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Investigation of the Physical Properties and Thermal Stability of Woven Raffia Palm Fibre-Groundnut Shell Powder Hybrid Composites as Material for Production of prosthetic Sockets

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Abstract
Prosthetic socket is a critical component of a prosthesis, as it connects the residual limb and the other prosthetic components. It is responsible for the amputee's comfort, due to force distribution and pressure on the stump. This study aims to investigate the physical properties and thermal stability of woven raffia palm fibre (RPF) and groundnut shell (GNS) reinforced epoxy hybrid composite, and to evaluate its suitability for use in the production of transfemoral prosthetic sockets. In the study, three laminated hybrid composites have been produced from alkaline treated woven raffia palm fibre mat and 300µm particulates of alkaline treated groundnut shells through the hand lay-up method using epoxy resin as matrix. The composites were characterized by subjecting the samples to density and water absorption as well as thermogravimetric analysis (TGA). The results of the physical properties which is density and water absorption in the composite gave density values in the range of 1.10 - 1.70 g/cm^3. Water absorption in the composite ranged from 2.1 – 6.9 % after 336 hours of immersion in water at room temperature. The results of the thermogravimetric analysis (TGA) of the composites gave a degradation temperature of 580^{o}C. The developed composites have met the requirement of low weight and is thermally stable for the application. Prosthetic sockets are unlikely to be exposed to temperatures as high as 580^{o}C during use. The high degradation temperature may make the material more suitable for extreme conditions.

Key words: *Prosthetic Socket, Transfemoral, Density, Water Absorption, Thermogravimetric Analysis.*

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I. Introduction

Prostheses are medical devices intended to restore the normal functions of the missing body part. The components of a prosthetic device are prosthetic socket, adaptors, joints, pylon and foot or hand. The prosthetic socket is the device that accommodates the residual limb (stump) and is the most important part of the prosthesis. The socket is made according to the condition and shape of the residual limb **(**Bhagirath and Makarand, 2022). Commonly used materials for prosthetic sockets are; glass fibre, carbon fibre, reinforced carbon fibre, and Kevlar (Walke and Pandure, 2017). Currently, the use of synthetic fibres such as carbon and glass fibres for prosthetic socket applications is discouraged due to environmental and health concerns (Ipilakyaa *et al.,* 2024). Prosthetic sockets produced from these synthetic fibres have high density and are not biocompatible (Santosh and Sumit, 2020). According to Monette *et al.* (2021) the utilization of high density synthetic fibres in lower limb prosthetic sockets resulted in adverse consequences, including: increased risk of skin breakdown and discomfort on the residual limb and higher energy expenditure for users, leading to increased fatigue and reduced mobility. In addition, the high carbon composition of these synthetic fibres causes problems to the environment as they are non-degradable (Tile and Nyior, 2023).

Nurhanisah *et al.* (2017) reported that, prosthetic sockets made from natural fibre reinforced composite are biocompatible, have low weight, less costly and less stiff compared to conventional synthetic fibre polymer composite, and more comfortable for users. Consequently, natural fibre reinforced polymer composite has been deployed in the manufacture of prosthetic sockets (Tile *et al.,* 2025). According to Ipilakyaa *et al.* (2024) the requirements of prosthetic materials, which are good strength, low weight, durability, size reduction, safety, and energy conservation, have made natural fibre-reinforced plastics very attractive in prosthetic applications. Materials for prosthetic sockets should have sufficient strength, light weight, resistant to thermal conditions, durable and biocompatible; it should not cause allergic reactions to the body (Tile *et al.,* 2025; Bhagirath and Makarand (2022).

Many significant researches (Tile *et al.,* 2025; Sulardjaka and Ismail (2020); Odusote (2016) and Sukania (2015) have been undertaken with natural fibres to develop fibre reinforced polymer composites for lower limb prosthetic sockets however, literature is limited on the physical properties and thermal stability of materials used for prosthetic socket applications. Most researches, investigated the mechanical properties of prosthetic materials. This study has therefore, close this gap by investigating the physical properties (density and water absorption) and thermal stability using thermogravimetric analysis (TGA) of woven raffia palm fibre and groundnut shell particulate/epoxy hybrid composite for the production of transfemoral prosthetic leg sockets. The use of low-density renewable natural materials such as raffia palm fibres and groundnut shells in polymer composite materials is a viable means to reduce environmental impact and support sustainable development in the manufacturing industry, providing lightweight sockets that reduce vibrations transmitted to the body during movement as alternative reinforcing materials. According to Tile and Nyior (2023), Ipilakyaa *et al*. (2024), Tile *et al.* (2024) and Nyior *et al.* (2018) raffia palm fibres and groundnut shells have the potential to substitute glass fibre for prosthetic sockets production. It has also, been reported that, addition of groundnut shell particulate to polymer composites, increase thermal stability as well as the glass transition temperature of the composites (Sesugh *et al.,* 2019).

