CHARACTERISATION OF A FIBRE REINFORCED MATERIAL FOR SMALL WIND TURBINE APPLICATIONS

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Abstract - This study assesses a plant-based fibre reinforced composite material for use in manufacturing wind turbine blades. The material is coconut fibre reinforced High Density Polyethylene (HDPE). The coconut fibre is combined with waste HDPE in weight percentage ratios, ranging from 2.4 wt% to 24 wt% of fibre, to produce ten test materials. Tests were performed to determine the tensile, bending, and impact strengths of the material. A water absorption test was also conducted to determine the moisture content of the specimens when exposed for 24 hours. Results established the strengths of the materials tend to increase with increasing coconut fibre content. The specimen with the highest coconut fibre content (24 wt%) registered the highest mechanical properties; a tensile strength of 22.84 MPa, bending strength of 1.9 GPa and impact energy of 0.9 kJ. Water absorption conducted on the formed composite showed that there were small changes in the moisture content of the test specimen when exposed to water over 24 hours. It was concluded based on the comparison of the mechanical properties with results from a previous study that, the material could potentially be used for wind turbine blade fabrication. However further tests are recommended in this direction.

Keywords: coconut fibre, coir, composite materials, wind turbine blades, high density polyethylene,

1. INTRODUCTION

Low and unreliable access to electricity continues to be one of the greatest challenges to social and economic development in Sub-Saharan Africa [1]. In Ghana, national electricity consumption has been on the rise over the years, increasing by almost 150% in the past two decades alone [2, 3]. Despite an increasing national generation capacity over the years, reliable supply of electricity continues to be a challenge. In recent times, wind energy has grown to become one of the major sources of electricity generation, with the rise of modern wind turbines. In view of this, measures such as diversifying the electricity generation mix through the development of alternative energy sources, such as wind energy, have been proposed as a possible solution to the country's electricity challenges.

Wind turbines play an important role in wind energy exploitation, as they are used to convert the kinetic energy of air flow into electrical energy. The rotor blades are relatively the most expensive components on wind turbines, and must be the most reliable [4]. To increase their efficiency, wind turbine rotor blades need to be long, which in turn requires them to be made of high strength, fatigue resistant materials.

Over the years, issues related to environmental impact and sustainability in development have increasingly encouraged the study of composite materials the world over for the production of structural components [5]. With evolving turbine designs, composite materials are increasingly being researched for the manufacturing of wind turbine rotor blades [4, 6]. To meet increasingly stringent environmental standards, natural fibre reinforced polymer composites are emerging as eco-friendly competitors to traditional composite materials [7-11]. And plant-based natural fibres such as coconut fibre (coir) has been found to be good alternatives to synthetic fibre reinforced polymer matrix composites due to their biodegradable nature [10].

Though plant-based fibre reinforced composites have been studied quite extensively the world over, such studies are few and far between in Ghana, and have often been limited to applications other than wind turbine manufacturing such as. For instance, the use of Coconut fibre reinforced Low Density Polyethene (LDPE), for the manufacture of everyday materials such as ceilings, partition boards and automobile interiors has been explored in a past study [12]. And in a more recent study [6], another plant-based composite; bamboo fibre reinforced High Density Polyethene (HDPE), was found to be potentially suitable for wind turbine blade fabrication. However, it has been suggested that bamboo fibre reinforced plastics plastic cannot control solidification in the molten stage and have relatively low mechanical properties [8], thereby necessitating the exploring of alternative fibre materials to use for reinforcing plastics.

The 2019 Ghana Renewable Energy Masterplan [13], which aims to increase the proportion of renewable energy in Ghana's national energy generation mix, identified the need for local research to aid in the promotion and development of Ghana's wind energy sector. Recent efforts in this direction have included resource assessment related research [14, 15], development of a composite material for wind turbine blades fabrication [16], and fabrication and testing of turbine blades with a local plant-based fibre reinforced composite material [6]. Therefore, this study will be a step in the right direction towards such efforts.

Against this background, this work explores the development and evaluation of the performance of a composite material using coconut fibre and recycled plastics for the manufacturing of low-cost wind turbine blades.

