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PREDICTION OF COMPRESSION STRENGTH OF BAMBOO REINFORCED LOW-DENSITY POLYETHYLENE WASTE (LDPEw) COMPOSITES

In this work, the compression strength of bamboo reinforced low-density polyethylene waste (water sachet waste) composites was predicted. The composites were produced using the compression moulding technique with the following formulations: LDPEw, 5, 10, 15, and 20 wt.% filler. The hardness and compression strength of the examined composites were found to increase when the amount of filler was raised, with the formulation containing 20 wt.% filler having the highest hardness and compression strength values of 59.37 HV and 12.72 MPa, respectively. The control (LDPEw) gave the lowest values of hardness (41.57 HV) and compression strength (8.6 MPa). Multiple regression (MR) and artificial neural networks (ANN) were utilized to predict the experimental compression strength of the produced composites with the hardness and filler composition as independent variables. The mean squared error results indicated that when compared with the multiple regression forecasts, the artificial neural network predictions not only had smaller errors but were also closer to the experimental compression strength values. It is recommended that other methods of producing composites, such as the pulverization process with a 40% higher filler content than what was used in this work, should be studied to ascertain if they provide better composite materials.

Keywords: **composite, compression strength, carbonized bamboo, low-density polyethylene waste, artificial neural network, multiple regression, hardness**

INTRODUCTION

People litter roadways with water sachets every day in underdeveloped nations like Nigeria. Waste goods such as maize cobs, vegetable debris, and other packaging materials are also generated in the markets. Household trash, on the other hand, may comprise paper, glass, plastic, or metal. Although other materials, such as plastics, do not decompose [1, 3], vegetables, on the other hand, are eco-friendly. Despite being an environmental pollutant and inadvertently blocking drainages after heavy downpours, polymeric materials are still largely found in the environment today. According to Sridhar et al. [4], responsible agencies have done nothing to clean up the littered wastes.

In lieu of the ever-growing and problematic issue with petroleum plastics all over our environment, a new alternative is becoming more widely accepted. This involves the incorporation of fillers into plastics with a view to obtaining a plastic composite, whose constituents act synergistically towards making it longer lasting during usage or processing by improving its durability against environmental factors such as heat fluctuation [5]. Composites are combinations of two or more materials that have been combined to create an integral unit. By optimizing the virtues and minimizing the shortcomings, composites allow designers to make better use of conventional material constraints [6, 7].

The versatility of plant fibres like bamboo makes them a great candidate for use in polymer composite development. Sisal, vakka, bamboo, and banana were all tested to see if they could be used as reinforcement materials to obtain fibre-reinforced polymer composites. It was found that the tensile strength and flexural stiffness of bamboo were three times higher than other plants such as sisal and banana. This means that bamboo would hold up better when put under stress, making it an ideal choice for people looking into new environmentally friendly products, and who want something sustainable even after years without maintenance [8-10]. In essence, bamboo produces an abundance of woody fibres that could be processed into composites [11-17].

The carbonization temperature range employed in this work is similar to that used earlier (250 to 900°C) in [18]. Thermal stability was recorded for bamboo carbonized at high temperatures (900°C) [19], while a rise in hardness and Young's modulus of over

2.1 GPa was observed for a polyethylene composite carbonized at 1100°C [20]. The carbonization of bamboo at 800°C for 60 minutes has been suggested to provide ideal conditions to produce advanced materials [21].

Different researchers have reinforced polymer wastes by means of a variety of methods to increase their viability for other uses. By using wood dust in a natural fibre reinforced polymer composite, Peretomode et al. [22] found that the mechanical qualities of the composite deteriorated significantly up to a 16.7 wt.% wood dust content, beyond which there was no significant change in the overall mechanical properties of the composite. On the other hand, bean pod particles were investigated to see how they affected the characteristics of recycled low-density polyethylene (RLDPE) composites. The composites outperformed the polymer matrix in terms of hardness, flexural, and tensile strength [23]. Porras et al. [24] investigated the chemical composition, morphological structure, thermal, physical, and mechanical characteristics of Manicaria saccifera fabric to ascertain its potential for application as a polymeric composite reinforcement material. The Manicaria fabric remained stable until roughly 220°C, according to the thermal analysis findings. The examined materials had tensile qualities that were comparable to most natural cellulose fibres and were found to contain certain synthetic fabrics like fiberglass fabrics.

