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Evaluation of Mechanical Properties of Composite Material Produced from Continuous Bamboo Fibre with Carbonized Bone Particles in an Epoxy Matrix

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ABSTRACT

This study investigated the potential use of bamboo fibre and carbonized bone with epoxy as a binder for the production of a new composite material to be used in small scale horizontal axis wind turbine blade production. Modulus of rupture and modulus of elasticity tests were carried out to assess the mechanical strength of the composite. Composites produced using a continuous bamboo fibre – carbonized bone – epoxy composition of 40%, 10% and 50% respectively gave the best results. The optimum values of modulus of rupture, modulus of elasticity, and tensile stress for the composite were obtained as 110.50 MPa, 13130.70 MPa, and 8448.41 MPa respectively. The results of analyses of variance carried out revealed all the model terms were significant indicating that changes in the levels of bamboo, epoxy and bone powder will have a significant influence on the modulus of rupture, modulus of elasticity and tensile stress of the composite material.

1. INTRODUCTION

A major component of the horizontal axis wind turbine is the rotor with the blades. It is the blades that extract the energy from the wind which is then transmitted through the shafts to drive the generator which produces the electricity. Research have been ongoing with the aim to develop optimum materials for the production of wind turbine blades (Mishnaevsky *et al.,* 2017).

Since the 1970s, most blades for horizontal axis wind turbines have been made from composites. The most common composites consist of fiberglass in a polyester resin, but vinyl ester and wood–epoxy laminates have also been used (Mishnaevsky *et al.,* 2017). More recently, carbon fibers have become widely used in blade construction, not necessarily as a replacement for fiberglass, but to augment it (Manwell et al., 2010).

Meng et al. (2018), in their research observed that there had been a steady increase in the use of carbon fibre reinforced polymers (CFRP) across a wide range of aerospace (e.g., Boeing 787 airplane wing structures), automotive (e.g., BMW i3 body panels), energy (e.g., wind turbine blades), and sporting applications (e.g., fishing rods, bicycles). This is because CFRP contributes to significant weight reduction of the product while providing excellent performance. In the past 10 years, the annual global demand for carbon fibre (CF) has increased from approximately 16,000 to 72,000 tonnes and is forecast to rise to 140,000 tonnes by 2020. (CES EDU Park 2014). Production of carbon fibre requires the burning of high energy fossil fuels that also create considerable amounts of pollution. The primary energy of production of carbon fibres is 380-420 MJ/kg and this production results in 23.9-26.4 kg/kg of CO_2 emissions (CES EDU Park 2014)

Gutu, (2013), observed that natural fibre reinforced polymers are a potential environmentally friendly alternative for carbon fibre reinforced polymers or glass fibre reinforced polymers and could replace these types of composites in some current applications. Furthermore, Bamboo has been found to possess tensile and compressive strengths stronger than several types of wood and close to the strength of steel. Using this material keeps the high mechanical strength while serving as natural resource. This in turn helps in the reduction of energy consumption and pollution creation when building woven composites.

Several researches has been carried out to investigate and ascertain the desirable effects of cow bone as reinforcement particles in composites (Asuke et al., 2012; Adewole and Oladele, 2015). The use of by-products as reinforcement is a modern technology for producing relatively inexpensive materials of high strength from suitable homogeneous matrix bases (Anagbo and Oguoch, 1989). Asuke et al. (2012) studied the effects of uncarbonized (fresh) and carbonized bone particles on the microstructure and properties of polypropylene composites. The results from their study revealed that the addition of carbonized bone particles reinforcement has superior properties than uncarbonized bone particles composite based materials with an increase in the compressive strength, hardness values, tensile strength and flexural strength.

The aim of this study therefore was to develop a material that is both environmentally friendly and possessing the required mechanical properties for deployment in small scale horizontal axis wind turbine blade manufacture.

