fabrication

As shown in Table 1, the composite samples were prepared using epoxy resin and hardner, palm kernel shell fibre (PKF), snail shell filler (SSF), aluminium oxide as synthetic filler and aminopropyl trimethoxy silane as a coupling agent. Based on different formulations as given in Table 1, each of the composite formulations was mixed using a kitchen blender. Consequently, the composite formulations were fabricated by casting method. After curing, the samples were retrieved and stored in a dessicator prior to characterizations.

Table 1: Epoxy-based composites using varying amounts of natural fillers

Sample ID	Epoxy matrix (wt. %)	Synthetic filler Al_2O_3 (wt. %)	Natural filler (wt. %)		Silane coupling agent (%)
			PKF	SSF	
1	100	0	0	0	0
2	80	9	10	0	1
3	60	9	30	0	1
4	40	9	50	0	1
5	80	9	0	10	1
6	60	9	0	30	1
7	40	9	0	50	1
8	80	9	5	5	1
9	60	9	15	15	1
10	40	9	25	25	1

In a nutshell, the composite samples preparation procedures are summarized in Figure 1.

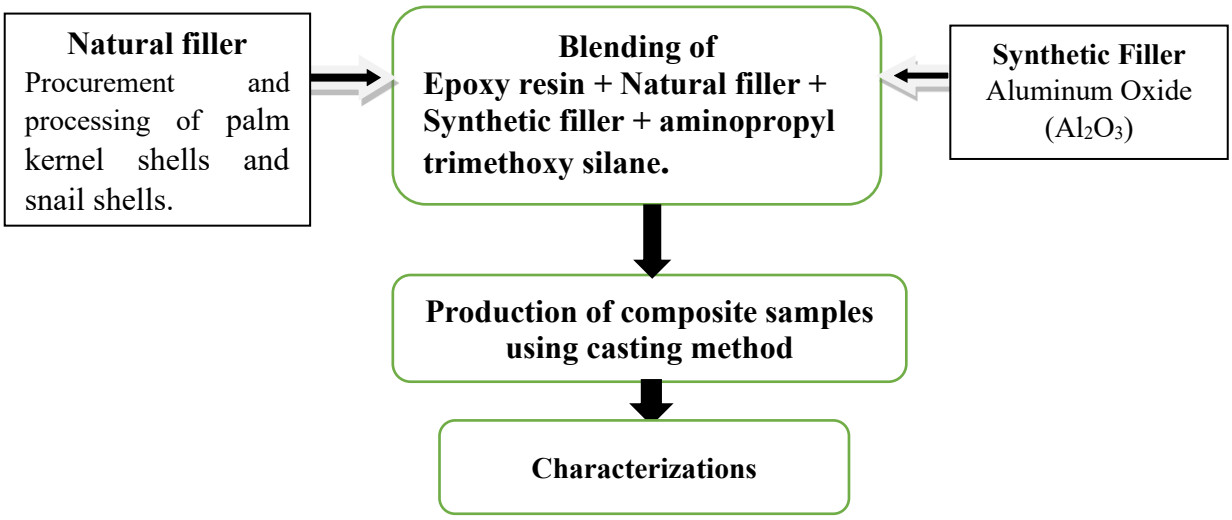

Figure 1: The process flow chart for composite samples preparation and characterization

2.2.3 Characterizations

(a) Microstructure analysis using optical microscope

Microstructure analysis of the composite samples were conducted to provide insights into the material's internal structure, including the spatial dispersion of the constituent materials, size, shape, and composition of the phases and constituents that make up the composite. Thus, a small portion of each of the samples was cut for examination under the microscope as shown in Plate 1. The mounted sample was polished using a series of abrasive papers

and diamond pastes, progressing from coarse to fine grit, to achieve a mirror-like surface finish. This step was crucial as it ensured that the internal structure was observed without interference from surface imperfections. The polished sample was etched using a sodium hydroxide solution to reveal the microstructure. The advanced software in the optical microscope was used to reveal the microstructural features such as size, shape, distribution of constituent materials. and pores observed under the microscope.

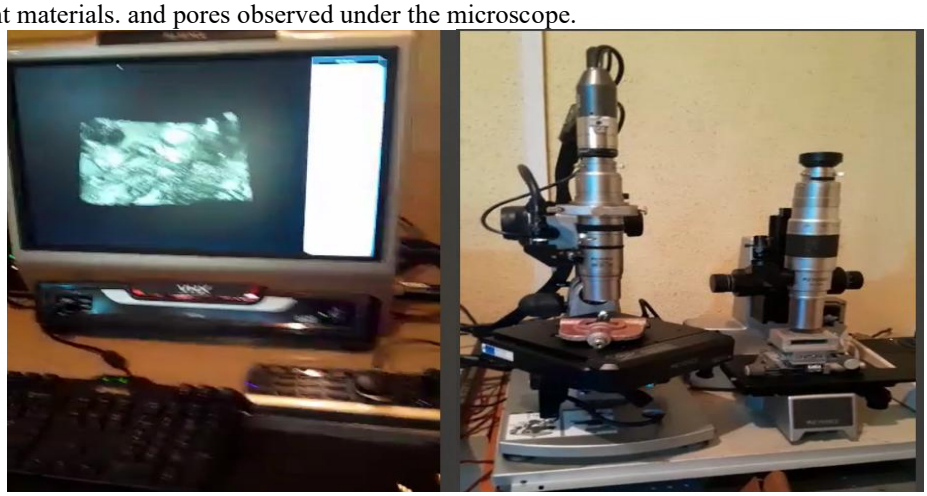

Plate 1: Keyence digital optical microscope: VHX-2000E

(b) Mechanical properties tests

(i) Tensile properties

The tensile strength test is a critical assessment to determine the material's ability to resist breaking under tension. Therefore the tensile strength for each sample was carried out using an electronic universal testing machine (Model: INSTRON 3369) as shown in Plate 2.