II. MATERIALS AND METHODS

2.1 Materials

The materials used for this research include Epoxy resin (885) part A, Hardener (995) part B, Raffia palm fibres, Groundnut shell powder, Sodium hydroxide (NaOH), Distilled water, Laminating Leather (mould release agent) and Hand gloves.

2.2 Methods

The following experimental procedure were followed in the research.

2.2.1 Preparation of Raffia Fibre and Groundnut Shell Powder

The raffia palm fibres used in this research were treated in line with Ipilakyaa *et al.* (2024). The fibres were weaved into bidirectional 0/90º fibre mat.

Groundnut shell powder was treated in line with Tile *et al.* (2024). The powder was sieved using standard test sieves to a particulate size of 300 µm.

2.2.2 Production of Woven Raffia Palm Fibre and Groundnut Shell Reinforced Epoxy Hybrid Composite Samples

Production of the hybrid composite was carried out by lamination lay-up method using wooden mould of size 180 × 130 × 8 mm^3 in line with Tile *et al*. (2025). Laminated samples were cut for the physical and thermal stability tests. Table 1 shows the composition of the samples.

Table 1: Composition of Woven Raffia Palm Fibre-Groundnut Shell Particulate/Epoxy (RPF-GSP/E) Hybrid Composite

RPF Mat No. of Layers	RPF Mat Volume (cm^3)	GNS Particles Volume (cm^3)	Reinforcement (%)	Epoxy Resin Volume (cm^3)	Volume of Sample (cm^3)
1	3.52	3.52	3.8	180.16	187.2
2	7.04	7.04	7.5	173.12	187.2
3	10.56	10.56	11.3	166.08	187.2

2.3 Evaluation of the Composite for Transfemoral Prosthetic Socket

2.3.1 Physical tests

Density Test

The density of the composite material was determined according to Archimedes principle at room temperature in line with Chukwu *et al.,* (2018). The volume of each sample was obtained by immersing the sample in a graduated beaker containing a known level of distilled water. The difference between the final and initial level of water was used to calculate the volume of water displaced. This was taken as the volume of sample while the mass of each sample was obtained using a digital weighing balance. Equation (1) was used to obtain the density of the samples. The results obtained were used to plot bar chart to show the trend of the effect of reinforcement on the density of the composites.

$$\rho = \frac{m}{v}(\text{g/cm}^3) \qquad (1)$$

where ρ is the density, m is the mass and v is the volume

Water Absorption Test

The effect of water absorption on the composites was investigated in accordance with ASTM D570 in line with Jacob *et al.,* (2019). The specimen of size 20 × 20 × 5 mm^3 was weighed to an accuracy of 0.1mg using digital weighing balance. Water absorption test was conducted by immersing the composite specimens in distilled water in plastic containers at room temperature for a duration of 336 hours. Once in 24 hours, a specimen was taken out from the water and all surface water was removed with a clean dry cloth and the specimen was reweighed to the nearest 0.1 mg. The specimen was weighed regularly from 24 hours to 336 hours exposure, at intervals of 24 hours. The water absorption was calculated by the weight difference using equation (2). The results obtained were used to plot graphs to show the trend of water absorption behaviour in the samples.

$$\text{Per cent Water Absorption} = \frac{\textbf{Wet weight} - \textbf{Dry weight}}{\textbf{Dry weight}} \times \frac{\textbf{100}}{\textbf{1}} \qquad (2)$$

2.3.2 Thermogravimetric analysis (TGA)

Thermo-gravimetric analysis (TGA) was done on the composite in line with Azwa and Yousif (2013). The machine consists of an analytical balance supporting a platinum crucible for the specimen, situated in an electric furnace. The sample was heated with a heating rate of 10ºC/min over the temperature range from 30.00°C to 910.00°C. The weight loss of the sample was measured in a nitrogen atmosphere with temperature and time as a function continuously in a confined space to decompose the composite. The machine was connected to a computer monitor and the weight loss curve was displayed on the screen.

III. RESULTS AND DISCUSSION

3.1 Results of the Physical Properties of the Composites

3.1.1 Density of Composites

The results of the densities of the composites with different reinforcements are presented in Figure 1. The densities are in the range of 1.10-1.70 g/cm^3. It is observed that as the reinforcement increased the corresponding density of the composite decreased.