2. MATERIALS AND METHODS

2.1 Materials for the composite material.

The composite material tested in this study is a plant-based fibre reinforced composite made from waste High Density Polyethylene (HDPE) and green coconut fibre. Some properties of waste HDPE, are presented and Table 1. Coconut fibre falls in the category of hard fibre due to its high flexural rigidity (1100 N.mm^2) [16] and large diameter (320 µm –795 µm)). It possesses highly variable fibre length (183 mm – 305 mm)), with a tensile strength of 26±0.26 MPa. Properties from recycled HDPE in Ghana from previous studies [16, 17] are presented in Table 1.

Table 1 - Properties of the HDPE plastic used [16, 17]

Material	Young's Modulus (GPa)	Ultimate Tensile Strength (MPa)	Percentage Elongation (%)
Recycled HDPE	0.0662±0.1	16.80±0.30	322.68±33.4

Fifty pieces of coconut husk, such as shown in Fig. 1 were harvested from a coconut tree and the fibres peeled off from the shell. The fibres were then cut into 5 cm length strips such as shown in Fig. 2. The extracted fibres were sun-dried for 24 hours to remove moisture content. The fibre was then immersed in a solution of 30 litres distilled water and 300 ml hydrochloric acid (HCL) for 12 hours to soften the fibre and improve its ability to mix with plastic on molten period, after which they washed as shown in Fig. 2.2, with Sodium Hydroxide solution to reduce the fibre moisture content and remove excess dirt.

Fig. 1 - Harvested Coconut husks

Fig. 2 - Fibre strips being washed after soaking in water-HCL solution

The waste HDPE was collected from a selected refuse site. The collected plastic was washed and cleaned with water. The HDPE was then cut into pieces as shown in Fig. 3 and washed with distilled water to enhance melting.

Fig. 3 - Waste high density polystyrene (HDPE) in pieces

2.2 Preparation of the composite material

The composite material preparation procedure incorporated lessons from previous studies [18, 19]. Each specimen was created from varying fibre-HDPE mass ratios as specified in Table 2. To prepare a specimen the specified mass of HDPE (as shown in Table 2) was melted. A paper was placed within a prefabricated aluminium mould of dimension 100 mm x 10 mm x 5 mm, after which the corresponding weight of coconut fibre was spread in the mould. About 30% of molten HDPE was poured into the mould in different patterns and mixed with the coconut fibre until a uniform mixture was obtained. This was allowed to cool, after which the rest of the molten HDPE was then poured into the mould on horizontally arranged fibre. The material was then cold-pressed to remove any porosity or air bubbles by covering the mould and a dead weight of 15 kg, placed on the mould cover. The obtained materials were then finished up for testing. Some of the specimens are shown in Fig. 4, Fig 5and Fig. 6.

Table 2 - Masses of fibre and HDPE for the preparation of test specimen.

Specimen	Mass of Fibre (g)	wt% of Fibre	Mass of HDPE (g)	wt% of HDPE	Total Mass (g)
I	1.2	2.4	48.8	97.6	50
II	2.4	4.8	47.6	95.2	50
III	3.6	7.2	46.4	92.8	50
IV	4.8	9.6	45.2	90.4	50
V	6.0	12.0	44.0	88.0	50
VI	7.2	14.4	42.8	85.6	50
VII	8.4	16.8	41.6	83.2	50
VIII	9.6	19.2	40.4	80.8	50
IX	10.8	21.6	39.2	78.4	50
X	12.0	24.0	38.0	76.0	50

Fig. 4 - Specimen (before finishiing) for Bending Test

Fig 5 - Specimen (before finishing) for Tensile Test

Fig. 6 - Finished speciment for Bending Test

2.4 Tests for properties of the prepared test specimen.

Three mechanical tests were performed to determine the properties of the coconut reinforced HDPE material, and how these properties vary with varying fibre-HDPE ratios. These are the Tensile, Impact, bending tests. A moisture content of 10% or more has been reported to negatively impact the tensile properties of plant fibre reinforced composites [19]. For this reason, a water absorption test was also conducted.

