

THE IMPACT OF VARYING WEIGHT FRACTIONS ON THE PHYSICOMECHANICAL PROPERTIES OF COMPOSITES REINFORCED WITH NEWBOULDIA LAEVIS FIBER PARTICLES

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Abstract

The growing awareness of environmental protection has sparked interest in researching plant-based particulate materials as sustainable alternatives to synthetic materials for reinforcing polymer composites. However, there is limited literature on how to optimize the properties of these natural particle-reinforced polymer composites. In this study, we fabricated and characterized polymer composites with different weight fractions of treated *Newbouldia fibre* particles as reinforcements. We evaluated the behaviour of these composites in terms of water absorption, mass density, impact strength, flexural strength, and compressive strength based on varying weight fractions using standard methods. The results showed that water absorption increased while mass density decreased with higher weight fractions of fibre particles. The impact strength exhibited inconsistent behaviour, initially increasing, then decreasing, and finally increasing again as the weight fraction rose. Meanwhile, flexural strength decreased, whereas compressive strength increased with higher weight fractions. These findings were confirmed through regression analysis, indicating that the weight fraction of fiber particles significantly affects the water absorption, mass density, impact strength, flexural strength, and compressive strength of *Newbouldia laevis* fibre particle-reinforced polyester composites. Therefore, when designing composite materials, it is essential to vary the weight fraction to optimize the properties of the polymer composite for lightweight applications.

1. Introduction

Composite materials typically exhibit better mechanical properties compared to their constituent materials. These materials are formed by combining a matrix or binder with reinforcement. Common matrix materials include polymers; reinforcement can come from fibres and particles. The proportion of reinforcement in a composite significantly influences its physical and mechanical characteristics. Fibre can be synthetic, like glass fibre, or sourced from natural materials like plant biomass. Over the years, synthetic fibre has found extensive applications in industries like aerospace and automotive due to its high strength and lightweight nature. However, there is growing global concern regarding synthetic fibre's environmental and economic drawbacks, including their non-biodegradable nature, pollution, greenhouse gas emissions, and high production costs. As a result, there is a rising interest in researching natural fibre particles as sustainable and effective alternatives to synthetic fibres for lightweight polymer composite applications. Various natural fibre particles, such as coconut, wheat, flax, and sisal, have been studied and shown to be effective reinforcements for polymer composites.

Additionally, research has demonstrated enhancements in the mechanical properties of polymer composites by adjusting factors like the weight fraction of fibre particles. One study found that tensile, compressive, and flexural strength increased by up to 30% with fibre particle loading but decreased with further loading. Tests on sisal/epoxy composites indicated flexural properties improved as fibre loading increased. An investigation into how the percentage content affects the

flexural and impact properties of a Phoenix sp. fibre particle-reinforced epoxy composite found that both properties improved as the fibre loading increased to 40% [15]. Similarly, research on a rice straw polyester composite indicated that the impact strength rose with higher fibre volume content [16]. However, the fibres from *Newbouldia laevis* plants have not been extensively studied for use in polymer composites. This plant, native to tropical Africa and referred to as 'Ogirisi' in Eastern Nigeria, is noted for its high crude fibre content and significant medicinal properties [17]. This study experimentally examined the impact of the fibre particle weight fraction on various properties, including water absorption rate, mass density, impact strength, flexural strength, and compressive strength of a *Newbouldia laevis* fibre particle reinforced polymer composite. The findings suggest *Newbouldia laevis* fibre particles could be a promising reinforcement material for lightweight polymer composite applications.

2. Methodology

2.1. Collection and Processing of *Newbouldia laevis* Fibre

The fibres were sourced from the Ogirisi plant in Enugu State, Nigeria (Figure 1a). Sodium hydroxide (NaOH) pellets, methyl ethyl ketone peroxide (MEKP) catalyst, cobalt naphthenate accelerator, and a wax release agent were all procured from Enugu State. Additionally, a polyester resin (matrix) specified by the manufacturer, with a density of 1.114 g/cm³, was utilised to fabricate the composite. The plant stem was harvested and soaked in water for 28 days to facilitate retting, after which the fibres were manually extracted from the epidermal layer of the retted stem (Figure 1(b,c)). The surfaces of the fibres were then modified by soaking them in a 3 w/v% sodium hydroxide solution for 1 hour, followed by rinsing in water to eliminate any excess NaOH [18]. The fibres were subsequently dried in sunlight for 48 hours, as illustrated in Figure 1(d).