Falemara et al. [25] studied the strength and water sorption characteristics of bamboo sawdust and recycled low-density polyethylene plastic composites. They reported that the tensile strength, modulus of elasticity, and modulus of rupture rose as the plastic/fibre mixing ratio and board density increased, but the thickness swelling, and water absorption decreased. Both talc and glass were able to strengthen recycled low-density polyethylene (RLDPE) in weathered and non-weathered circumstances, according to Ilori et al. [26]. The effects of bamboo-leaf carbonization (at various temperatures) were investigated by Pattnaik et al. [18], including the fixed carbon content (almost 21% by proximate analysis). The results demonstrated the existence of numerous phases, such as cristobalite (SiO_2) and calcite (Ca_2O_3), including changes in the crystal structures. In addition, between the randomly spaced lamellae structure, uneven stacking configurations and variations in the carbonizing temperature were also observed. In another development, Kamal et al. [27] used injection moulding to study the impact of varied loadings of bamboo filler reinforced with recycled high-density polyethylene composites. They concluded that adding natural fillers to composites increased the mechanical qualities of the material.

The mechanical and thermal characteristics of clay powder-filled recycled low-density polyethylene were studied in [28]. The findings showed that the mechanical properties increased with the filler clay content. A thermographic study of the rLDPE/clay composite revealed that increasing the filler loading reduced weight loss. Consequently, the thermal stability of the rLDPE composite was enhanced. The use of an artificial neural network (ANN) to forecast the deflection of plain, steel-reinforced, and bamboo-reinforced concrete beams based on experimental data was investigated in [29]. The authors reported that in predicting the deflection behaviour of beams, the ANN technique performed satisfactorily (with a coefficient of determination = 0.9983, and mean square error (MSE) = 0.00049). In a different study [30], regression predictive protocol was used to forecast the relationship between the properties of the examined composites (bamboo fibres/polypropylene non-woven reinforced composites) and the thermal conductivity of non-woven fabrics. In accordance with the results of the regression analysis, the thermal conductivity and shear strength of the reinforced composites rose linearly, reaching the thermal conductivity of non-woven fabrics by linear fitting. It was also established that the regression-based prediction model has enormous potential for use in the automobile sector as technical assistance for developing non-woven textiles and their composites [30].

Numerous scholars have effectively employed ANN to simulate recycled high-density polyethylene (RHDP) composites [31] and PET solid waste as a partial sand substitute [32]. The ANN model was found to be better than response surface methodology (RSM) because of its higher accuracy [32].

In order to forecast the experimental findings, it is possible to compare the dependent variable parameter to the independent designate parameter. To achieve this aim, artificial neural networks and multiple regression may be used. The following are the objectives of this research:

1) to gather litter water sachet wastes [low-density polyethylene wastes (LDPEw)] and bamboo stems;
2) to conduct differential scanning calorimetry and thermogravimetric analyses of the filler (bamboo);
3) to carbonize the bamboo stems in preparation for their reinforcement with the water sachet wastes;
4) to produce bamboo reinforced LDPEw composites;
5) to determine the hardness and compression strength of the produced composites;
6) to predict the compression strength of the composite using ANN and multiple regression modelling protocols.

MATERIALS AND METHODS

Study materials and equipment

The following materials were locally sourced and used for this present study: about four-year-old dry phyllostachys (bamboo stem of the leptomorph (running) rhizome category), which was harvested in 2021 (obtained from Ihiagwa, Owerri-West L. G. A., Imo State, Nigeria), and water sachets or pure water (as popularly known in Nigeria) wastes, which are heat-sealed bags made of plastics. During heavy rainstorms, the accumulation of these water sachets usually blocks water drainage. The samples, used for this study were hand-picked within the vicinity of the Department of Polymer Techology of the Nigerian Institute of Leather and Science Technology (NILEST), Samaru-Zaria, Kaduna State, Nigeria. The water sachets were identified as a low-density polyethylene material because of its density (0.92 g/cm^3) and the fact that the material made a whooshing sound when rubbed between the palms.