2.4.1 Tensile test.

Five samples for each of the ten specimens were prepared for the tensile test experiment. Some of the finished test specimen are shown in Fig. 6. The tests were performed on a Universal Tensile Testing machine shown in Figure 7. After ensuring that each sample had been gripped and accommodated firmly in the two vices attached to the machine, the sample was strained to an extension of 1.27 mm and the corresponding force determined by a balance system attached to the machine. The extension and its corresponding force were then recorded. The specimen was given successive further extensions of 1.27 mm each time and the corresponding force recorded until the material failed. This procedure was carried out for all fifty samples and the results were recorded. The plot of the stress versus strain was used to obtain the modulus of elasticity (E), the yield and the ultimate strength.

Fig. 7 - Specimen in the Universal Tensile Test machine

2.4.2 Bending Test

Three-point bending tests were performed to determine modulus of rupture (MOR), modulus of elasticity (MOE) and toughness. A span of 100 mm and a deflection rate of 5 mm/min were used for all tests using a Proti Universal Testing Machine. Different specimen types were tested with 6 samples per specimen. Load–displacement plots were obtained for the test sample for the five samples of each type of specimen tested.

2.4.3 Impact Test

Five samples with dimensions 10 mm by 10 mm by 55 mm were prepared for each of the ten specimens for the impact test. The test was performed on the HSM55

Pendulum Impact Tester, shown in Fig. 8. A v-notch was made in the middle of all the samples. The pendulum was moved to its lock position. Each sample was clamped into the jig with the notch facing towards the direction of the pendulum. The pendulum was released using the two-hand release mechanism**.** The impact energy obtained was recorded. The procedure was repeated for the remaining samples and their respective impact energies recorded.

Fig. 8 - HSM55 Pendulum Impact Tester

2.4.4 Water absorption test.

Water absorption test was conducted on the formed composite to determine whether the composite would perform well in a humid environment. Ten rectangular specimens (five samples each) of dimension 80 mm x 60 mm and thickness 8 mm were prepared for this test. Five samples prepared from each specimen were dried in an oven for 24 hours at a temperature of 114^{o}C. After 24 hours, the specimens were removed from the oven and allowed to cool at room temperature. After weighing and recording of their initial masses, the specimens were then immersed in water for 24 hours at room temperature. The masses of the specimen after removal from the water were then determined. Water absorption was expressed as a percentage of increase in weight. Mathematically percentage water absorbed is given as;

$$\%Water\ Absorption = \frac{Wet\ Weight}{Dry\ Weight} \times 100\% \quad (1)$$

3. RESULTS AND DISCUSSION

3.1 Tensile Properties

Fig. 9 shows the results of the tensile test experiments. Tensile load and deflections representing stress and strain values respectively, are plotted for the composite Specimen I. The tensile load was directly proportional to the deflection, satisfying Hooke's Law. The composite matrix yield strength was about 2.1 MPa. There was a slight decrease in the load after yield strength that was obtained before increasing continuously to achieve an ultimate tensile strength value of 4.2 MPa, beyond which the material was no longer capable of withstanding any additional load.

The test results of yield strength, ultimate tensile strength and modulus of elasticity obtained for all the specimen samples, based on variations in fibre content are shown in Fig. 10. It can be seen that sample X, recorded the highest value of ultimate tensile strength as compared to the other specimens due to the increasing amount of coconut fibre content. The yield strength values were relatively the same for samples V to VIII because the effect of the fibre content variations on recycled plastic was very small. However, there was a sudden increase in yield strength values for the specimens IX and X since the weight of the recycled plastic decreased. There was an increase in the Modulus of Elasticity as concentration of coconut fibre content increased to about 10%. The specimen with composition of 24 wt% coconut fibre and 76 wt% high density polyethylene (HDP) obtained ultimate tensile strength, yield strength and Modulus of Elasticity of 45.7 MPa, 22.8 MPa and 0.134 GPa, respectively.