2.2. Preparation and determination of the density of the fibre particles.

Natural fibres consist of smaller networks of fibres, leading to varying diameters along their length. Therefore, assuming circularity during the tensile testing of a single fibre is inaccurate for natural fibres, while it holds for synthetic fibres [19]. This variability often results in failure occurring at weak points along the fibre length, complicating the acquisition of precise results during mechanical testing due to significant discrepancies in the values obtained. Consequently, reducing the fibre to a particle size enhances its surface area. It ensures uniform dispersion when mixed with the resin matrix, resulting in consistent strength in all directions of the manufactured composite, unlike fibres that provide unidirectional reinforcement [20]. Additional advantages of using fibre particles as reinforcements include lower production costs, a simpler composite fabrication process, and enhanced strength of the composite [21]. The fibres of *Newbouldia laevis* were processed by grinding the dried material into a powder using a laboratory grinding machine, followed by sieving through a standard sieve with a mesh size of 180 µm (BSS 85), as illustrated in Figure 1(e, f).

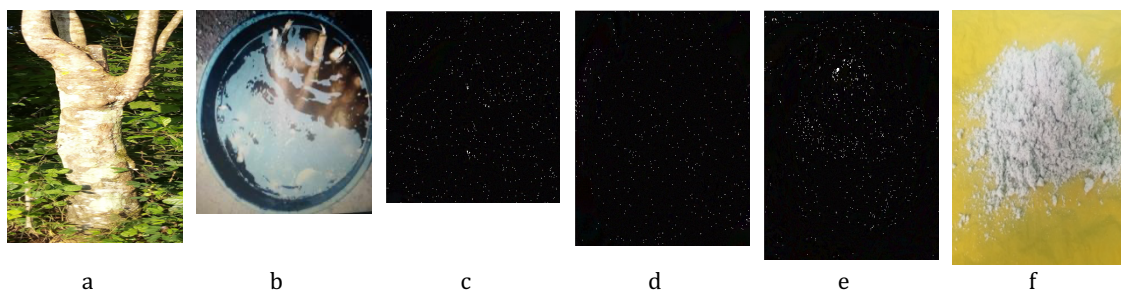


Figure 1:(a) *Newbouldia laevis* plant; (b) water retting; (c) extracted fibres; (d) fibre treatment; (e) sieving; (f) fibre particle

Finally, the bulk density of the fibre particles was determined according to the ASTM D7481 standard method via Eq. (1):

$$\rho_f = \frac{M_2 - M_1}{V_f} \quad (1)$$

Where ρ_F is the bulk density of the *Newbouldia laevis* fibre particle, M_1 is the mass weight of the empty measuring cylinder (g), M_2 is the mass weight of the measuring cylinder and *Newbouldia laevis* fibre particle (g), and V_f is the volume of the *Newbouldia laevis* fibre particle (ml) [22].

2.3. Composite Preparation

The hand lay-up method was used to fabricate this composite. First, the appropriate quantities of fibre particles (10%, 20%, 30%, and 40% weight fractions) were measured and mixed with a corresponding amount of polyester resin. The mixture was stirred for 10 minutes at a speed of 1400 RPM using a mixer. After that, the cobalt naphthenate accelerator and MEKP catalyst were added, followed by an additional 30 seconds of stirring. The prepared mixture was then applied to the molds and allowed to cure at room temperature for 72 hours. Once cured, the composites were molded and trimmed to the required sample size by ASTM standards (Figure 2).