The equipment used include a weigh scale (AE 200), a two roll mill (518), a hydraulic hot press (0557), a compressive strength testing machine (3851-0), and a Vickers microhardness tester (MV1-PC).

Carbonization of bamboo stem

The as-received bamboo stems were sun dried for a period of 14 days and cut into small sizes, 3 x 2c x 0.4 cm. The trimmed bamboo sticks were later put into a cylindrical pot and placed at room temperature into a furnace (FUTO bale-out crucible (TETFUND)), where it was heated to about 250°C for 2 hours. After heating, the system was allowed to cool in the cylinder for 24 hours before removing the carbonized material. All the carbonized particles passed through an 80 BSS mesh size.

Production of composites

Mixing of carbonized bamboo powder and low-density polyethylene waste (LDPEw)

According to the formulation as shown in Table 1, the composite samples were produced by a mixing process involving introduction of the low-density polyethylene waste [LDPEw] (water sachet wastes) while the movement of the two rolls of the mill machine were in counter clockwise motion to soften the material for a period of 3 minutes at the temperature of 150°C. The purpose was to mix the water sachet waste in preparation for its blending with the filler (carbonized bamboo stem). Upon achieving a long strip of the water sachet waste on the front roll, the carbonized bamboo powder was manually added to the bank as the rolls rotated at the rate of 50 rpm for 5 mins with cross mixing several times using a cutting knife. The produced composite was cut and labelled accordingly. The procedure was repeated for all the specimens, and the manufactured samples were designated LDPEw, 5 wt.% filler, 10 wt.% filler, 15 wt.% filler, and 20 wt.% filler.

TABLE 1. **Formulation of composite specimens**

Samples	Carbonized bamboo powder [g]	Low-density polyethylene waste (LDPEw) [g]
LDPEw	0	100
5 wt.% filler	5	95
10 wt.% filler	10	90
15 wt.% filler	15	85
20 wt.% filler	20	80

Moulding of composite specimens

The composite obtained from the mixing process was put into different metal moulds of dimensions 100 x 100 x 3 mm and a designed 25 x 25 x 10 mm mould for the plate sample and compressive strength specimens, respectively. The filled moulds were placed on the hydraulic hot press machine for shaping at the temperature of 150°C and pressure of 2.5 MPa for 5 min. It was transferred to a cool platen for cooling under the pressure of 2.5 MPa for 3 mins.

Compression strength test of produced composites

The 25 x 25 x 10 mm specimen was placed in the middle of the specimen holder below the machine crosshead plunger. The crosshead was adjusted until the plunger contacted the specimen. The compressive strength testing machine (Carver Inc.) model no. 3851-0 was used for the test. Force was applied slowly until failure occurred. The peak force/load value at failure displayed on the digital readout gauge was recorded. The procedure was repeated for all the examined specimens. However, the compression strength was calculated using Equation (1):

$$Compression\ Strength = \frac{Load\ at\ Rupture}{Cross\ Sectional\ Area}\ [\text{MPa}] \quad (1)$$

where cross-sectional area of specimen = width x thickness = 25 x 10 mm = 250 mm^2.

Standard test method for rubber property-Vickers hardness

The hardness tests were carried out using the Vickers microhardness tester. The specimen measuring 1 x 2 x 0.3 cm was placed on the mounting stage, and the indenter was lowered until it met the specimen at a uniform pressure. The procedure was repeated three (3) times at different positions on the specimen and readings were recorded for all the tested specimens.

Thermal analyses of filler – differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA)

The thermogravimetric analysis of the bamboo stem (sample weight = 4.727 mg) was performed using a Hi-Res 2950. The DSC and TGA of the filler were conducted using the procedures previously published in [28].

SPSS software

SPSS Statistics is a statistical analysis software program. IBM SPSS Statistics is the official name for the current edition [33]. The neural network and multiple regression are fully incorporated into the SPSS program. IBM SPSS technology is used by commercial, government, and academic organizations all around the world.