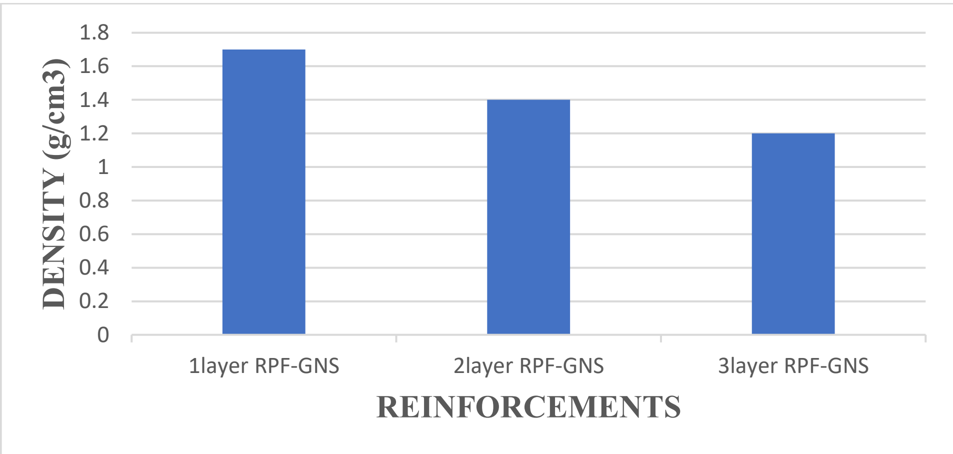

Figure 1: Bar Charts showing Density of the Composite

This is because the fibres used for reinforcements are light weight fibres with low densities. The density result is in agreement with the findings of Shereen *et al*. (2021) on Investigation of Some Properties for Laminated Composite Used for Prosthetic Socket where the values of density decrease with increasing the volume fraction of reinforcements. Density measurements for laminated composite is an important indicator to know the light composite materials. Typically, natural fibre composite materials are lighter than synthetic composite materials. This is one of the reasons behind the use of natural fibre composite materials for prosthetic sockets (Shereen *et al*., 2021).

According to Quintero and Zasulich (2017) low density materials are a requirement for materials used in prosthetic sockets applications. The light weight nature of the fibre reinforced composites reduces the overall weight burden on the body, which can be beneficial in load bearing applications. This helps minimize stress on the residual limb tissues and facilitates patients comfort and mobility (Monette *et al.,* 2021).

3.1.2 Water absorption in the composite

The percentage of water absorption in the composites was calculated by weight difference between the samples immersed in water and the dry samples. Variation of water absorption with the reinforcement at room temperature is shown in the Figure 2.

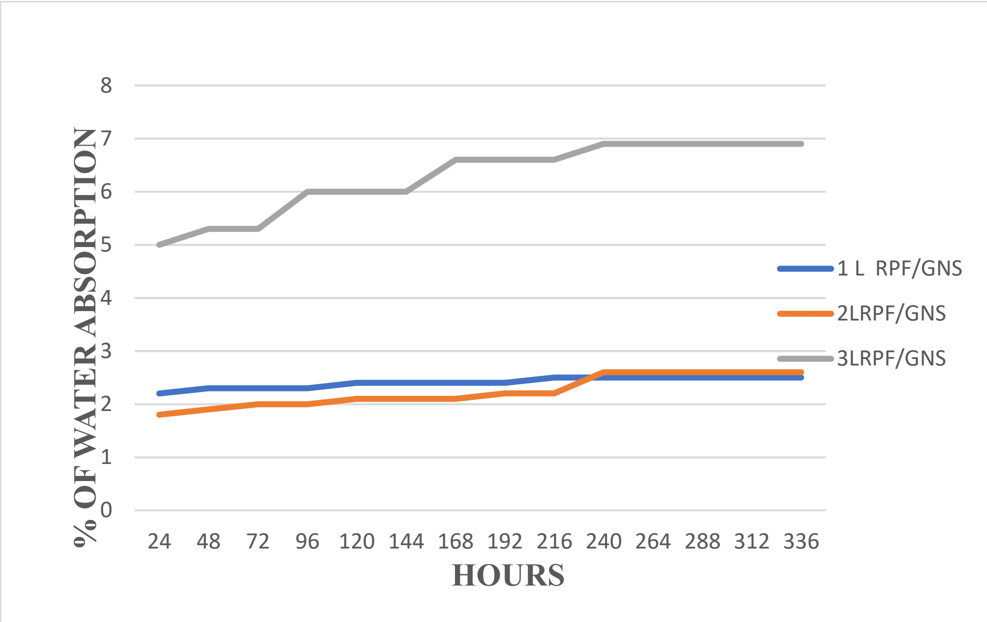

Figure 2: Water Absorption Trends in the Composite

The percentage of water absorption in the composites depended on fibre content in the samples. The results show that water absorption increased with increase in the percentage of reinforcements in the composite. It can be seen that the composites absorbed water at the initial stage, and later at 240 hours saturation level was attained without any further increase in water absorption in the samples.