Plate 2: Universal Testing Machine

This was conducted using dumb-bell shaped samples. One end of the dumb bell sample was gripped by the jaws attached to the adjustable crosshead. The tensile load was hydraulically applied to the sample by pressing the start button and the magnitude of the applied load would be indicated in the input and output display unit. The load will gradually be increased until the sample breaks off and the corresponding extension recorded. From this analysis, the ultimate tensile strength, yield strength, Young's modulus, and elongation at break were obtained.

The ultimate tensile strength (UTS) was obtained as the breaking strength of the samples, Yield strength was determined as the maximum strength of the elastic region of the samples. Young's modulus is the ratio of the stress to strain within the elastic region of the samples. While the elongation at break values were determined as the ratio of extension to the original length expressed in percent.

(ii) Compressive strength

The compressive strength test for the composite samples were measured to determine the maximum compressive stress that the composite can endure before failure. It is a crucial property because for structural application, the composite needs to resist deformation and maintain structural integrity under the intense pressures experienced under compressive loads.

Thus, to determine the compressive strength, each composite sample was placed between the plates of the local frame. Compressive load was applied gradually over the composite material's surface, and immediately the

sample fails, the values of compressive strength were read on a digital device based on the established equation (1). From each formulation, three samples were tested for compressive strength and the mean value was determined and recorded.

$$\sigma_c = \frac{F}{A_s} \quad (1)$$

where; F = Applied force, A_s = Cross sectional area.

(iii) Hardness

The hardness test is an important quality control process used to evaluate the material's resistance to deformation, which is critical for ensuring the performance of the composite samples. Thus, the shore D durometer (see Plate 3), a standard method that measures the resistance of the material to indentation was used following the ASTM D2240. Each of the samples was placed on a flattened surface. The indenter of the instrument was then pressed into the sample with an applied load of 50 N for 15 seconds. The hardness value was read from the durometer, and recorded.

Plate 3: Shore D Durometer for Hardness Test

(iv) Impact Strength

The Izod impact test method was used to determine the impact strength of the composite samples. It is a standardized method for evaluating the toughness of materials by measuring the energy absorbed when a notched sample is struck and broken by a pendulum-mounted hammer.

During the test, each sample was prepared in a rectangular-shaped form. Subsequently, a V notch was created at the centre of the sample to create a stress concentration point, making the sample more susceptible to fracture under impact. The notched sample was taken to the Izod impact testing machine (see Plate 4), and clamped vertically in the machine's vise, with the notch facing the direction of the pendulum. Then, the pendulum-mounted hammer was made to strike the sample at the notched face. The pendulum-mounted hammer continued to swing until the sample got broken.

The energy absorbed by the sample during fracture was determined by measuring the difference between the initial potential energy of the pendulum-mounted hammer and its potential energy after the impact. Higher impact energy values indicate a tougher material that can withstand greater impact forces. The impact strength subsequently determined by dividing the energy with the area of sample surface.

Plate 4: Impact testing machine

(c) Water absorption test

Water absorption test determines the amount of water a material absorbs, and it is typically expressed as a percentage of its dry weight. This test is crucial for evaluating the durability and suitability of various materials for an intended application.

Thus, the water absorption test was conducted by firstly, drying the samples in an oven to a constant weight to establish a baseline. Secondly, the initial weights of oven-dried samples were determined. Thirdly, the samples were immersed in 200 ml water at two different temperature regimes – 25 and 65 ^{o}C for 10, 30, 45, 60, 75, 90, 105, 120, 135, 150, 165 and 180 min. After the immersion, the samples were retrieved, excess water was gently wiped off, and the final weighs determined. The water absorption was then calculated by comparing the difference between the initial dry weights before immersion and final wet weights after immersion to the initial dry weight before immersion, expressed as a percentage as given in equation (2).

$$\text{Water Absorption} = \frac{W_f - W_0}{W_0} X\ 100\ \% \qquad (2)$$

where W_0 = initial weight (g) of sample before immersion, W_f = final weight (g) of sample after immersion.

3. Results and discussion

(a) Results of microstructure analysis

The micrographs for the microstructural examinations of the composite samples are presented in Figure 2. From the Figure 2, it can be clearly observed that sample 1 is plain with characteristic lustre of polymeric matrix.