Regression with multiple steps

Lærd Statistics [34] defines multiple regression as an extension of simple linear regression. When we seek to forecast the value of a variable based on the values of two or more other variables, we utilize this method. The dependent variable (also known as the outcome, goal, or criteria variable) is the variable we seek to forecast. The independent variables (also known as predictor, explanatory, or regressor variables) are the variables we use to predict the value of the dependent variable. The experimental compression strength is the dependent variable in this study, whereas the hardness and filler makeup of the produced composites are the two independent factors.

The multiple regression formula is written as follows [35, 36]:

$$Z_r = c_o + c_1Q_{1r} + c_2Q_{2r} + \ldots + c_wQ_w \quad (2)$$

In this study, Equation (2) is better expressed as:

$$Z_r = c_o + c_1(\textit{composition of filler}) + c_2(\textit{hardness of composite}) \quad (3)$$

where: Z_r = Z_r predicted value (which is the experimental compression strength of the produced composite).

The 'Z intercept' is denoted by c_o.

For each increment change in Q_{1r}, c_1 equals the change in Z.

For each increment change in Q_{2r}, c_2 equals the change in Z.

Q_{1r} = the Q score for the first independent variable for which you are attempting to predict a Z value.

Q_{2r} = the Q score for the second independent variable for which you are attempting to predict a Z value.

Artificial neural network (ANN)

Artificial neural networks are based on what we now know about organic nerve systems. They are also known as neurocomputing, connectionism, or parallel distributed processing (PDP), and are an alternative to algorithmic and symbolic approaches for problems where they are ineffective [37].

Artificial neural networks were developed as generalizations of mathematical models of human cognition or neural biology, according to [38], based on the assumptions that information processing occurs at many simple elements called neurons in the first instance. Subsequently, signals are passed between neurons over connection links. Consequently, each connection link has a weight that multiplies the signal conveyed in a conventional neural net, and each neuron uses an activation function on its net input to calculate its output signal.

In other words, a neural network is defined by its architecture (the pattern of connections between neurons), its training or learning algorithm (the method of determining the weights of the connections), and its activation function.

The prediction approach is the same as that used before in [39-46]. Figure 1 shows an artificial neural network diagram for predicting the experimental compression strength of the manufactured composite. In this investigation, the experimental compression strength is the dependent variable, while the hardness and filler composition of the produced composite are the two independent variables. Consequently, the hidden layer activation function was a hyperbolic tangent, while the output layer activation function was the "identity".

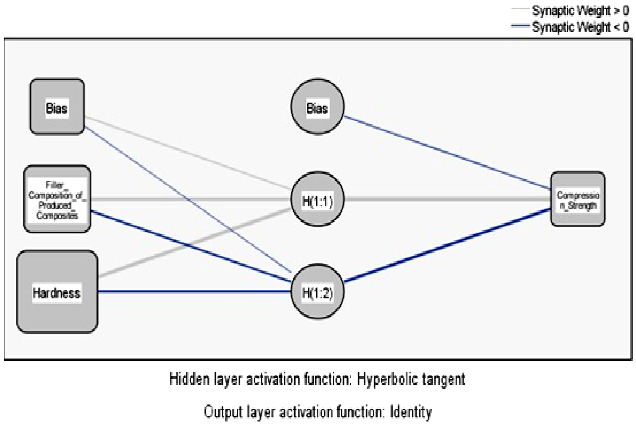

Fig. 1. Diagram of artificial neural network for predicting experimental compression strength of produced composite

Fausett [38] gives the net output, z_r thus:

$$z_r = f(z_{-inr}) \quad (4)$$

$$z_{-inr} = c_r + \sum_k p_k q_{kr} \quad (5)$$

$$f(p) = \frac{1}{1+exp(-p)} \quad (6)$$

where: f stands for the activation function, z_{-inr} = z_r net input, c_r is the unit's bias.

Error in prediction assessment

To determine how near a projected value is to the actual value, the mean squared error (MSE) is utilized. It is expressed mathematically as follows [47]:

$$MSE = \frac{1}{T}\sum(s_t - u_t)^2 \quad (7)$$

where: T = total number of specimens, s_t = predicted experimental value, u_t = experimental value.