Figure 2. Composite Samples

2.4. Composite characterisation

2.4.1. Physical characterisation

(i) Water Absorption of the Composite

The test was conducted using the ASTM D570 standard method to assess the water absorption rate of the composite over a specific duration. For this test, five equally sized samples of each composite with different fibre particle weight fractions (10, 20, 30, and 40% wt) were weighed before being submerged in water for 24 hours at room temperature. The final weight was recorded at the designated time. The average water absorption rate (W_{AR}) was calculated using Eq. (2):

$$W_{AR}(\%) = \frac{W_{A1} - W_{A0}}{W_{A0}} \times 100 \quad (2)$$

where W_{A0} is the weight of the conditioned sample (g), and W_{A1} is the final weight (g) after immersion [23].

(ii) Mass Density of the Composite

The mass density of the composite was determined according to the ASTM C134 standard method via Eq. (3):

$$\rho_C = \frac{M_C}{L_C \times W_C \times t_C} \quad (3)$$

Where ρ_C is the mass (bulk) density of the composite sample, M_C is the mass weight of the composite sample (g), L_C is the length of the composite sample (mm), W_C is the width of the composite sample, and t_C is the thickness of the composite sample (mm) [24].

2.5. Mechanical characterisation

(i) Impact test

This Charpy (unnotched) impact test followed the ISO 179-1 standard method. The testing was carried out using an XJJC-50 computer-controlled Charpy impact testing machine, operating at a speed of 3.8 m/s with a pendulum energy of 7.5 J. Five composite samples, each containing different weight fractions of fiber particles measuring 55 × 10 × 9 mm, were positioned on the test fixture and

subjected to a single impact from the pendulum dropped from a height. The energy required to fracture the composite samples was recorded, and the impact strength of the samples was calculated using Eq. (4):

$$I_p = \frac{K}{A} \quad (4)$$

where I_p is the impact strength (J/m^2), K is the impact energy required and A is the cross-sectional area of the composite sample (m^2) [25].

(ii) Flexural test

This test used the ASTM D-790 three-point bending test method with a universal tensile testing machine (Testometric). The composite samples, containing 10, 20, 30, and 40 wt% fibre particles, measured 150 x 13 x 4 mm. They were bent at a crosshead speed of 10 mm/min while a span length of 100 mm was maintained. The system recorded the load and deflection values as the test sample bent until failure. The flexural strength (σ_{fs}) was calculated using Eq. (5).

$$\sigma_{fs} = \frac{3PL}{2 \times W_C \times t_c^2} \quad (5)$$

where P is the maximum load applied (N) and L is the length of the support span (m) [26, 27].

(iii) Compression test

This was conducted using a universal testing machine following the ASTM D695 test method. For the test, five samples were prepared for each of the 10, 20, 30, and 40wt% fibre particle composites, all with the same dimensions of 12.7 mm x 12.7 mm x 25.4 mm for length, width, and thickness, respectively. These samples were subjected to compressive force, and the load and deformation values were recorded until failure occurred. The compressive strength (C_s) was calculated using Eq. (6):

$$C_s = \frac{P}{L_C \times W_C} \quad (6)$$

The experimental results were statistically analysed. The standard deviation (S) and the 95% confidence interval (C) were computed using Eqs. (7) and (8):

$$S = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{X})^2}{n-1}} \quad (7)$$

$$C = \bar{X} \pm (1.96 \times \frac{S}{\sqrt{n}}) \quad (8)$$

where x_i represents the sample data, and \bar{X} represents the sample mean.

Additionally, regression analysis was performed using Pearson product-moment correlation with Minitab 16 software to explore the relationships identified in the analysis [28].

3. RESULTS AND DISCUSSION

3.1. Physical properties

(i) Bulk density of fibres

The average weights measured for the empty measuring cylinder (W_1), the cylinder with fibre (W_2), and the corresponding volume of the fibre (V_F) were 104.636 g, 103.652 g, and 10 mL, respectively. The average bulk density of the *Newbouldia laevis* fibres was 0.098 ± 0.005 g/cm³. This density is significantly lower than synthetic fibres, such as carbon and glass, which have 2 g/cm³ densities and 2.4 g/cm³, respectively. This indicates that the *Newbouldia laevis* fibre particle polyester composite is lighter than polyester composites made from synthetic fibres with the same percentage content [29].