2. MATERIALS AND METHODS

2.1. Material Collection and Pretreatment

Fresh bamboo was procured from a local wood shop along Benin Lagos Express way, Isihor in Benin City, Nigeria. The culms were thereafter processed into segments by cutting them before each node, and then into strips. The strips were sized to a desired width of range 1.5-2.5 cm in order to ensure the bamboo was semi flat and not curved. The bamboo strips were delignified, by soaking it for approximately 72 hrs in 0.1 M sodium hydroxide solutions. This solution was chosen based on the research by Deshpande et al. (2000), who determined that a very strong NaOH solution and a long soaking time will lead to greater lignin dissolution. The bamboo was then rinsed with distilled water to neutrality, air dried and later heated at 110 ^oC for two hours in an oven until they were dry. Edwards Rolling Machine in the sheet metal lab in the Faculty of Engineering workshop in University of Benin was employed to press and splinter the bamboo. The fibres were obtained from these splintered bamboos manually. The diameter of the fibres ranged from 0.8 mm to 2.3 mm.

Cow bone which was carbonized in a crucible furnace at about 550 ^oC for 45 min, was obtained at an animal feed processing factory along Sapele road in Benin City. The carbonized cow bone was crushed and grounded using a vegetable grinding machine. A sieve analysis was performed on the grounded carbonized bone using a sieve size of 212 μm to obtain a fine particle size distribution.

The epoxy resin and catalyst which served as the matrix binder was obtained under the brand name of Epochem 105 Resin and Epochem 205 epoxy curing agent, from Epoxy Oilserv Nigeria Ltd, located in Port-Harcourt, Rivers State, Nigeria.

2.2. Composite Experimental Sample Formation and Testing

A three-variable simplex-lattice mixture experimental design with three variables serving as mixture components was adopted in this study to plan the experiments for the production of the composite for the wind turbine blade. This design was chosen because it has been established by numerous researchers as the best experimental design for production formulation in the field of engineering (Zen et al., 2015; Abutu et al., 2018). This design is typically used whenever the components form a simplex region (the factor ranges are equal) which was the case in this study. Since the number of points may be equal to just the number needed to estimate the model, the simplex-lattice design was augmented to allow for detection of lack of fit. For this purpose, the overall centroid was added to the check blends (50-50 combinations of the center point and each vertex). Five replications of the design points was done in order to appropriately estimate the lack of fit from the pure error. This took the total number of experimental runs to 15 which was implemented in the Design Expert® software version 7.0.0, (Stat-ease, Inc. Minneapolis, USA). The Design Expert® software was also used to develop the statistical models to relate the input factors to the chosen responses. The factors investigated in this study as well as their respective ranges are shown in Table 1. Equations 1 and 2 show the relationship between the components of the mixture which also represent factors of the design.

Table 1: Coded and actual levels of the factors for the composites for the wind turbine blade formulation

Factors	Unit	Symbols	Variable levels	
			Low level	High level
Bamboo fibre	%	X_1	40	45
Epoxy	%	X_2	45	50
Bone powder	%	X_3	10	15

$$0 \le X_i \le 100 \tag{1}$$

Where $i = 1, 2, 3$

$$X_1 + X_2 + X_3 = 100 \tag{2}$$

These equations show that the components of the mixture formulation are not independent meaning that changes in the levels of one component affect those of the others (Hirata et al., 1992). The continuous bamboo fibre was measured out in weights using a digital electronic scale having accuracy of 0.01 g into a pan in batches according to the experimental design matrix in. The carbonized bone particles were also respectively measured out using the digital scale. Lastly the epoxy resin with the corresponding mixing ratio of the hardener (catalyst) was also measured out by weight using the digital scale according to the experimental design matrix. The epoxy and hardener were prepared according to the manufacturer's specification. Each configuration was homogeneously mixed and put into the preformed wooden mould with dimensions based on ASTM D638 which had been previously rubbed with a petroleum jelly for the purpose of ease of removal of the cured specimens. A pressure of about 80 kN was applied to compress the composite. It was allowed to cure at room temperature for 24 hours before extraction. They were thereafter subjected to mechanical tests – modulus of rupture, modulus of elasticity and tensile stress tests in the University of Benin, Strength of Materials Laboratory.