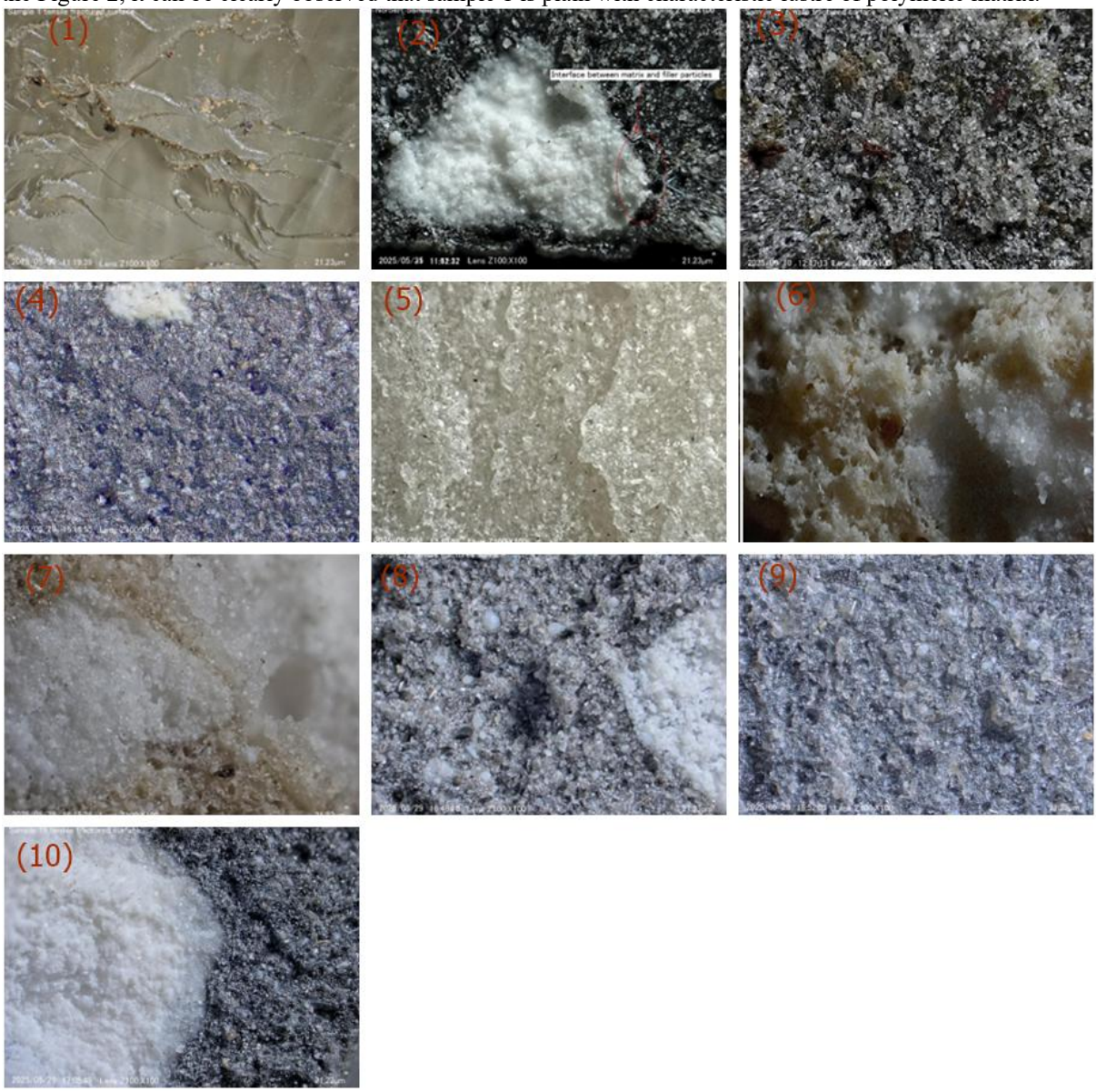

Figure 2: Micrographs of plain epoxy and epoxy-based composite samples.

Notably, samples 2, 3 and 4 are composite samples made with only PKF. Evidently, the microstructures of samples 2 and 4 showed improper mixing which resulted to segregation and non uniform distribution of the filler materials. This created a zone of stress concentration and brittle behaviour. However, the microstructure of sample 3 showed evidence of relatively good mixing, but revealed rough structural feature.

On the other hand, samples 5, 6, and 7 are composites with only SSF. The microstructure of sample 5 with 10 wt.% snail shell filler (SSF) revealed small discontinuities and a reasonably uniform distribution of particles and other constituents within the matrix. However, it could be observed that the SSF particles are well embedded within the amorphous epoxy matrix, resulting to layered cleavages. Also, sample 6 with 30 wt.% SSF and sample 7 with 50 wt.% SSF showed increased surface roughness with increase in filler concentration. The observed surface roughness is associated with some micro-pores.

Further, samples 8, 9 and 10 are composites with hybrid of PKF and SSF. Good observation of the microstructures revealed improper mixing and non uniform distribution of the filler materials, particularly on samples 8 and 10. However, sample 9 appear to be uniformly distributed.

(b) Results of mechanical properties

The mechanical properties of the plain epoxy and epoxy-based composite samples were conducted, and the results are as given below.

(i) Ultimate tensile strength

Figure 3 presents the ultimate tensile strength (UTS) for the the plain epoxy and epoxy-based composites. The UTS value for sample 1 (plain epoxy) is 5.099 MPa. In sample 2, the amount of epoxy was reduced and a given amount of Al_20_3, PKF and silane coupling agent were incorporated. In this sample 2, the UTS increased to 7.875 MPa. With further decrease in the amount of epoxy and increased incorporation of PKF, the UTS further increased to 9.763 and 11.165 for samples 3 and 4, respectively.