RESULTS AND DISCUSSION

Results of TGA DSC of filler

The filler (bamboo stem) was subjected to TGA DSC studies, with the findings reported in Figure 2. The TGA thermogram (Fig. 2a) reveals a gradual loss in weight of the filler following the application of heat. The weight losses recorded at 49.5, 99.4, 149.7, 199.8, 249.8, 299.4, 345.2, and 399.8°C were 5.06, 9.94, 10.58, 10.89, 13.31, 29.98, 66.77, and 95.43%, respectively. In essence, the TGA findings of the filler material demonstrated a near steady drop in weight. Up to 199.8°C, the dehydration phase, during which moisture evaporation from the bamboo fibre occurred, a gradual weight loss of roughly 10.89% was seen. This discovery is consistent with the results in [48]. After the first phase, the second phase of weight loss was observed to be rapid (249.8 to 399.8°C). This stage is best defined as active pyrolysis [48], and it relates to the degradation of the bamboo's cellulose and lignin components. The second phase of weight loss was found to double from 13.31 to 29.98% to 66.7% at 249.8°C, 299.4°C, and 345.2°C, respectively. At 399.8°C, the highest weight loss of 95.43% was observed.

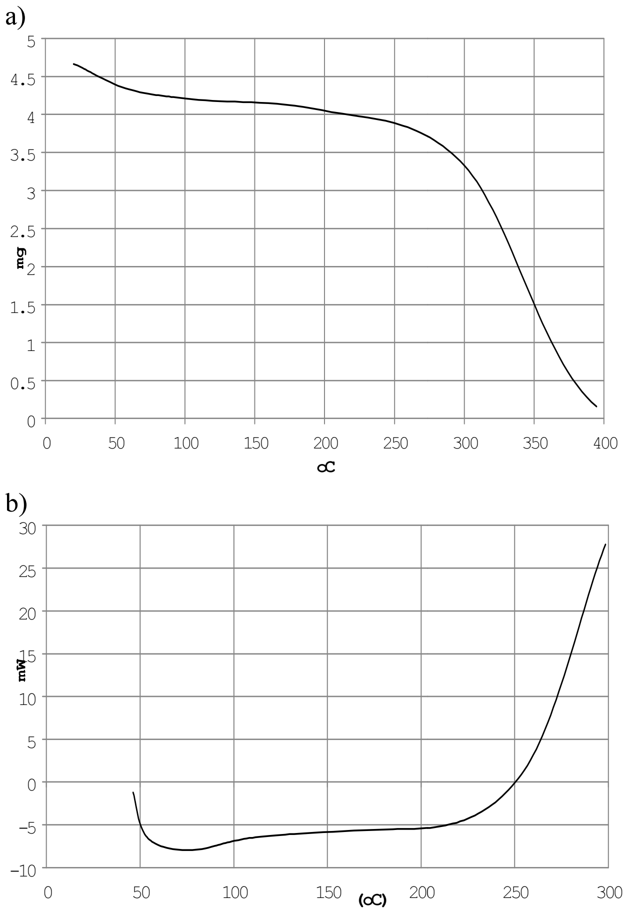

Fig. 2. Results of thermal analyses of filler: a) thermogravimetric analysis, and b) differential scanning calorimetry

Exothermic reactions with enthalpies of –1573.8, –589.58, –725.67, –919.33, –1066.79, and –580.41 J/g were observed at temperatures of 49.5, 71.9, 99.0, 149.7, 199.4, and 236.9°C in the DSC test (Fig. 2b). In this investigation, the exothermic process started at around 50°C, whereas in a recent study [49] an exothermic peak for bamboo fibre of 327.38°C was found. A significant amount of heat was absorbed as the temperature reached 250°C, producing an endothermic reaction of 79.97 J/g at 249.9°C. With an enthalpy of 8223.21 J/g, this reaction peaked at 298.7°C.

Results of hardness, experimental and predicted compression strength of bamboo reinforced LDPEw composites

The results of the hardness, experimental, and predicted compression strength of the bamboo reinforced LDPEw composites are tabulated in Tables 2-5 and are shown in Figures 3-6. When the quantity of filler was increased, the hardness and compression strength of the composite rose, with the formulation of 20 wt.% filler having the highest hardness value of 59.37 HV and compression strength of 12.72 MPa. The trend of this result agrees with an earlier work [50] for compression strength.