3. RESULTS AND DISCUSSION

3.1. Analysis of Statistical Models

Statistical analysis of the chosen models was done by fitting the models to the experimental data as obtained from the mixture experimental design. The special cubic model was fitted to the experimental data for modulus of rupture and modulus of elasticity, while the quadratic model was fitted to the experimental data for tensile stress. The process of fitting the appropriate models to the respective experimental data was achieved through multiple regression analysis which culminated in the estimation of the unknown model parameters. Substitution of the estimated model parameters into the respective models resulted in the final models for predicting modulus of rupture, modulus of elasticity, and tensile stress for the composite. The final model equations representing these responses in terms of the input factors, bamboo fibre level (X_1), epoxy level (X_2) and bone powder level (X_3) are presented thus.

$$\begin{aligned}\textit{Modulus of rupture} &= -1067.33X_1 - 887.75X_2 - 6398.41X_3 + 39.99X_1X_2 \\ &\quad + 177.06X_1X_3 + 159.79X_2X_3 - 3.97X_1X_2X_3\end{aligned} \tag{3}$$

$$\begin{aligned}\textit{Modulus of elasticity} &= -3.01\times10^5 X_1 - 2.40\times10^5 X_2 - 1.73\times10^6 X_3 + 11030.56X_1X_2 \\ &\quad + 48281.89X_1X_3 + 42450.86X_2X_3 - 1062.37X_1X_2X_3\end{aligned} \tag{4}$$

$$\begin{aligned}\textit{Tensile stress} &= 6641.41X_1 + 7730.95X_2 - 14974.67X_3 - 229.97X_1X_2 \\ &\quad + 223.03X_1X_3 + 33.48X_2X_3\end{aligned} \tag{5}$$

Equations 3 to 5 were used to predict modulus of rupture, modulus of elasticity, and tensile stress for the composite for the wind turbine blades and the results are shown in Tables 2 – 4. For all the results obtained for all the responses under investigation, it was observed that the model predicted results were very similar to the experimental results. This is an indication of the validity of the statistical models developed to predict the responses.

Table 2: Experimental and RSM predicted results for modulus of rupture

Run	Actual values of factors			Response (MPa)	
	Bamboo (%)	Epoxy (%)	Bone powder (%)	Actual experiment	RSM predicted
1	40.0	45.0	15.0	102.5	103.0
2	45.0	45.0	10.0	81.4	81.9
3	41.7	46.7	11.7	77.2	77.6
4	40.8	45.8	13.3	89.2	88.6
5	40.0	50.0	10.0	110.6	110.5
6	43.3	45.8	10.8	77.5	77.0
7	42.5	47.5	10.0	97.6	97.6
8	42.5	47.5	10.0	97.6	97.6
9	45.0	45.0	10.0	82.2	81.9
10	42.5	45.0	12.5	80.5	80.8
11	40.0	47.5	12.5	111.5	111.5
12	40.0	45.0	15.0	103.5	103.0
13	40.8	48.3	10.8	96.4	96.7
14	42.5	45.0	12.5	80.8	80.8
15	40.0	50.0	10.0	110.6	110.5

Table 3: Experimental and RSM predicted results for modulus of elasticity

Run	Actual values of factors			Response (MPa)	
	Bamboo (%)	Epoxy (%)	Bone powder (%)	Actual experiment	RSM predicted
1	40.0	45.0	15.0	12500	12577
2	45.0	45.0	10.0	11843	11815
3	41.7	46.7	11.7	9822	9916
4	40.8	45.8	13.3	12049	11562
5	40.0	50.0	10.0	13162	13131
6	43.3	45.8	10.8	11978	12121
7	42.5	47.5	10.0	15076	15015
8	42.5	47.5	10.0	15075	15015
9	45.0	45.0	10.0	11844	11815
10	42.5	45.0	12.5	15117	15165
11	40.0	47.5	12.5	12489	12578
12	40.0	45.0	15.0	12502	12577
13	40.8	48.3	10.8	11541	11697
14	42.5	45.0	12.5	15118	15165
15	40.0	50.0	10.0	13162	13131

Table 4: Experimental and RSM predicted results for tensile stress

Run	Actual values of factors			Response (MPa)	
	Bamboo (%)	Epoxy (%)	Bone powder (%)	Actual experiment	RSM predicted
1	40.0	45.0	15.0	5380	5380
2	45.0	45.0	10.0	4974	4977
3	41.7	46.7	11.7	6148	6148
4	40.8	45.8	13.3	6329	6328
5	40.0	50.0	10.0	8447	8448
6	43.3	45.8	10.8	5432	5432
7	42.5	47.5	10.0	4838	4838
8	42.5	47.5	10.0	4838	4838
9	45.0	45.0	10.0	4981	4977
10	42.5	45.0	12.5	6574	6572
11	40.0	47.5	12.5	7123	7123
12	40.0	45.0	15.0	5379	5380
13	40.8	48.3	10.8	6773	6773
14	42.5	45.0	12.5	6570	6572
15	40.0	50.0	10.0	8450	8448