The overall maximum percentage of water absorption in the composites was low, maximum values of water absorption ranged from 2.5 - 6.9 % in 336 hours. Maximum Water absorption in 1layer RPF-GNS was 2.5% and Maximum Water absorption in 2layer RPF-GNS was 2.6% in 240 hours of immersion in distilled water. The percentage of water absorption was highest in 3-layer woven RPF-GNS/Epoxy hybrid composite, maximum of 6.9% water was absorbed in the sample in 240 hours. The increased water absorption as the reinforcement increased is due to void content created at higher fibre loading leading to increased number of pores. It could also be observed that after 240 hours of immersion, there was no further increase in water absorption, which is evident from the linearity of the plots. According to Jacob *et al.* (2019) this could be attributed to the fact that the pores created may have been saturated with water, thus giving rise to such behaviour.

Water absorption, which is an important criterion used in selecting material for prosthetic sockets and outdoor applications was low in 1layer RPF-GNS and 2-layer woven RPF-GNS/Epoxy Hybrid composite. This may be attributed to lower void content in the composite arising from better interfacial bonding between the treated RPF and GSP and the epoxy matrix. According to Shereen *et al*. (2021) chemical treatment removes non-cellulosic materials like lignin, pectin, hemicelluloses and natural fats which make natural fibres prone to water absorption.

3.2 Results of the Thermogravimetric Analysis (TGA) of the Composite

Thermogravimetric analysis (TGA) was carried out in Nitrogen gas atmosphere. Figure 3 shows the TGA curve for the composites. Three stages of weight loss are observed on the curve, the first is in the range of 90-500ºC involving the loss of 2 % of the total mass of the sample. This can be ascribed to the release of absorbed moisture in the reinforced fibres. In the second stage, the decomposition temperature of the sample ranges from 500-680ºC where a sudden drop in the mass of the sample is observed with a loss of 30 % of the total mass of sample. This could be related to the degradation of substances in the composites such as hemicelluloses and celluloses in the fibre. According to Jagadeeswaran and Chandrasekaran, (2023) the decomposition temperature is usually taken at the point of sudden drop in weight of sample on the TGA curve which in this composite occurs at 580ºC. The third stage ranged from 680-860ºC with loss of 40 % of the total mass of the sample. This decomposition is due to the degradation of non-cellulosic materials in the fibres.

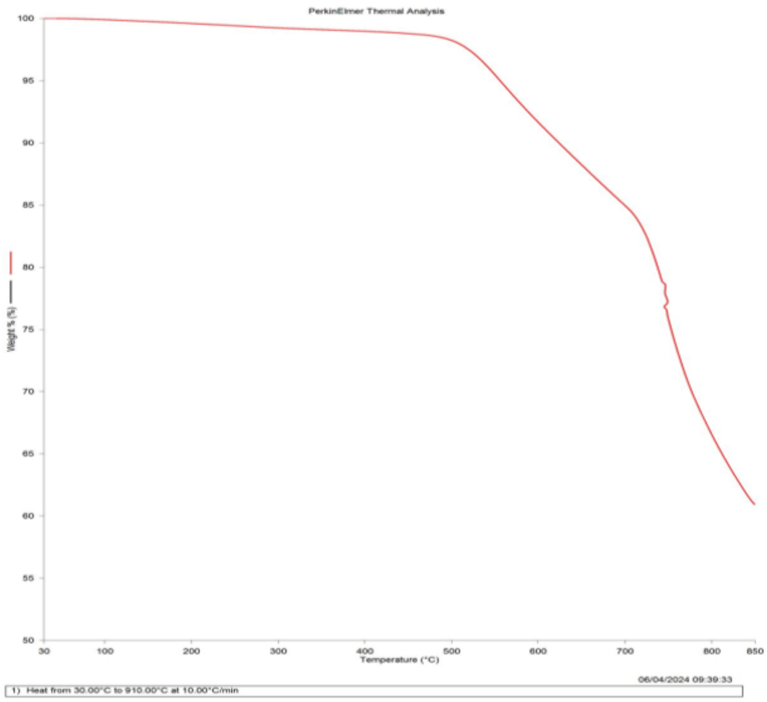

Figure 3: TGA of the Hybrid Composite

As shown in Figure 3, the thermal stability decreased with increase in temperature and time. This result is in line with the work of Isabela *et al.* (2012) where a similar trend in the TGA curve was observed on thermal Characterization of Jute Fibres. While prosthetic sockets are unlikely to be exposed to temperatures as high as 580ºC during use, a high degradation temperature may make the material more suitable for extreme conditions or applications, such as fire resistance or exposure to high temperature environments. The information provided by TGA is essential for assessing the material's thermal stability and ensuring it can withstand temperature fluctuations experienced during prosthetic socket use.