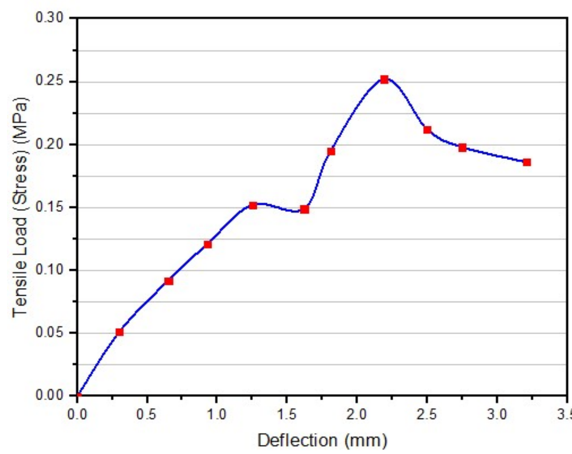

Fig. 9 - Variation of tensile load with deflection

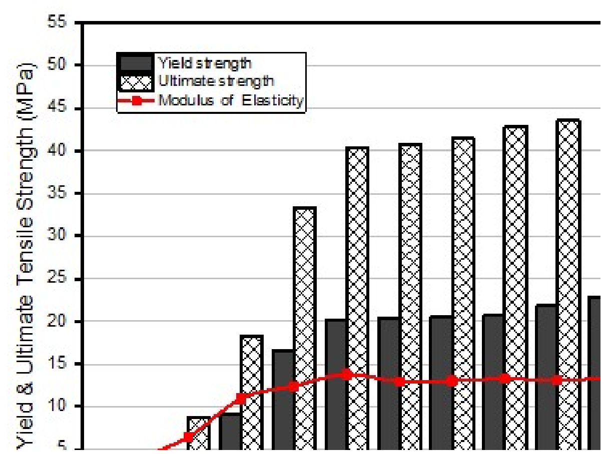

Fig. 10 - Tensile properties with specimen variations

To ascertain the significance of the data obtained for yield strength, ultimate tensile strength and modulus of elasticity, the t-distribution test was used. The standard deviation and mean errors were analysed for each sample specimen after undergoing testing for a repeated five times as shown in Fig. 11. The results of t-values shown in Fig. 12 were determined from the mean and standard error values obtained for each specimen. Using a degree of freedom of 9 for ten samples and confidence level of 95%, with significance value (α) of 0.05, a p-value of less than 0.05 makes the results obtained for yield strength and ultimate tensile strength significant. As indicated in Fig. 10, p-values for all samples with different amounts of coconut fibre content were below 0.05. Thus, all test results for tensile properties of the specimens were significant.

In an assessment of a small wind turbine constructed from bamboo reinforced HDPE, it was found that the equivalent stress of modelled wind turbine was 5 MPa whiles the maximum deformation was approximately 3.4 mm [6]. The results from this study suggest that coconut reinforced HDPE could also be a good material for fabrication of small wind turbines, as the yield stress that was recorded in this study is higher than that of the bamboo reinforced HDPE that was used in that study (22.8 MPa and 5.28 MPa respectively) whiles the deformation levels follow a similar trend (around 2.5 mm and 3.4 mm respectively).