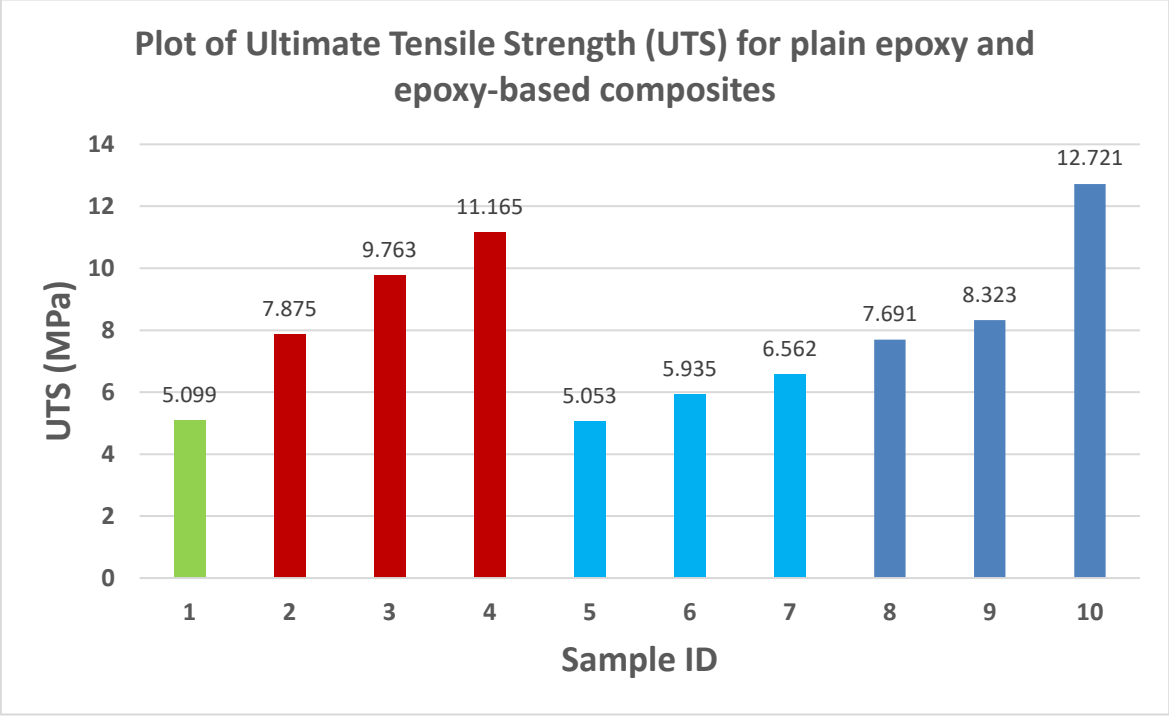

Figure 3: Plots of ultimate tensile strength for plain epoxy and epoxy-based composites.

When snail shell filler (SSF) was used in the composite production, sample 5 with the lowest amount of SSF (10 wt.%) gave UTS value of 5.053 MPa. The UTS value increased to 5.935 MPa with increased addition of 30 wt.% of SSF in the sample 6. However, with further increase in the amount of SSF to 50 wt.%, there was further increase in the value of UTS to 6.562 MPa.

When the composite samples with SSF were compared to the composite samples with PKF, it was clearly observed that the composite samples with PKF exhibited higher tensile strength. This reason could be due to lignocellulosic structure of PKF and its fibrous nature which provided excellent tensile and reinforcing properties and allowed for strong bonding and effective stress distribution, leading to greater tensile strength. However, the snail shell powder, despite containing calcium carbonate and silica, are inherently brittle and lacks a fibrous structure that could effectively transfer loads in a composite material.

In order to evaluate the effect of hybridization on the composites, the two natural fillers – PKF and SSF were used as fillers in the composite, as seen in samples 8 – 10. In sample 8, the UTS value was observed to be 7.691 MPa.

With increase in the addition of PKF and SSF in sample 9, there was observed increase in the value of UTS (8.323 MPa). As the amount of PKF and SSF were further increased in sample 10, there was pronounced increase in the UTS value.

(ii) Elongation at break

Equally, the results of the elongation at break for the plain epoxy and epoxy-based composites were determined and depicted in Figure 4.

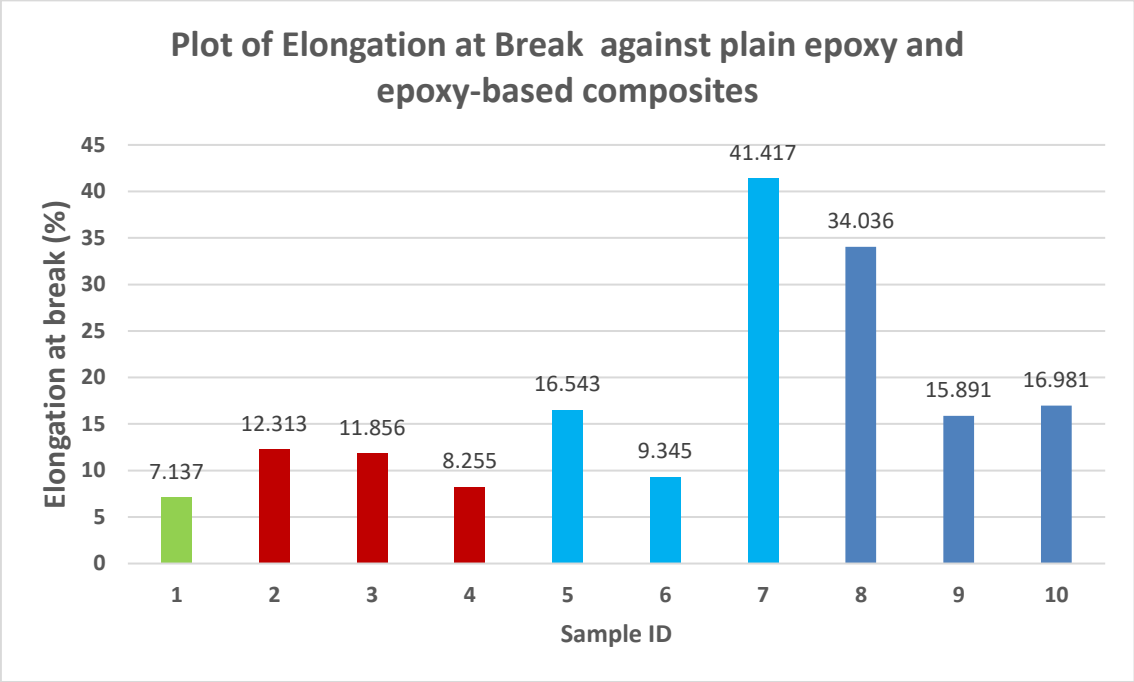

Figure 4: Plots of percent elongation at break for the various composite samples

Determination of elongation at break is a measure of durability and optimal performance of materials. Thus, when the elongation at break is high, it implies that the material is more ductile and flexible, and when the elongation at break is low, it means the material is brittle and cannot undergo long stretching. From the obtained results, it is clear that sample 1 has low elongation at break. The composite sample 2 – 4 that have only PKF as natural filler have relatively low elongation at break. However, sample 2 with lowest amount of PKF has highest elongation at break among them, and therefore implies that it is more ductile and flexible.