3.2. Analysis of Variance of Models

The statistical significance and fit of the models developed (Equations 3 to 5) was assessed by carrying out analysis of variance (ANOVA) and the results are shown in Tables 5 to 7. Tables 5, 6 and 7 show the ANOVA results for modulus of rupture, modulus of elasticity, and tensile stress for the composite respectively. Model terms are considered to be significant if they have a p value less than 0.05. This is usually interpreted to mean that changes in the values of the factor represented by that model term will have a significant effect on the response under consideration (Beg et al., 2002). Conversely, model terms with p values greater than 0.05 are not considered significant and this means that that factor does not significantly influence the response under consideration. The models developed to predict modulus of rupture, modulus of elasticity, and tensile stress were all significant. This can be seen from the fact that the model p value in all cases was very much less than 0.05 ($p < 0.0001$). This is an indication that the models were useful for predicting their corresponding responses. The lack of fit of the models developed to predict modulus of rupture, modulus of elasticity, and tensile stress was not significant. The level of fit indicates the degree of agreement between the experimental observations and the model predictions (Montgomery, 2005).

Table 5: ANOVA results for model representing modulus of rupture

Source	Sum of squares	Degree of freedom	Mean square	F value	p value
Model	2267.0600	6	377.8400	1684.5500	< 0.0001
Linear mixture	1531.1400	2	765.5700	3413.1700	< 0.0001
X_1X_2	2.7200	1	2.7200	12.1300	0.0083
X_1X_3	181.4900	1	181.4900	809.1500	< 0.0001
X_2X_3	18.2100	1	18.2100	81.2000	< 0.0001
$X_1X_2X_3$	298.7500	1	298.7500	1331.9200	< 0.0001
Residual	1.7900	8	0.2200		
Lack of fit	0.9800	3	0.3300	2.0100	0.2307
Pure error	0.8100	5	0.1600		
Cor. total	2268.8600	14			

Table 6: ANOVA results for model representing modulus of elasticity

Source	Sum of squares	Degree of freedom	Mean square	F value	p value
Model	3.47E07	6	5.79E06	142.57	< 0.0001
Linear mixture	2.63E05	2	1.32E05	3.24	0.0931
X_1X_2	8.68E06	1	8.68E06	213.88	< 0.0001
X_1X_3	1.18E07	1	1.18E07	291.64	< 0.0001
X_2X_3	63181.62	1	63181.62	1.56	0.2475
$X_1X_2X_3$	2.13E07	1	2.13E07	525.38	< 0.0001
Residual	3.25E05	8	40596.23		
Lack of fit	3.25E05	3	1.08E05	2.08E05	0.0601
Pure error	2.60	5	0.52		
Cor. total	3.51E07	14			

Table 7: ANOVA results for model representing tensile stress

Source	Sum of squares	Degree of freedom	Mean square	F value	p value
Model	2.018E07	5	4.037E06	1.068E06	< 0.0001
Linear mixture	1.135E07	2	5.673E06	1.500E06	< 0.0001
X_1X_2	5.278E06	1	5.278E06	1.396E06	< 0.0001
X_1X_3	2.918E06	1	2.918E06	7.716E05	< 0.0001
X_2X_3	46442.53	1	46442.53	12282.69	< 0.0001
Residual	34.0300	9	3.7800		
Lack of fit	2.0700	4	0.5200	0.0810	0.9848
Pure error	31.9600	5	6.3900		
Cor total	2.018E07	14			

The fit of the models for predicting all the responses was further assessed by using goodness of fit parameters such as coefficient of determination (R^2), adjusted coefficient of determination (adjusted R^2), predicted coefficient of determination (predicted R^2), coefficient of variation, standard deviation, adequate precision and the results are shown in Tables 8. The R^2 value was greater than 0.99 for all the models considered. The

R^2 value is used to assess the level of fit between a model and experimental results. As seen from the results presented in Table 8, the models were characterised by high R^2 values indicating very good fit between the experimental observations and model predictions. Another important parameter used to assess the fit of the models was the adjusted R^2 value. For a good fit, there should be an excellent agreement between the R^2 value and the adjusted R^2 value. The value of standard deviation was small compared to the mean of the observations and this shows that there was very little deviation between the individual experimental results compared to the mean value. This is a further confirmation of the very good fit of the model to the experimental results. The coefficient of variation (CV) was small for all the models considered.

