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Original Article

Optimization of Mechanical Properties of a Banana/Recycled PET Fibre Composite

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Abstract *- Sustainability and environmental awareness have resulted in natural fibres gaining significant traction in the past few years in composite manufacture. Natural fibres are relatively inexpensive and biodegradable, which makes their disposal easier. There has been high pollution of single-use polyethylene terephthalate plastic bottles. The study's main objective is to optimize the mechanical properties of recycled polyethylene terephthalate and banana fibre hybrid composite. Banana fibres were extracted using a combination of water retting and mechanical decortication. Thereafter, the extracted banana fibres were treated with sodium hydroxide solution and then characterized. During characterization, it was found that banana fibres had a moisture content of 10%, a fibre diameter of 166 µm and an average tensile strength of 58 MPa. Using hand layup, a hybrid composite with the banana fibres and the recycled polyethylene terephthalate fibres was used fabricated the hybrid composite with polyester as the resin. The mass fraction of the banana fibre was increased from 0-10%, and that of recycled polyethylene terephthalate was increased from 0-15%. The hybrid composite was fabricated using the hand layup method. The density of the composite ranged from 480 to 1025 kgm-3, and the tensile strength ranged between 9.01 to 20 MPa, compression strength from 41.7 MPa to 152.8 MPa and flexural strength from 5.6 MPa to 48 MPa. Numerical modelling of the composite properties was done using Minitab software to obtain the optimum mechanical strength properties. Additional tests like flammability and hardness tests can be carried out as a recommendation for further study. Furthermore, characterization using artificial neural networks can be done to improve the prediction of the mechanical properties of the composite.*

Keywords *- Banana fibre, Composite, Numerical modelling, Polyethylene terephthalate.*

1. Introduction

There has been growing concern over using non-environmentally friendly resources in various end uses. The research trend has shifted to finding alternative materials that are sustainable and have a low carbon footprint [1] [1].

Natural fibres are a renewable resource that is relatively inexpensive [2][2]. There has been a growing trend in using natural fibres in composites due to their inherent properties, including low density and cost, sustainability and being biodegradable. Furthermore, natural fibres can be used as a substitute for synthetic fibres in several applications [3][3].

Using natural fibres has gained traction within the composite engineering field [4-7] [4, 5, 6, 7]. Research has focused on evaluating the effectiveness of using natural bast fibres in composite materials over the last two decades.

Natural fibres have gained importance in being biodegradable and having sufficient mechanical properties [8]. Natural fibres and their composites are environmentally friendly as they are derived from natural sources.

The most used natural fibres include jute, sisal and coir; these are used extensively in engineering applications as substitutes for glass fibres and carbon fibres in applications where high mechanical properties are not required [9, 10][9, 10]. Glass fibres and carbon fibres are quite expensive to manufacture, taking into consideration the energy used, and equipment. Besides the cost, the carbon footprint that glass fibres leave during their production is significant [11] [11].

The natural fibre composites' ultimate mechanical properties largely depend on the various fibre properties, which include fibre volume fraction, aspect ratio, fibre-matrix interfacial bond strength, stress transfer at the interface, and orientation of the fibres.

Several studies determine the ultimate mechanical properties of the composite as a function of fibre volume fraction, fibre treatments, and the use of any additives [12][12]. The resin and fibre properties are key components that affect the ultimate composite mechanical properties. The composite material's properties vary with resin and reinforcement compositions per the rule of mixtures [13] [13].

Polyethylene Terephthalate (PET) is a plastic material that is largely used in packaging and in making bottles of single use because of its various desirable properties [14][14]. These include its lightweight, high strength, durability, high chemical resistance and good barrier properties (for both gas and moisture).

However, after use in packaging, the PET items find themselves in landfills. The PET does not easily degrade and takes around 300 to 450 years to decompose naturally [15][15]. Hence, it remains as waste, which leads to environmental issues.

This creates a gap and raises the need to find ways to reuse or recycle PET waste material effectively. Using recycled PET (rPET) minimizes environmental issues such as greenhouse effects and addresses the issue of excessive PET within landfills [16][16]. There has been some research into incorporating rPET into composite materials, and it has been shown to improve the mechanical properties of composites [17][17].

The use of banana fibres in composites has the potential to create value addition to agricultural waste from banana plantations [18-20][18, 19, 20]. When utilized in the manufacturing of hybrid composites, this can help bring income to plantation owners. Furthermore, banana fibres have good mechanical properties and serve as effective reinforcement in natural fibre composites [21][21].