The composite samples that have SSF as the only natural filler (sample 5 – 7) has sample 7 exhibited the highest elongation at break, and it is the most ductile of all the composite samples. Among this category, sample 6 has the lowest elongation at break and therefore it is very brittle. Considering the composites with hybrid of PKF and SSF (samples 8 – 10), sample 8 with lowest amount of filler displayed highest elongation at break among the group, and therefore, it is ductile and flexible.

(iii) Young's modulus of elasticity

The Young's modulus of elasticity were determined from the elastic regions of the stress-strain curves. Thus, the results of the Young's modulus of elasticity for the samples 1 – 10 are given in Figure 5.

As already established, high value of Young's modulus means that the material is stiff, and low value of Young's modulus indicates that the material can easily be deformed. Therefore, samples 4, 5 and 9 have values of Young's modulus of elasticity above 100 MPa. This is a clear indication that they are stiff and can sufficiently resist deformation.

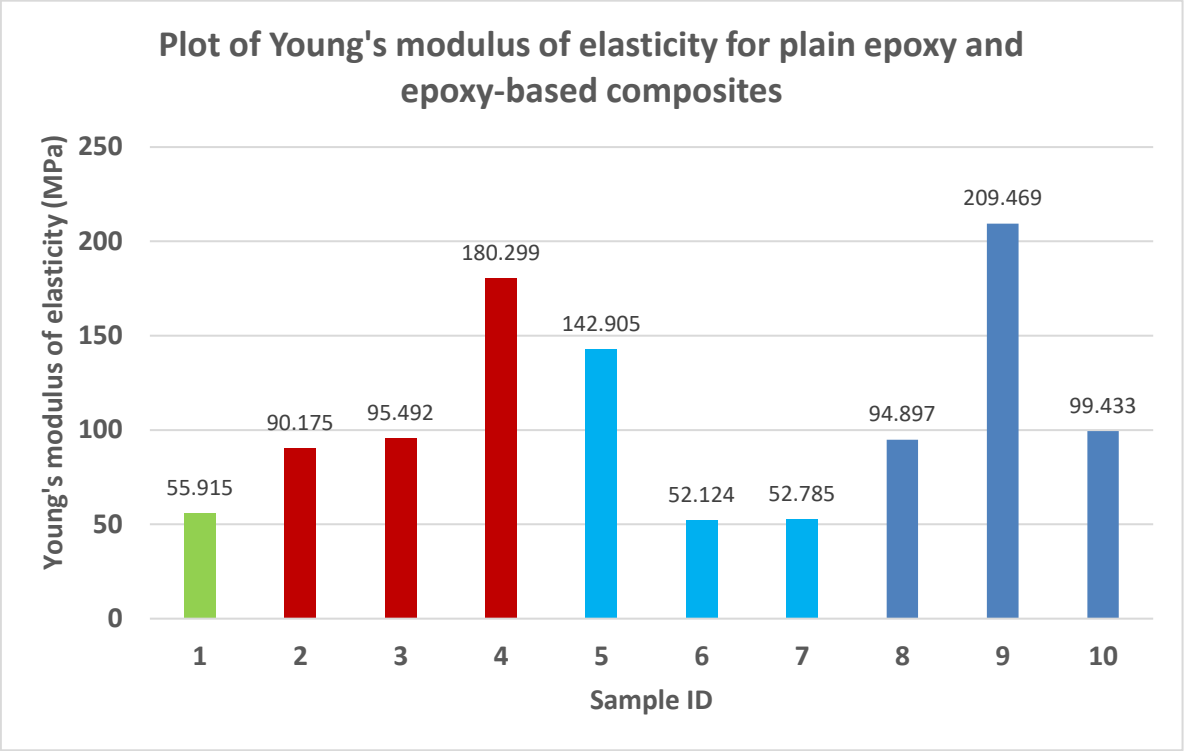

Figure 5: Plots of Young's modulus for the plain epoxy and epoxy-based composites

(iv) Compressive strength

The compressive strength analysis was conducted to evaluate the composite samples' ability to resist compressive forces. Thus, the results of the compressive strengths for the plain epoxy material (sample 1) and composite samples 2 – 10 are presented in Figure 6. From the results, the plain epoxy material exhibited lowest compressive force as expected, because there was no reinforcement. For the composite samples 2 – 4 with PKF as the only natural filler, the compressive strength increased with increase in PKF content. For the composite samples with SSF as the only natural filler (samples 5 – 7) , the compressive strength decreased marginally with increasing filler content. When the two natural fillers – PKF and SSF were incorporated into the composite, sample 9 with 30 wt. % filler content exhibited the highest compressive strength.