Table 8: Goodness of fit statistics for response models

Parameter	Modulus of rupture	Modulus of elasticity	Tensile stress
R^2	0.9992	0.9907	1.0000
Adjusted R^2	0.9986	0.9838	1.0000
Mean	93.2700	12885.2000	6149.0900
Standard deviation	0.4700	201.4900	1.9400
CV	0.5100	1.5600	0.0320
Adeq. Precision	106.6400	38.1300	293.5700

3.3. Model Diagnostics

Diagnosis of the models developed to predict the responses for the composite for the wind turbine blades was also carried out to assess their accuracy and indeed adequacy for the intended purpose.
Figures 1 to 3 show the normal probability plots for the models representing the modulus of rupture, modulus of elasticity, and tensile stress for the composite for the wind turbine blades made from the continuous bamboo fibres. A look at the results obtained for the composite shows that the residuals of the models did follow a normal distribution as seen from the fact that the points clustered around the straight line.

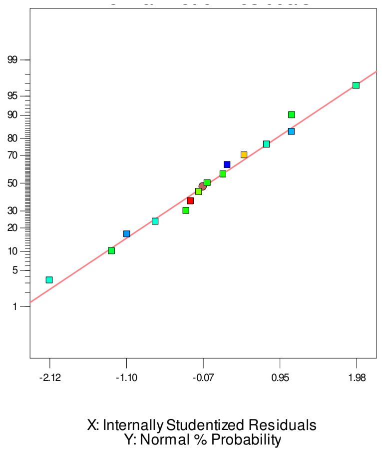

Figure 1: Normal probability plot for model representing modulus of rupture

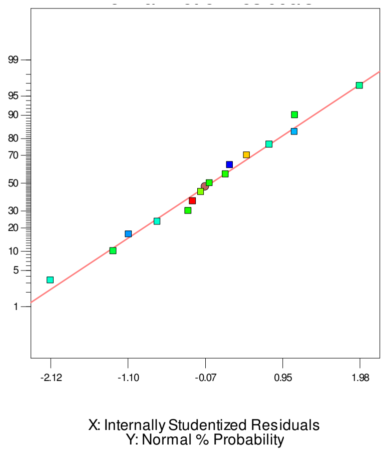

Figure 2: Normal probability plot for model representing modulus of elasticity

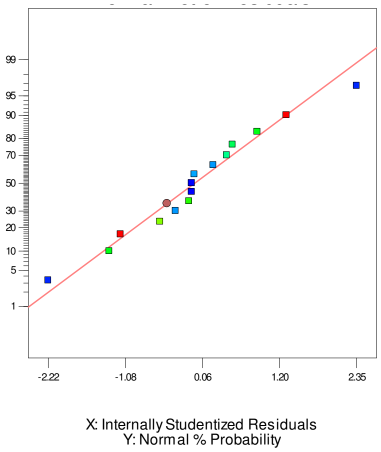

Figure 3: Normal probability plot for model representing tensile stress

3.4. Validation of RSM Model Results

The model results were validated by comparing their values with those obtained from the actual experiments. This was done in the form of parity plots which shows the comparison. Figures 4 to 6 show the parity plots for the models representing the modulus of rupture, modulus of elasticity, and tensile stress for the composite. As shown in Figure 4 to 6, there was significant fit between the experimental results and the model predictions because all the points clustered around the 45^o diagonal line.