This study seeks to carry out numerical modelling on hybrid banana fibre/rPET fibre composite to ascertain suitability for various applications.

The research includes fabricating a hybrid composite according to the full factorial experimental design and, thereafter, driving empirical models to optimize the properties of the composite. Using this composite in various applications encourages sustainability in line with Sustainable Development Goal 12. Furthermore, the alternative use of PET plastic in the composites reduces the problems of pollution.

2. Materials and Methodology

2.1. Extraction and Characterization of Banana Fibres

Banana fibres used in the study were subjected to water retting and then extracted through mechanical decortication. Thereafter, the banana fibres were treated with a 5% NaOH alkaline solution.

2.1.1 Scanning Electron Microscope Analysis Test

Morphology of the banana fibres was characterized by using a Scanning Electron Microscope (SEM). Figure 1 shows the image obtained, which shows the fibres' morphology, lateral features, roughness, and topography.

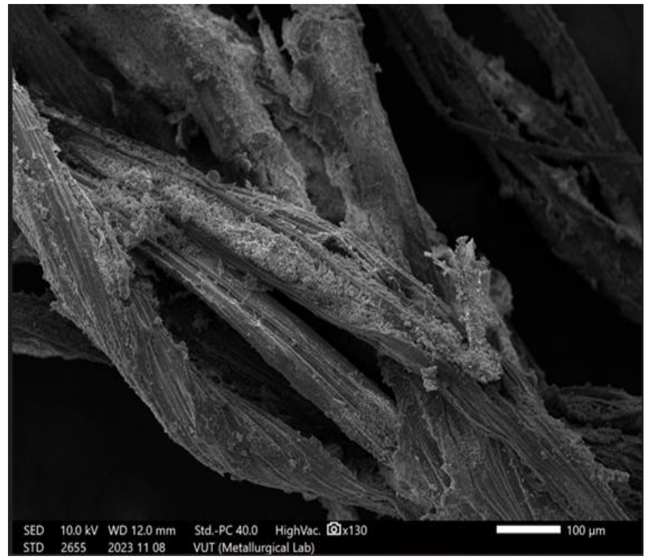

Fig. 1 Treated banana fibre SEM analysis

2.1.2. Fibre Diameter

The fibre diameter was established per ASTM D2130-90 through a Leica DM/LS optical microscope. The average diameter of the fibres was calculated and found to be 166 ± 0.1 μm. The top of the fibre had a diameter of 164.2µm, while the middle section had a low diameter of 166.1 µm. The diameter of the untreated was found to range from 250 µm.

2.1.3. Fibre Tensile Strength

The tensile strength test was done in accordance with ASTM D3822 on a Universal Tensile Strength (UTM). The fibre tensile strength was recorded to be 58.5 MPa.

2.2. Recycled Polyethylene Terephthalate Fibres

The recycled Polyethylene Terephthalate fibres (rPET) had the properties indicated in Table 1.

Table 1. Showing properties of rPET fibres

Properties	Value
Length (mm)	3
Diameter range (µm)	20 – 30
Tensile strength (MPa)	11.20 -25
Young modulus (GPa)	1.02 - 3.10
Elongation at break (%)	5.00 -7.05

2.3. Polyester Resin

A general polyester resin NCS 901 with the properties indicated in Table 2 was used. The properties of the polyester resin were taken as the control properties.

2.4. Experimental Design

The hybrid composite in this study was developed using the hand layup method. Table 3 shows the experimental design followed in the study.

Table 2. Properties of general polyester resin

Properties	Value
Density g/cm^3	1.2
Young modulus (GPa)	3.1
Tensile strength (MPa)	57.0
Compression strength (MPa)	100.0
Elongation at break (%)	4.0
Water absorption (%)	0.1
Izod impact strength	2.5

Table 3. Full factorial experimental design

Sample Number	Banana fibre Volume fraction (%)	rPET fibres Volume fraction (%)
1	0	0
2	5.0	0
3	10.0	0
4	0.	7.5
5	5.0	7.5
6	10.0	7.5
7	0	15.0
8	5.0	15.0
9	10.0	15.0

2.5. Characterization of Composite

The developed composite samples were then characterized to ascertain their tensile, compression, flexural strength and moisture absorption.

2.5.1. Tensile Strength Test

The tensile test followed the ASTM D3039M standard. A Testometric Micro 500 model universal testing machine was used.

2.5.2. Flexural Strength Tests

The flexural strength tests were done according to ASTM D7264. This was done on a three-point flexural fixture. The span-to-thickness ratio was kept at 32:1, and a speed of 0.20 kN/sec was used.