TABLE 2. **Results of hardness, experimental and predicted compression strength of bamboo reinforced LDPEw composites**

Examined specimens	Hardness [HV]	Experimental compression strength [MPa]	Prediction of compression strength by ANN		Prediction of compression strength by MR	
			ANN	Error	MR	Error
LDPEw	41.57	8.60	8.5716	0.0284	8.5430	0.0570
5 wt.% filler	50.13	9.07	9.0822	-0.0122	8.9869	0.0831
10 wt.% filler	52.47	10.10	10.0162	0.0838	10.2797	–0.1797
15 wt.% filler	54.77	11.46	11.4421	0.0179	11.5780	–0.1180
20 wt.% filler	59.37	12.72	12.7364	–0.0164	12.5624	0.1576

The control (LDPEw) exhibited the lowest hardness (41.57 HV) and compression strength (8.6 MPa) values as revealed in Figure 3. This observed trend agrees with work [51], which studied the production and characterization of a recycled LDPE/Periwinkle (Turritella communis) shell particulate composite. An increase in hardness as the filler quantity increased was observed.

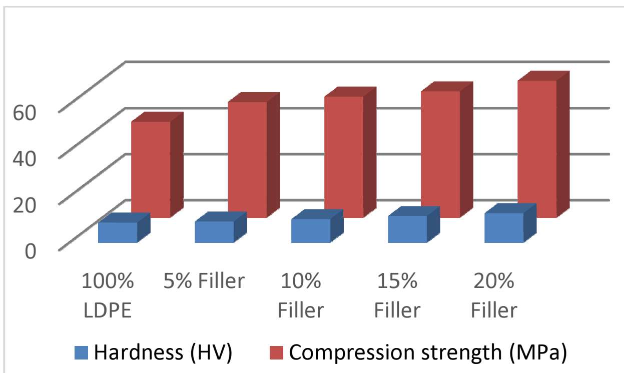

Fig. 3. Results of hardness and compressive strength of composite specimens

This accomplishment shows that the hardness and compressive strength of the water sachet waste might be enhanced by adding carbonized bamboo filler, and utilized for several purposes, including flooring and table tops. Any serious efforts to convert low-density polyethylene waste (particularly water sachet waste) into useful materials will be driven by this breakthrough.

Prediction of compressive strength of composite using ANN and MR

MR and ANN were utilized to predict the experimental compression strength of the produced composites. The predicted values are presented in Tables 2-5. By using multiple regression, the predictive equation for the compressive strength is stated in Equation (8):

$$\textit{Compressive strength} = 14.217 + 0.322\ \textit{(composition of filler)} - 0.136\ \textit{(hardness of composite)} \quad (8)$$

TABLE 3. **Multiple regression analysis for predicting compression strength of manufactured composite**

Predicted	Model coefficients of		
	Constant	Composition of filler	Hardness of composite
Compression strength	14.217	0.322	–0.136

The experimental compression strength prediction was substantially impacted by the hardness of the composite (57.7%), followed by the filler composition (42.3%), according to the artificial neural network modelling procedure as presented in Table 4.

TABLE 4. **Prediction of compression strength of produced composite using artificial neural network**

Independent variables		Importance		
Filler_Composition_of_Produced_Composites		0.423		
Hardness		0.577		
Parameter estimates for prediction				
Predictor		Predicted		
		Hidden layer 1		Output layer
		H(1:1)	H(1:2)	Compression_Strength
Input layer	(Bias)	0.211	–0.025	
	Filler_Composition_of_Produced_Composites	0.606	–0.346	
	Hardness	0.696	–0.432	
Hidden layer 1	(Bias)			–0.121
	H(1:1)			0.808
	H(1:2)			–0.456

The mean squared error was used to investigate how close the predicted value was to the actual value (Table 5 and Fig. 4). The error comparison between MR and ANN for predicting the compression strength of produced composites is shown in Figure 4.