(ii) Water absorption of the composite

The result presented in Figure 3 shows that the water absorption rate rises from 0.587% for the composite containing 10% fiber particle content to 1.254% for the composite with 40% fiber particle content. This observation is consistent with earlier research on kenaf fiber [30].

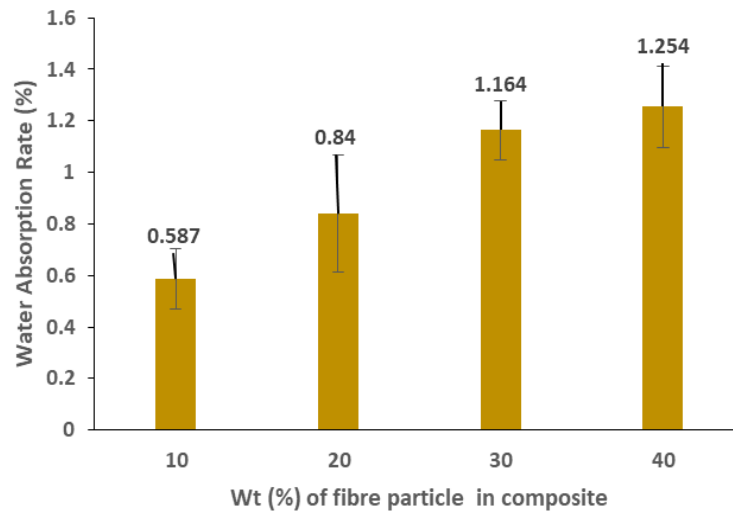


Figure 3: Effect of the weight fraction (%) of the fibre particles on the water absorption of the composite

The trend can be attributed to the hydrophilic nature of *Newbouldia laevis* fibre particles. As the content of these fibre particles increases in the composite, more of them become exposed at the surface. This leads to more water being absorbed by the surface particles than those embedded within the composite, ultimately resulting in higher water absorption in the composite samples [31]. Furthermore, the regression model presented in Eq. (9) (see Appendix i) shows a coefficient of determination (R^2 value) of 96%, a P-value of 0.02, and a strong positive correlation ($r = 0.98$) between water absorption and weight fraction.

$$\text{Water absorption} = 0.3805 + 0.02323 * \text{Weight fraction}(\%) \quad (9)$$

The findings indicate a statistically significant relationship ($P < 0.05$) between water absorption and the weight fraction of the composite.

(iii) Mass density of the composite

The results for the mass density of the composite samples, which have lengths of 55mm, widths of 10 mm, and thicknesses of 9 mm, are illustrated in Figure 4. The graph shows that as the weight fraction of the fibre particles in the composite increases from 10% to 40%, the mass density decreases from 1.273 g/cm³ to 1.192 g/cm³. This decrease can be attributed to the fibre particles' lower density than the matrix's higher density. Therefore, as the proportion of fibre particles rises, the matrix in the composite diminishes, leading to a reduction in the overall mass density. This finding aligns with a previous study on Areca nut leaf sheath fibres [32].

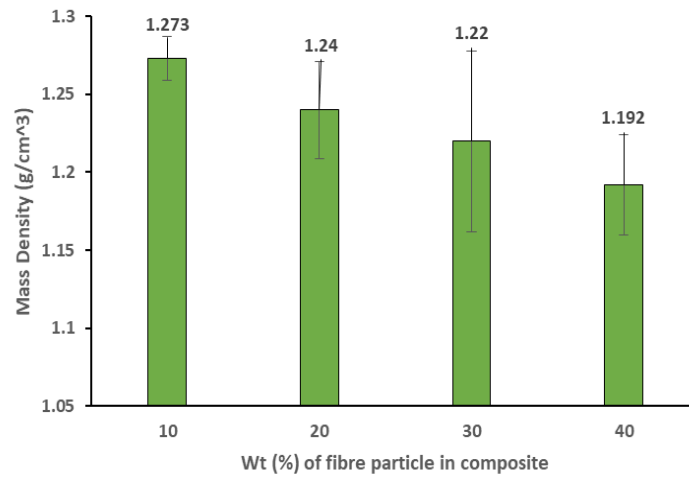


Figure 4: Effects of the weight fraction (%) of the fibre particles on the mass density of the composite