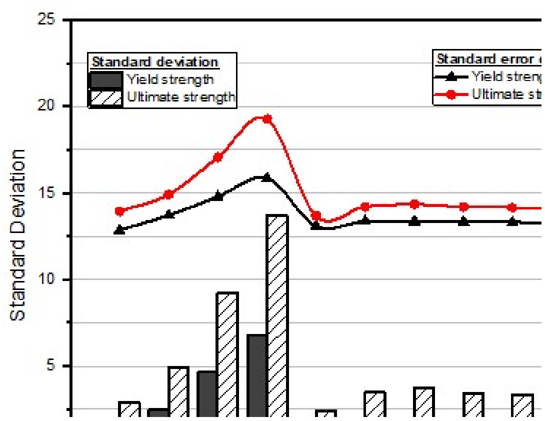

Fig. 11 - Standard deviation and mean error of test samples

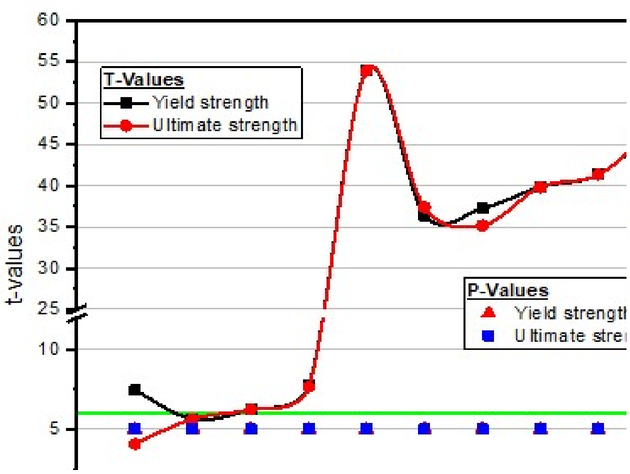

Fig. 12 - t-test analysis of sample specimens

3.2 Bending Properties

Fig. 13 shows the flexural loads and deflections for the specimens. It was observed that flexural loads increased as the fibre content in the composite material increased. Similarly, deflection also showed an increasing trend. This indicates that bending of the composite material strongly depends on the percentage composition of the fibre content in the material. The flexural stress and modulus of elasticity obtained from the slope of load against deflection graph are shown in Fig. 14. Consistent with the findings of a past study [12], it can be seen that values for both bending properties increased as the coconut fibre content in the specimen also increased. However, it is realised that the modulus of elasticity was almost the same for the specimens VIII to X and this implies that composition of fibre content in the recycled plastic has a limit beyond which flexural modulus does not increase when the fibre content increases. The maximum bending moment was 30.63 Nm at specimen VIII where the fibre content was around 16%. Beyond this content of coconut fibre, the bending moment was relatively the same as the fibre content increased for specimens, IX and X.

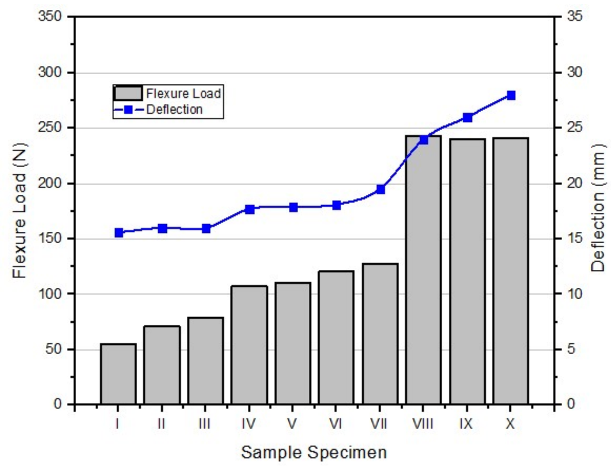

Fig. 13 - Flexure load and deflection of sample specimens

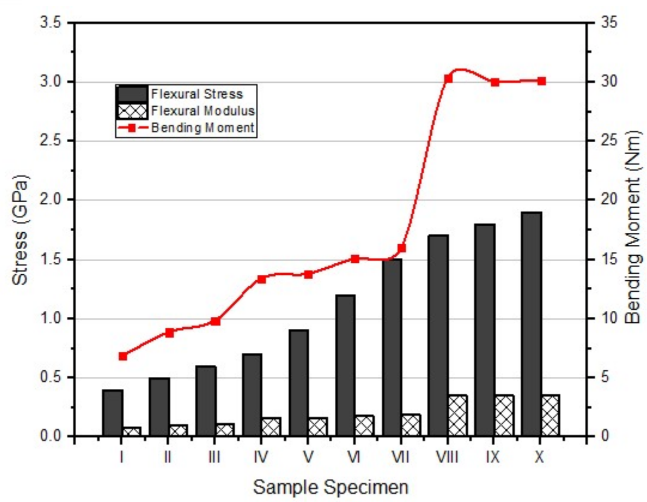

Fig. 14 - Bending properties of sample specimens

3.3 Impact Test Properties

Fig. 15 shows the impact energy and strength of the composite material specimens that were subjected to impact testing. The amount of coconut fibre in the recycled plastic influenced the impact properties. As the percentage composition of fibre content increased, the impact energy and strength of the specimen also increased. The highest impact energy and strength were seen in specimen X, with the maximum composition of fibre content in the recycled plastic which were 900 J and 1.1 MPa, respectively.