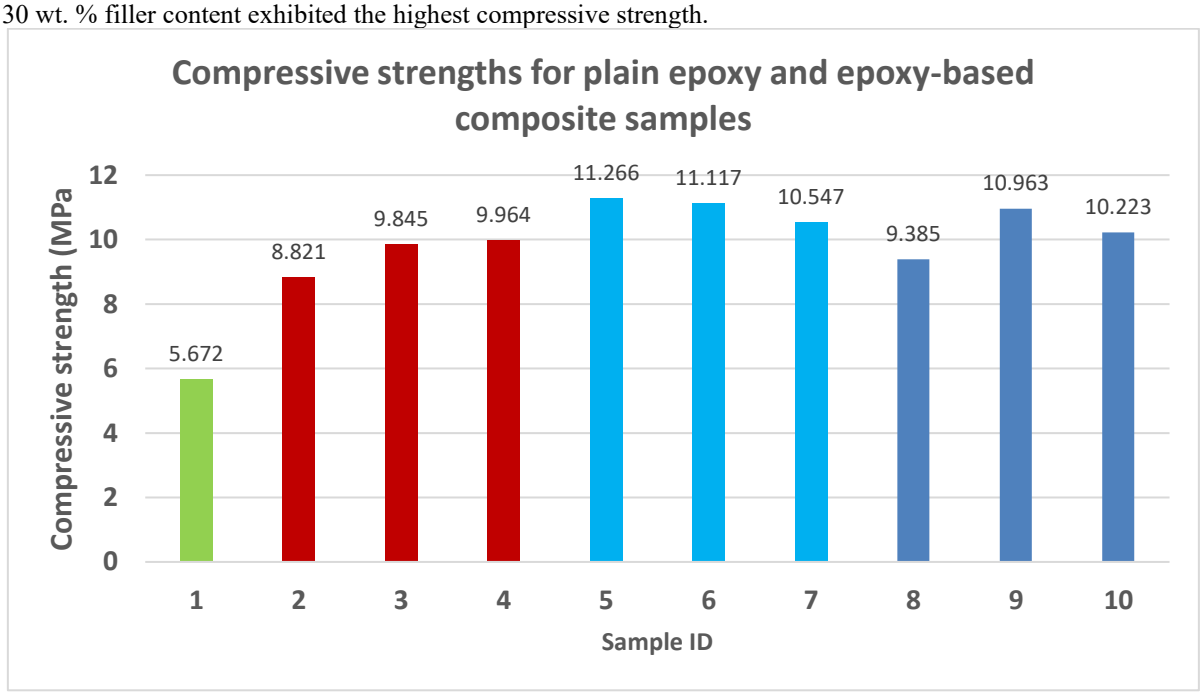

Figure 6: Plots of compressive strengths for the plain epoxy and epoxy-based composites

(v) Hardness

Shore D hardness of the composite samples were determined, and the results of the Shore D hardness values for the plain epoxy sample 1, and the composite samples 2 – 10 measurements are given in Figur 7. For the composite samples with PKF only the Shore D hardness value increased with increase in filler content. On the other hand, the composite samples with only SSF, the Shore D hardness value decreased with increase in filler content. For the composite samples with hybrid of the two natural fillers, the Shore D hardness value increased with filler content.

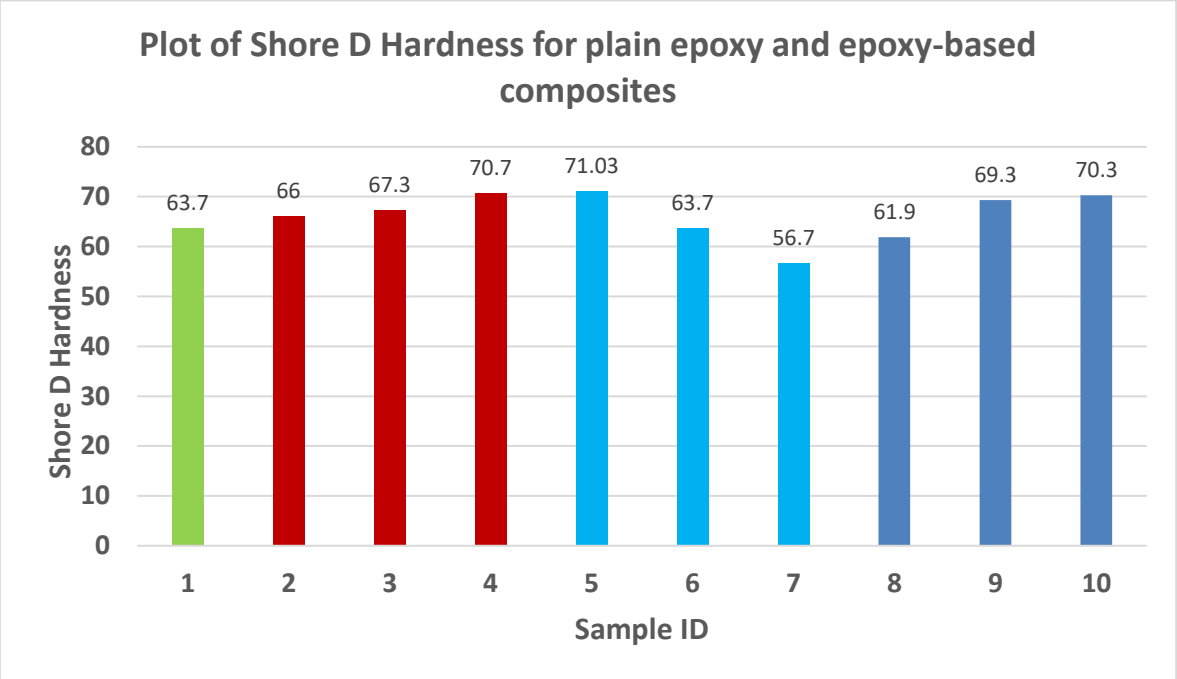

Figure 7: Plots of Shore D Hardness values for the plain epoxy and epoxy-based composites

(vi) Impact Strength

Impact strength is related to the dispersion of constituent materials in the composite. It is a measure of the amount of energy that a material can absorb before fracture. Thus, the impact strength of the plain epoxy sample 1 and fabricated composite samples 2 – 10 are given in Figure 8. Therefore, among the samples containing only PKF, sample 3 exhibited the highest impact strength. For the composite samples conataining SSF as the only filler, the impact strength increased with increase in filler content. As for the composite samples with hybrid of the two natural fillers, sample 10 with highest amount of filler content displayed highest impact strength.