The regression analysis (Appendix ii) showed an R^2 value of 99.3%, indicating a statistically significant relationship ($P < 0.05$) and a strong negative correlation ($r = -0.996$) between mass density and the weight fraction of the composite. The regression model derived from this analysis is presented in Eq. (10):

$$\text{Mass density} = 1.297 + 0.002626 * \text{Weight fraction}(\%) \quad (10)$$

3.2 Mechanical Properties

(i) Impact strength

The results (Figure 5) showed that the composite with a 40% weight fraction of fibre particles achieved the highest impact strength at 3.60 kJ/m², while the composite with a 30% weight fraction had the lowest impact strength at 3.11 kJ/m². Furthermore, the composites containing 10% and 20% fibre particles exhibited greater impact strength than those with 30%. This trend of increasing impact strength for the composites with 10%, 20%, and 40% fibre particle contents can be attributed to the improved adhesion of these fibre particles within the matrix, leading to stronger bonding and enhanced impact strength, allowing for effective stress transfer during impact. The observed increase in impact strength with higher weight fractions of fibre particles aligns with the findings of Bettini *et al.* [33].

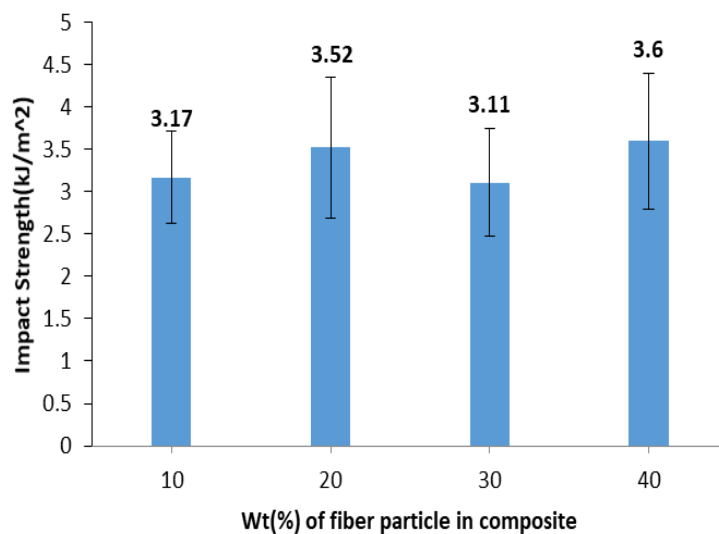


Figure 5. Effects of the weight fraction (%) of the fibre particles on the impact strength of the Composite

The reduction in impact strength for the composite with 30% fibre particle content could be attributed to voids or moisture within the fibre particles, leading to inadequate interfacial adhesion between the fibre particles and the matrix. These voids create stress concentration points and hinder adhesion, resulting in uneven stress transfer during impact. This finding aligns with the observations made by Praveena *et al.* [32], which indicate that composites perform better in absorbing external stresses when there is a strong bond between the fibre and the matrix. Furthermore, the regression analysis (Appendix iii) indicated a weak relationship, and the correlation between impact strength and the weight fraction of fiber particles was not statistically significant ($P > 0.05$). The regression model derived is presented in Eq. (11):

$$\text{Impact strength} = 3.130 + 0.00880 * \text{Weight fraction}(\%) \quad (11)$$

(ii) Flexural strength

The results (Figure 6) indicate that the composite's flexural strength diminishes as the fibre particles' weight fraction rises from 10% to 40%. This decline occurs because a higher fibre particle content leads to increased fibre-fibre interactions, which generate stress concentration points within the composites [30]. A similar finding was noted in research on bamboo polymer composites, where the flexural strength also decreased with higher fibre loading [34].