TABLE 5. **Error analysis for predicting compression strength of produced composite using MR and ANN**

Error	Prediction of compression strength by ANN	Prediction of compression strength by MR
MSE	0.0017134	0.0162416

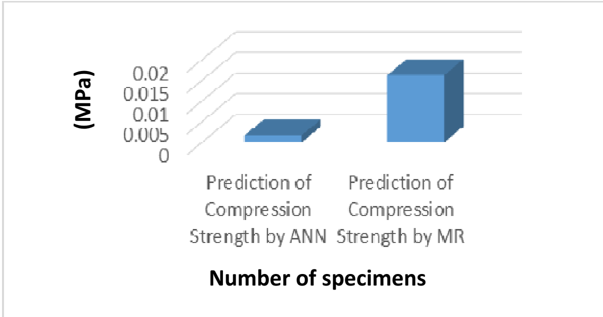

Fig. 4. Error graph for MR and ANN prediction of compression strength of manufactured composite

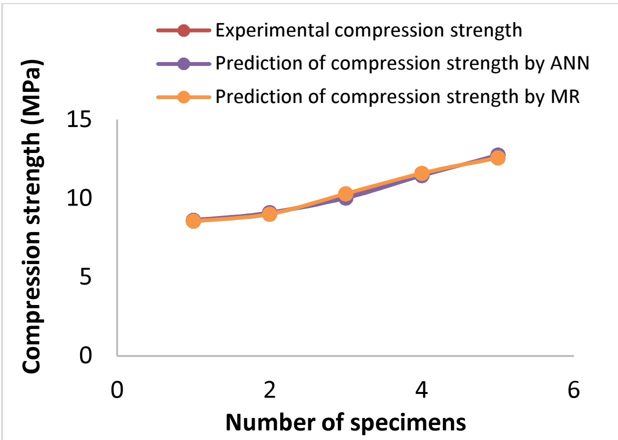

Fig. 5. Error comparison between MR and ANN for predicting compression strength of produced composites

The results as shown in Figure 5 revealed that when compared to multiple regression forecasts, the artificial neural network predictions not only had minimum errors but were also closer to the experimental compression strength values. This is consistent with previous reports [29] for forecasting beam defection behaviour and [39-46] for predicting the corrosion rate of mild steel in acidic media.

CONCLUSIONS

In this study, it was found that when disposed water sachet waste is mixed with carbonized bamboo sticks, the result can be improved hardness and compression strength.

Following the application of heat, the TGA and DSC findings of the filler material demonstrated a near steady drop in weight. Up to 199.8°C, the dehydration phase, during which moisture evaporation from the bamboo fibre occurred, a gradual weight loss of roughly 10.89%

was seen. The second phase of weight loss was found to be extremely fast, doubling from 13.31% to 29.98% to 66.7% at 249.8°C, 299.4°C, and 345.2°C, respectively. At 399.8 °C, the highest weight loss of 95.43% was observed. Exothermic reactions with enthalpies of –1573.8, –589.58, –725.67, –919.33, –1066.79, and –580.41 J/g were observed at temperatures of 49.5, 71.9, 99.0, 149.7, 199.4, and 236.9°C in the DSC test. A significant amount of heat was absorbed as the temperature reached 250°C, producing an endothermic reaction of 79.97 J/g at 249.9°C. With an enthalpy of 8223.21 J/g, this reaction peaked at 298.7°C.

The hardness and compression strength of the composite increased when the amount of filler was raised, with the formulation containing 20 wt.% filler having the greatest hardness value of 59.37 HV and compression strength of 12.72 MPa. The control (LDPEw) exhibited the lowest values of hardness (41.57 HV) and compression strength (8.6 MPa). This breakthrough suggests that the hardness and compressive strength of water sachet waste can be increased (by adding carbonized bamboo filler) and used for a variety of applications, including flooring and table tops. This development will drive any significant efforts to transform low-density polyethylene waste (especially water sachet waste) into useful materials.

Multiple regression and artificial neural networks were utilized to predict the experimental compression strength of the produced composites. The mean squared error results indicated that when compared to the multiple regression forecasts, the artificial neural network predictions not only had minimum errors but were also closer to the experimental compression strength values.

Recommendation

It is recommended that other methods of producing composites, such as the pulverization process with a 40% higher filler content than what was used in this study should be investigated to determine if they provide better composite materials.

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