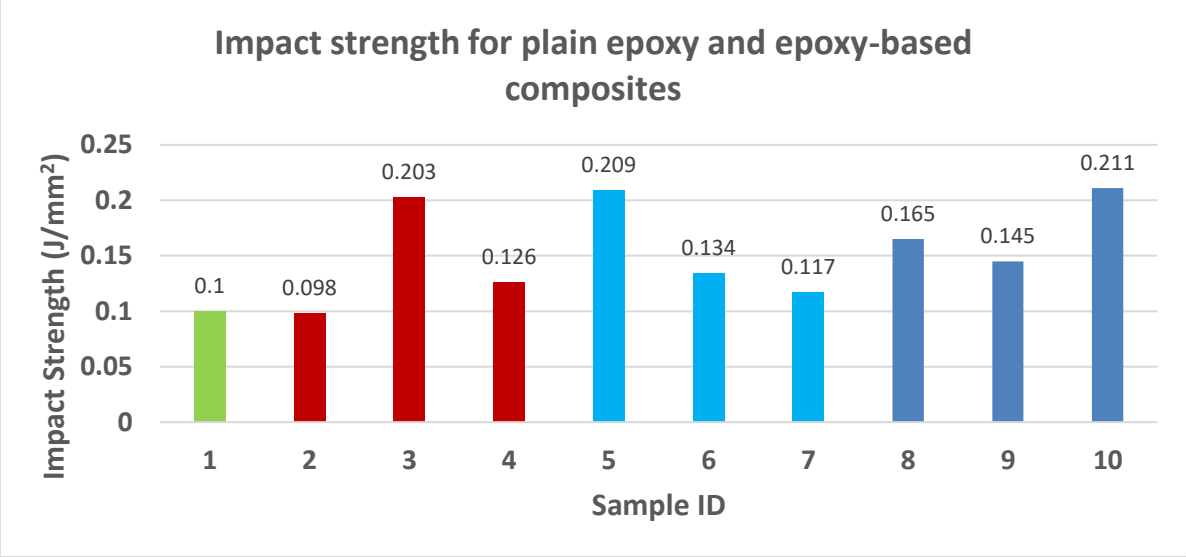

Figure 8: Plots of impact strength values for the various composite samples

(c) Water absorption

For applications that require contact with water, it is necessary to investigate the water absorption capabilities of the various composite samples. Thus, the percent water absorption for the plain epoxy sample 1 and composite samples 2 – 10 at three (3) different temperatures - 25, 40 and 55 ºC were determined, and the results are Figure 9.

A good look at Figure 9 shows that water absorption increased with increasing temperature. At each temperature, the composite samples displayed undulating pattern of water absorption. This is because of poor dispersion in the composite samples, and porous nature of the samples which encouraged sippage of water through their internal structures.

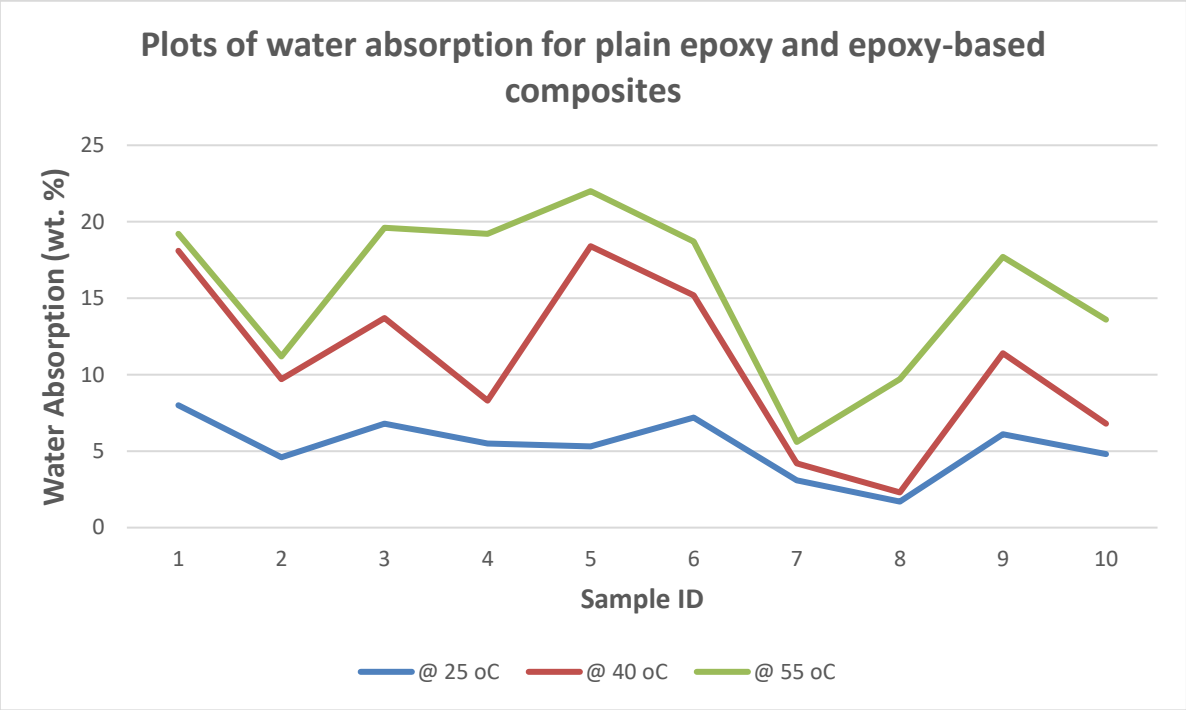

Figure 9: Plots of percent water absorption for the plain epoxy and the composites

(d) Effect of hybridization on some end-use properties of the epoxy-based composites

Hybridization, which is the combination of different materials within a composite enhances some end-use properties like mechanical strength, stiffness, and toughness. Incorporation of hybrid fillers into composites is aimed at overcoming the limitations of individual components, leading to improved performance. For example, combining natural fibres with synthetic fibres can create a more versatile and cost-effective material.

However, in a few cases, hybridization of composites can sometimes reduce the overall properties of composites if the combination of fibres leads to poor fibre-matrix adhesion and fibre damage during processing and moisture absorption issues. While hybridization often enhances properties by providing a better balance of strengths, these adverse effects can occur, especially if the constituent fibers are not compatible or the processing conditions are not optimized.