2.5.3. Compression Test

The compressive strength test was done following ASTM D695 standard. The composite samples were loaded at a rate of 180 kN/min.

2.6. Numerical Modelling

Modelling for optimization of composite properties was done using Minitab software. The experimental results obtained were fed into the developed model and optimized. Optimization included setting the model to the maximum of all the measured mechanical properties to obtain a composite with superior properties.

2.7. Validation of Model

The developed model was validated experimentally to ascertain the predicted response's deviation level compared to the model outputs.

3. Results and Discussion

Table 4 displays the results of the mechanical properties from the various fibre mass fractions fabricated. Thereafter, numerical modelling of the composite properties was done.

Table 4. Response analysis of the composite

Fibre fraction mass	Fibre Mass fraction total	Tensile strength	Flexural strength	Compressional strength	Water absorption	Density
%	%	MPa	MPa	MPa	%	Kg/m^3
5% BF	5	13.14	37.5	140.30	4.34	820
10% BF	7.5	12.16	25	152.80	4.57	840
7.5% RPET	10	9.01	15.75	41.70	1.59	480
15% RPET	15	11.08	33.3	83.40	1.99	485
5%BF,7.5%rPET	12.5	11.82	48.75	130.90	3.1	525
5%BF,15%rPET	20	12.27	23.3	18.00	3.61	620
10% BF,7.5%rPET	17.5	14.87	12.5	100.93	3.26	1025
10%BF,15%rPET	25	20.00	5.625	72.24	4.74	925

BF: Banana fibre, rPET: Recycled Polyethylene Terephthalate

3.1. Tensile Strength

The composite tensile strength analysis is shown in Table 5. Analysis of Table 5 indicates statistical significance for the linear terms for B (Banana fibre), as the t-test indicated a p-value of 0.573. However, the linear terms for A (rPET fibre) were statistically insignificant, with a p-value of 0.298. The linear interaction between A and B was statistically significant, with a p-value > 0.5. The 2-way interaction that existed between A and B was considered statistically significant as it had a p-value of 0.922. The 2-way interaction that existed between A and B was considered statistically significant as it had a p-value of 0.186. This model for the composite tensile strength is statistically significant when considered at a 0.95 confidence level, as it gave an F-value of

4.22 and a p-value of 0.203. The regression Equation (1) was derived for tensile strength, giving a high R^2 index of 0.9134.

$$\text{Composite Tensile Strength} = 15.49 - 0.1212A - 0.143\,B + 0.000593A^2 + 0.00178\,B^2 + 0.001916\,AB \quad (1)$$

Table 5. Tensile strength ANOVA table

Attribute	DF	Adjusted SS	Adjusted MS	F Value	P Value	Comment
Model	5	68.268	13.654	4.22	0.203	S = 1.79868
Linear	2	6.411	3.206	0.99	0.502	R^2 = 91.34%
A	1	6.288	6.288	1.94	0.298	Adj. R^2 = 69.70%
B	1	1.441	1.441	0.45	0.573	Pred R^2 = 0.00
Square	2	6.277	3.139	0.97	0.508	
AA	1	5.485	5.485	1.70	0.323	
BB	1	1.926	1.926	0.60	0.521	
2-Way Interaction		12.704	12.704	3.93	0.186	
AB	1	12.704	12.704	3.93	0.186	
Error	2	6.470	3.235			
Total	7	74.739				

A = rPET Fibre Mass Fraction (%); B = Banana Fibre Mass Fraction (%)

3.2. Flexural Strength

Analysis of Table 6 shows statistical significance for the linear terms for both A and B with individual p-values of 0.624 and 0.239, respectively. There was a statistically significant linear interaction between the two factors AB with a p-value > 0.05. This model for flexural strength is statistically significant when considered at a 0.95 confidence level, as it gave an F-value of 1.37 and a p-value of 0.473. The regression Equation (2) was derived for flexural strength with an R^2 value of 0.7737.

$$\text{Composite Flexural Strength} = -4.8 + 0.353\,A + 2.31\,B - 0.00111\,A^2 - \quad - 0.0317\,B^2 - 0.00790\,AB \quad (2)$$

Table 6. Flexural strength ANOVA table

Attribute	DF	Adj Adjusted SS	Adjusted MS	F Value	P Value	Comment
Model	5	1090.13	218.03	1.37	0.473	S = 12.6252
Linear	2	480.66	240.33	1.51	0.399	R^2 = 77.37%
A	1	52.57	52.57	0.33	0.624	Adj. R^2 =20.81%
B	1	439.66	439.66	2.76	0.239	Pred R^2 = 0.00
Square	2	610.03	305.02	1.91	0.343	
AA	1	19.13	19.13	0.12	0.762	
BB	1	608.74	608.74	3.82	0.190	
2-Way Interaction	1	216.03	216.03	1.36	0.364	
AB		216.03	216.03	1.36	0.364	
Error	2	318.79	159.39			
Total	7	1408.92				

A = rPET Fibre Mass Fraction (%); B = Banana Fibre Mass Fraction (%)

3.3. Compressive Strength

Table 7 indicates statistical significance for A and B linear terms. The linear interaction between the two factors AB was statistically significant with a p-value of 0.815.