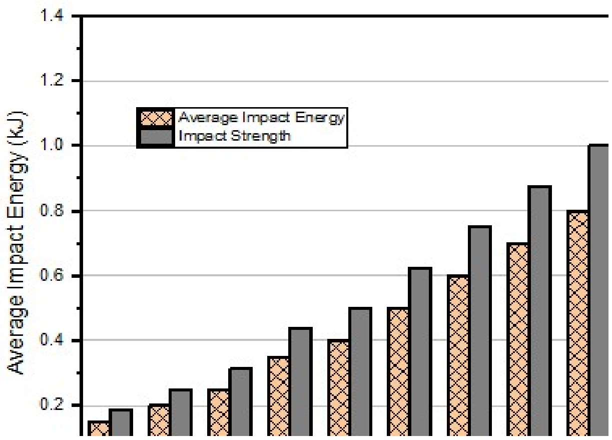

Fig. 15 - Results of Impact tests on samples

3.4 Water Absorption Test

To avoid a lot of moisture content in the composite material, for wind turbine blades to withstand environmental conditions, the amount of water absorbed in the specimens was analyzed. As seen in Fig. 16, for the same initial mass, the amount of water absorbed in each specimen was relatively the same. This indicates that the moisture content in each specimen is independent of the amount of coconut fibre in the composite material. The outcome of the water absorption test showed that the amount of water absorbed after 24 hours of immersion in water is insignificant, about 2.5%, which is less than the 10% that has been found to affect tensile properties of plant-based composites [19]. A similar observation on the moisture content in a previous study [12]. Though they found that moisture content tended to increase with fibre content, it should be noted that their study characterised the Low-Density Polyethylene reinforced with a relatively higher fibre content (up to 50wt%), while this study tested the High-Density polyethylene with much lower fibre content (up to 24wt%). This could be reason for the differences in results.

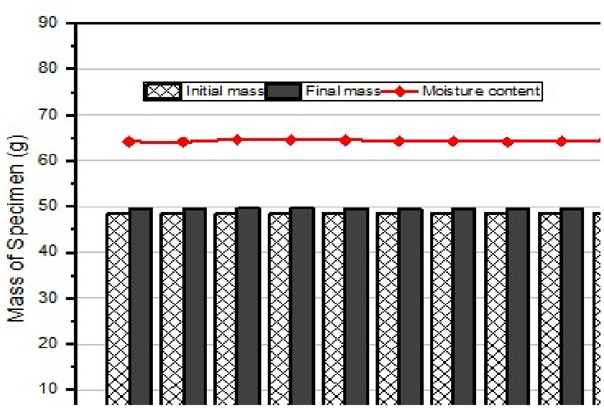

Fig. 16 - Results of water absorption test

4. SUMMARY AND CONCLUSIONS

To meet increasingly stringent environmental standards, natural fibre reinforced polymer composites are emerging as eco-friendly competitors to traditional composite materials in recent times. Characterization of these materials to better understand their properties is key to evaluating their suitability for any application. However, few of such characterization studies have been conducted on coconut husks in Ghana, necessitating this study, which was carried out to characterise waste high density polyethylene reinforced with coconut fibre will be suitable for the production of engineering parts, and more specifically wind turbine blades.

Four tests; Tensile, Impact, Water absorption and bending tests were performed on test specimen with varying wt% content of fibre; from 2.4 to 24 wt%. Consistent with observations of [12], properties generally tend to improve with increasing fibre content. Tensile tests showed that the composite with the highest content of coconut fibre had the highest strength value of 22.84 MPa and bending strength of 1.9 GJ. The results obtained for the impact and bending tests also exhibited similar trends with the flexural and impact strengths increasing with increasing fibre content. The maximum impact strength from the tests was 900J. The outcome of the water absorption test showed that the amount of moisture absorbed after 24 hours of immersion in water is insignificant and also does not depend on the percentage of coconut fibre in the composite.

When compared to results from a study [6] on the small wind turbines the results suggest that the coconut fibre reinforce HDPE composite possess desirable mechanical properties and might be a good alternative for the fabrication of wind turbine blades and for other structural applications. More research in this direction is highly recommended. Additional tests such as number of loading cycles to failure and other tests such as compressive and shear tests are recommended. Some cost analysis will also be useful. Future studies should also focus on determining the effect of controlling the rate of solidification on the mechanical properties of the resulting composite material. Other coconut fibre extraction methods on the mechanical properties of the composite material should also be considered.

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