In view of the foregoing, Table 1 presents formulation for two natural hybrid fillers (PKF and SSF) which produced samples 8 – 10. From Figure 3, the ultimate tensile strength result shows the sample 10 with 50 wt.% PKF and SSF hybrid fillers gave highest UTS value of 12.721 MPa. Also, sample 10 exhibited highest value of Young's modulus of elasticity as given in Figure 5. Equally, the sample 10 displayed highest value of impact strength as shown in Figure 8. Thus, the observed values of UTS, Young's modulus of elasticity and impact strength for the composites with hybrid fillers are higher than the composites with mono filler. The reason is linked to the synergistic effect of PKF and SSF.

Conclusion

Epoxy-based composites using PKF and SSF as natural fillers were successfully fabricated. The effects of hybridization of PKF and SSF on the microstructural, mechanical, and water absorption properties of epoxy-based composites have been conducted. With respect to the epoxy-based composites samples (8 – 10) with hybridized PKF and SSF, the ultimate tensile strength of sample 10 with 50 wt.% PKF and SSF hybrid fillers gave highest UTS value of 12.721 MPa, highest value of Young's modulus of elasticity of 209.469 MPa, and highest value of

impact strength of 0.211 J/mm^2, compared to the composites with mono fillers. The reason for the observed results is linked to the synergistic effect of PKF and SSF. The water absorption assay shows that water absorption increased with increasing temperature. However, the percent water absorption by the composites with hybrid fillers is relatively low.

Acknowledgement

The authors were grateful to Dr. Q. Ochieze for his assistance in the characterization of some samples. We are equally grateful to the laboratory Technologists at the Department of Mechanical Engineering, Federal University of Technology Owerri (FUTO) for their assistance during the composite preparation. Finally, the authors are grateful to the School of Engineering and Engineering Technology and School of Postgraduate Studies, FUTO.

Conflict of Interest

The authors declare there are no conflicts of interest regarding the publication of this article.

Authorship contribution statement

NNN was involved in the conceptualization, investigation, and writing of the manuscript. **OCN**, **IOA and RU** were involved in the conceptualization, supervision, analysis of results and review of the manuscript draft. All authors read and approved the manuscript.

References

Achukwu E.O., Barnabas A M., Mamman A., Uzochukwu M.I. Fabrication of palm kernel shell epoxy composites and study of their mechanical properties, *Nigerian Journal of Materials Science and Engineering*, 2015, 6(1):32-38.

Baffour-Awuah E., Akinlabi S.A., Jen T.C., Hassan S., Okokpujie I.P., Ishola F. Characteristics of Palm Kernel Shell and Palm Kernel Shell-Polymer Composites: A Review, *IOP Conf. Series: Materials Science and Engineering*, 2021, 1107, 012090. doi:10.1088/1757-899X/1107/1/012090

Bello S.A., Agunsoye J.O., Hassan S.B., Zebase Kana M.G., Raheem I.A. Epoxy Resin Based Composites, Mechanical and Tribological Properties: A Review, *Tribology in Industry*, 2015, 37(4):500-524.

Demir O, Yar A, Eskizeybek V, Avcı A. Combined effect of fiber hybridization and matrix modification on mechanical properties of polymer composites. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*. 2023;237(9):1935-1951. doi:10.1177/14644207231162547.

Kamo, Y. and Matsumoto, A. Stress relaxation and improved fracture toughness of metal bonding using flexible monolith sheets and an epoxy adhesive. *Polym J.* 2025, **57**, 203–214. https://doi.org/10.1038/s41428-024-00975-w.

Kolawole M.Y., Aweda J.O., Abdulkareem S., Bello S.A., Ali A., Iqbal F. Influence of calcined snail shell particulates on mechanical properties of recycled aluminium alloy for automotive application. *Journal of Acta Periodica Technologica,* 2020, 51:163-180.

Oladele I.O, Ibrahim I.O, Adediran A.A., Akinwekomi A.D., Adetula Y.V., and Olayanju T.M.A. Modified palm kernel shell fiber/particulate cassava peel hybrid reinforced epoxy composites, Results in Materials, 5, 2020. https://doi.org/10.1016/j.rinma.2019.100053.

Olaitan A.J., Ufuoma O.D., King G.D. and Raphael O. Production of a safety helmet, palm kernel fibre and shell particulates, *International Journal of Engineering Science Invention*, 2017, 6(2):44-55.

Ramasamy B., Ramesh M., Ramanujam R., Sasikala G., Deepa C. Physical Properties of Glass-Hemp-Banana Hybrid Fiber Reinforced Polymer Composites, 2017 10(1), DOI: 10.17485/ijst/2017/v10i7/103310.

Sukanto H., Raharjo W.W., Ariawan D., Triyono J. and Kaavesina M. Epoxy resins thermosetting for mechanical engineering, *Open Engineering*, 2021, 11(1):797-814. https://doi.org/10.1515/eng-2021-0078

Valášek P., Habrová K., and Müller M., Experimental description of aging of palm oil kernel shell powder/epoxy composite, *IOP Conf. Ser.: Mater. Sci. Eng.*, 2019:617. DOI 10.1088/1757-899X/617/1/012009.

Xu H., Zhang X., Yu Y., Yu Y., Weng L. Enhanced adhesion property of epoxy resin composites through dual reinforcement mechanisms, *Next Materials*, 2024, 3,100072. https://doi.org/10.1016/j.nxmate.2023.100072.

Zhang, J., Zhang, Z., Huang, R., and Tan, L. Advances in Toughening Modification Methods for Epoxy Resins: A Comprehensive Review. *Polymers*, 2025, *17*(9), 1288. https://doi.org/10.3390/polym17091288