Differential thermal analysis (DTA) curve shown in Figure 4 provides further information about the thermo-physical changes associated with mass change such as; melting point, glass transition temperature and crystallization temperature. The DTA also, detect the presence of impurities or contaminants. Two peaks can be observed on the Differential thermal analysis (DTA) curve. The first peak of the DTA curve correspond to the decomposition temperature of the composites, at 580ºC. The second peak occurred at 780ºC as seen on the DTA curve corresponds to the melting temperature of the sample. This result is similar with the study of Devi *et al.* (2021).

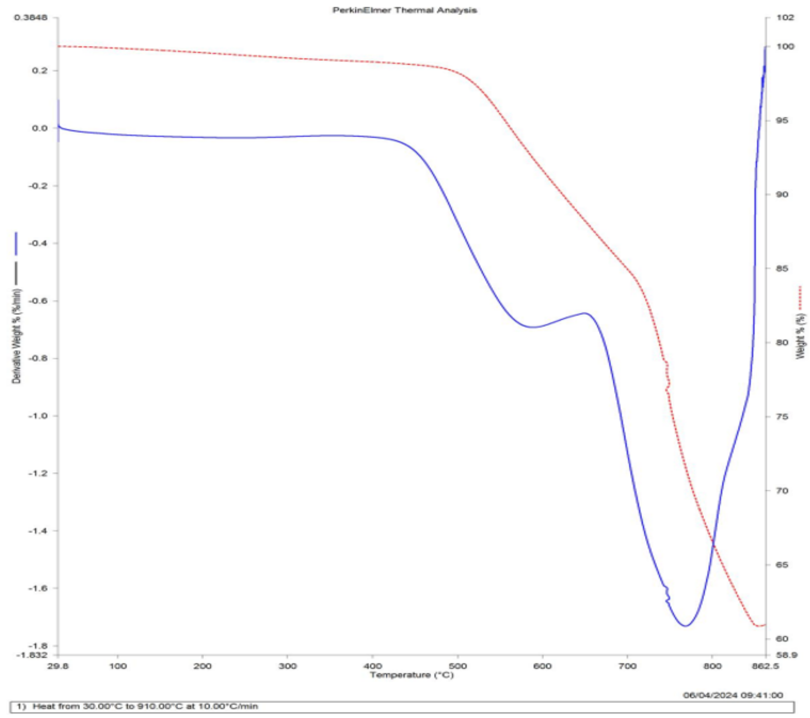

Figure 4: TGA/DTA Curve of the Hybrid Composite

According to Devi *et al.* (2021) analysing the derivative weight loss curves obtained from DTA, researchers can identify the degradation mechanisms occurring within the material, which can inform the development of more stable and durable prosthetic socket materials. A material with a degradation temperature of 580ºC can maintain its properties and structural integrity at elevated temperatures. This suggest the composites is relatively stable and less prone to degradation over time due to thermal factors, which can contribute to a longer lifespan and overall performance of the prosthetic socket.

IV. CONCLUSION

The study evaluated the density, water absorption, and thermal stability using thermogravimetric analysis (TGA) of hybrid composite material for transfemoral prosthetic socket produced from alkaline treated raffia palm fibres and alkaline treated groundnut shell powder using epoxy resin as matrix. The results of the physical properties which is density and water absorption in the composite gave density values in the range of 1.10 - 1.70 g/cm^3. Water absorption in the composite ranged from 2.5 – 6.9 % in the composite after 336 hours of immersion in water at room temperature.

Thermogravimetric analysis showed three stages of weight loss in the composite, the first is in the range of 90 - 500ºC involving the loss of 2% total mass of composite. The second stage, ranges from 500 - 680ºC where a sudden drop in the mass of composite is observed showing a degradation temperature of 580ºC with loss of 30% total mass of composite. The third stage ranged from 680 - 860ºC with loss of 40% total mass of the composite. Based on the results obtained, the research recommends the deployment of the hybrid composites for the production of prosthetic sockets.

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