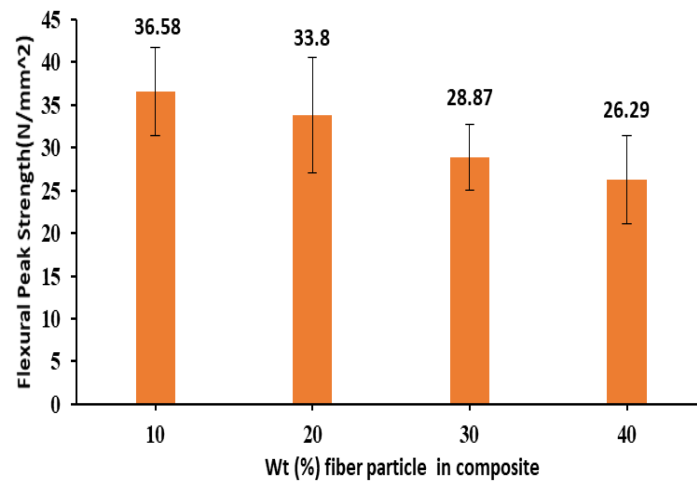


Figure 6: Effects of the weight fraction (%) of the fibre particles on the flexural peak strength of the composite

The regression analysis (Appendix iv) showed an R^2 value of 98.4%, indicating a statistically significant relationship ($P < 0.05$) and a strong negative correlation ($r = -0.992$) between the flexural strength and the weight fraction of fibres in the composite. The regression model derived from this analysis is presented in Eq. (12):

$$\text{Flexural strength} = 40.34 + 0.3580 * \text{Weight fraction}(\%) \quad (12)$$

(iii) Compression strength

The results (Figure 7) indicate that the composite's compression strength increases as the fibre particles' weight fraction rises from 10% to 40%. This improvement is attributed to enhanced adhesion of the fibre particles within the matrix, leading to stronger bonding and more effective stress transfer during compression. This finding aligns with previous studies on the compression strength of wood dust epoxy composites [35]. Furthermore, the regression analysis (Appendix v) showed an R^2 value of 80 and a positive correlation ($r = 0.895$) between the compression strength and the weight fraction of fibres in the composite. The regression model derived from this analysis is presented in Eq. (13).

$$\text{Compression strength} = 40.08 + 0.4299 * \text{Weight fraction}(\%) \quad (13)$$

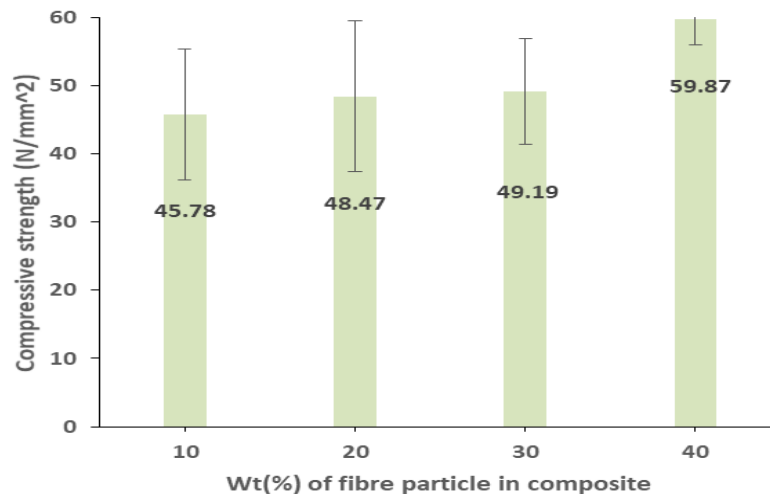


Figure 7. Effect of the weight fraction (%) of the fibre particles on the compression strength of the composite

4. Conclusion

The study's findings indicated that as the weight fraction of the fibre particles in the composite increased from 10% to 40%, the composite's water absorption and compression strength improved. Conversely, the composite's mass density and flexural strength decreased with the same fibre particle weight fraction increase. The impact strength showed some variability; it rose from 10% to 20%, dropped to 30%, and then increased again to 40%. These results were subjected to statistical analysis through regression, which confirmed that the weight fraction of the fibre particles influences the physical and mechanical properties of the *Newbouldia laevis* fibre particle-reinforced polyester composite. Ultimately, the analysis suggested that *Newbouldia laevis* fibre particles could be effective reinforcement materials for lightweight polymer composites, particularly in the automotive and aerospace sectors.

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