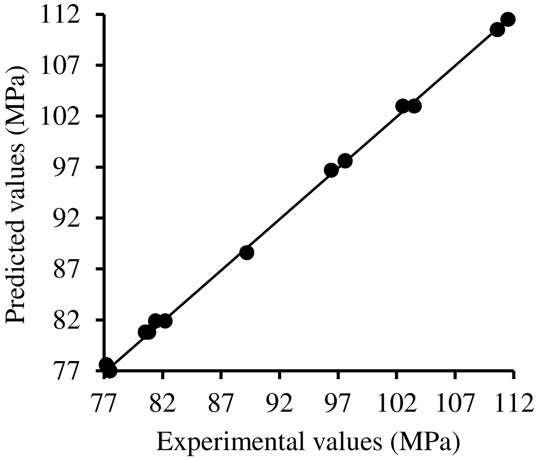

Figure 4: Parity plot for model representing modulus of rupture

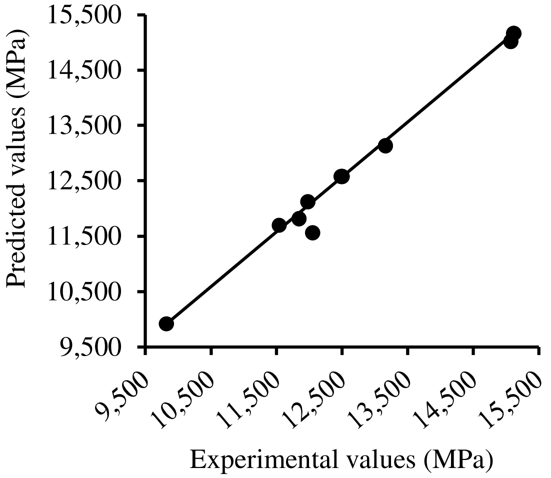

Figure 5: Parity plot for model representing modulus of elasticity

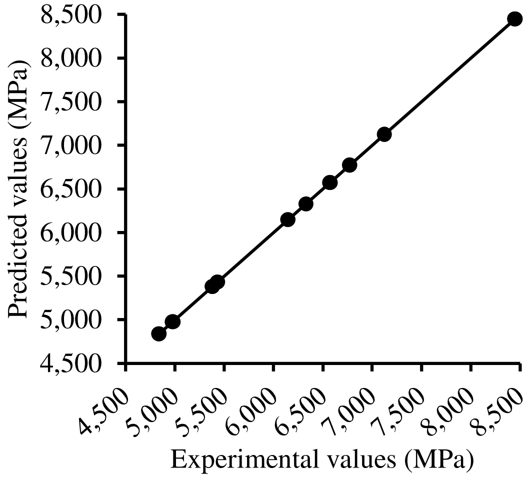

Figure 6: Parity plot for model representing tensile stress

3.5. Optimisation of Input Factors and Responses

The responses and the corresponding input factors were optimised via numerical optimisation. For the responses, modulus of rupture, modulus of elasticity, and tensile stress were all maximised. This is because they needed to be maximised for better productivity. After evaluating the model graphs and the solutions suggested by the numerical optimisation package, the optimum conditions were chosen as the one with the highest desirability value. The optimisation results are shown Table 9. This optimal point was chosen with the highest desirability of 0.968. The optimum values of modulus of rupture, modulus of elasticity, and tensile stress for the composite for the turbine blades produced from the continuous bamboo fibre were obtained as 110.50 MPa, 13130.70 MPa, and 8448.41 MPa respectively. The corresponding values of bamboo, epoxy and bone powder were 40%, 50% and 10% respectively.

Table 9: Optimisation results

Variable	Value
Bamboo	40%
Epoxy	50%
Bone powder	10%
Maximum modulus of rupture	110.50 MPa
Maximum modulus of elasticity	13130.70 MPa
Maximum Tensile stress	8448.41 MPa
Desirability	0.968

4. CONCLUSION

The potential use of bamboo fibre and carbonized bone particles for production of composite material for small scale horizontal axis wind turbine blades using epoxy as a binder was investigated in this study. The following conclusions were drawn:

- A new hybrid composite material produced from continuous bamboo fibre with carbonized cow bone using epoxy as a binder recommended for the production of small scale horizontal axis wind turbine blades has been formulated
- The optimum values of modulus of rupture, modulus of elasticity, and tensile stress for the composite produced from the continuous bamboo fibre were obtained as 110.50 MPa, 13130.70 MPa, and 8448.41

MPa respectively with corresponding values of bamboo, epoxy and bone powder of 40%, 50% and 10% respectively.

- ANOVA results shows that the model terms were significant indicating that changes in the levels of bamboo, epoxy and bone powder will have a significant influence on the mechanical properties of the wind turbine blades produced from the continuous bamboo fibres.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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