This model for the compressive strength is statistically significant when considered at a 0.95 confidence level, as it gave an F-value of 0.82 and a p-value of 0.630.

The regression Equation (3) was derived for flexural strength with an R^2 value of 0.6721.

$$\text{Composite Compressional Strength} = 73 - 0.19\,A + 2.41\,B + 0.0001\,A^2 - 0.0118\,B^2 - 0.0144\,AB \quad (3)$$

3.4. Water Absorption

Table 8 indicates statistical significance for linear terms A and B according to the t-test.

The linear interaction between the two factors AB was statistically significant with a p-value of 0.020. This model for water absorption is statistically significant when considered at a 0.95 confidence level, as it gave an F-value of 41.06 and a p-value of 0.024.

The regression Equation (4) was derived for water absorption with an R^2 value of 0.9903.

$$\text{Composite Water Absorption} = 3.695 - 0.06153\,A + 0.0558\,B + 0.000362\,A^2 - 0.000646\,B^2 - 0.000304AB \quad (4)$$

Table 7. Compressive strength ANOVA table

Attribute	DF	Adjusted SS	Adjusted MS	F Value	P Value	Comment
Model	5	10814.6	2162.93	0.82	0.630	S = 51.3618
Linear	2	1195.8	597.88	0.23	0.815	R^2 = 67.21
A	1	39.4	39.43	0.01	0.914	Adj. R^2 =0.00
B	1	561.2	561.24	0.21	0.690	Pred R^2 =0.00
Square	2	91.8	45.88	0.02	0.983	
AA	1	0.3	0.33	0.00	0.992	
BB	1	84.5	84.54	0.03	0.874	
2-Way Interaction	1	715.2	71518	0.27	0.654	
AB	1	715.2	715.18	0.27	0.654	
Error	2	5276.1	2638.03			
Total	7	16090.7				

A = rPET Fibre Mass Fraction (%); B = Banana Fibre Mass Fraction (%)

Table 8. Water absorption ANOVA table

Attribute	DF	Adjusted SS	Adjusted MS	F Value	P Value	Comment
Model	5	9.37465	1.87493	41.05	0.024	S = 0.213720
Linear	2	4.57416	2.28708	50.07	0.020	R^2 = 99.03%
A	1	1.77482	1.77482	38.86	0.025	Adj. R^2 =96.62%
B	1	0.31353	0.31353	6.86	0.120	Pred R^2 =81.84%
Square	2	2.75367	1.37683	30.14	0.032	
AA	1	2.04446	2.0446	44.76	0.022	
BB	1	0.25335	0.25335	5.55	0.143	
2-Way Interaction	1	0.31929	0.31929	6.99	0.118	
AB		0.31929	0.31929	6.99	0.188	
Error	2	0.09135	0.04568			
Total	7	9.46600				

A = rPET Fibre Mass Fraction (%); B = Banana Fibre Mass Fraction (%)

3.5. Validation of Developed Model

The model's validity was checked using experimental data and compared to the numerical model's output.

This model suits hybrid banana fibre, rPET and polyester resin composite.

4. Conclusion

This research made use of a full factorial experimental design to develop composite samples. Thereafter, regression models were derived to optimize the composite properties.

The developed optimization model was validated. There was an expected increase in the tensile strength of the composite with the progressive addition of banana fibre mass fraction.

The compression strength was found to range from 41.70 MPa to 152.80 MPa, with the maximum compression strength being found when the combination of fibres is 5% BF and 15% rPET. The flexural strength increased with hybridization, but it declined with an increase in the fibre mass fraction of banana fibres, as it moved from 23.31MPa to 5.63 MPa with the rPET kept constant at 15% and the BF varied from 5% to 10%. The response of the composite to moisture was good, with a maximum of 8.9% water gain recorded.

This indicates that the composite can be used in environments where it will be exposed to moisture with minimum water absorption. The fabricated composite can find potential applications in furniture boards and the automotive industry.

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