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Statistical Modeling of the Moisture Absorption Behaviour of Plantain Peel and Bamboo Fibers Reinforced Polystyrene Composites

Adewale George Adeniyi [1,*], Joshua O. Ighalo [1], Samson O. Odeyemi [2], Olatokunbo M. Ofuyatan [3]

[1] Department of Chemical Engineering, Faculty of Engineering and Technology, University of Ilorin, Ilorin, P. M. B. 1515, Nigeria
[2] Department of Civil Engineering, Kwara State University, Malete, Nigeria
[3] Department of Civil Engineering, Covenant University, Ota Nigeria
* Correspondence: adeniyi.ag@unilorin.edu.ng (A.G.A.);
Scopus Author ID 57203847713

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Abstract: The use of natural particles from forestry or agricultural resources as filler materials in thermoplastic composites is used to achieve less abrasive products on lightweight processing tools and potentially offer biodegradability. This study statistically modeled the moisture absorption behavior of plantain peel (PPC) and bamboo fiber (BFC) reinforced composites using response surface methodology – historical data design. The 100 μm size fraction of both biomass fillers were used. The composites were prepared manually and hand-layup and cured at room temperature (25 ± 2°C) for 7 days. The most suitable model for the experimental results was the cubic model. The ANOVA for PPC and BFC observed that the RSM model was statistically significant (at a significance level of <0.05). Parametric studies revealed that moisture absorption increased with time and filler content for both BFC and PFC, and their behavior was quite similar. At equilibrium (11 days), the moisture absorbed for PPC was 21.72 g, 24.72 g, 30.60 g, and 38.04 g for 10 wt%, 20 wt%, 30 wt%, and 40 wt% filler content, respectively. At equilibrium (11 days), the moisture absorbed for BFC was 16.29 g, 20.25 g, 22.95 g, and 28.53 g at 10 wt%, 20 wt%, 30 wt%, and 40 wt% filler content, respectively.

Keywords: bamboo; composite; modelling; moisture absorption; plantain peel; polystyrene.

1. Introduction

Composite materials consist of two or more constituents with physically separable phases [1]. The utilization of biomass particles from forestry or agricultural resources as filler materials in thermoplastic composites has attracted the interest of researchers in many years [2-5]. However, the performance of thermoplastic natural filler composites typically varies considerably due to variations in the fillers' chemical, physical, and microstructure properties [6-10]. The natural fiber-filled composites are less abrasive on processing and machining tools, lightweight, and potentially offer biodegradable products than manufactured material-filled thermoplastic composites [11,12]. The advantage of composites over conventional materials spans is their higher specific strength, higher stiffness, and better fatigue characteristics which gives them greater versatility in multiple applications [13].

One advantage of natural fibers as reinforcement in plastic composites is their low density, resulting in higher tensile strength and stiffness than glass fibers, besides its lower manufacturing costs [14,15]. Both bamboo (*Bambusa vulgaris*) and plantain (*Musa paradisiaca*) residues are forestry and agricultural wastes that do not have a competitive use industrial use. Bamboo (*Bambusa vulgaris*) fibers have previously been considered as reinforcement in composites with Polyvinylchloride [2], polylactic acid [16,17], polyester [18], and epoxy [19,20]. Plantain (*Musa paradisiaca*) residues have only a few studies in composite development [21] in the open literature [22,23]. However, plantain peels are unreported.

Within the scope of the authors' exhaustive search, there are no papers considering the statistical modeling of the moisture absorption behavior of biomass reinforced composites. Furthermore, composite studies using polystyrene resins have been observed to be relatively rare [6,21], and many investigations are still needed in the research area. The aim of this study is to model the moisture absorption behavior of plantain peel and bamboo fiber-reinforced composites using response surface methodology – historical data design. The factors considered were the filler content and immersion time, and the responses were the moisture absorbed for both composites. The importance of such a study is justified in light of the need to develop composites with better properties usable in a variety of applications.

2. Materials and Methods

2.1. Materials.

Plantain (*Musa paradisiaca*) peel waste was gathered from a local canteen within the University of Ilorin, Nigeria. The plantain peels were washed, sun-dried, ground and sieved to 100 μm size. Bamboo (*Bambusa vulgaris*) dust was also obtained from a bamboo mill in Ilorin, Nigeria. It was sun-dried and sieved to 100 μm in size. Waste expanded polystyrene (EPS) obtained from solid waste streams was collected from Ilorin town, Nigeria.

2.2. Composite preparation.

Polystyrene-based resin (PBR) was produced from expanded polystyrene (EPS by solvolysis in a petroleum solvent at room temperature (25 ± 2°C) as described by Abdulkareem and Adeniyi [24]. A steel mold (with dimensions 130 × 100 × 6 mm) was used for casting the composite sheet. A known amount of PBR was taken and mixed with the biomass filler with gentle stirring to minimize air entrapment. The composites were prepared by manual mixing and hand-layup. The composite with plantain peel filler was denoted as PPC, while the composite with bamboo fiber filler was denoted as BFC. The amount of the fillers in the composite was varied between 10 and 40 wt% in steps of 10. The composites were allowed to cure for 7 days.

2.3. Moisture absorption tests.

The test samples of the PPC and BFC composites were immersed in distilled water for about 11 days under ambient temperature (25 ± 2°C). The samples were removed from water every 24 h and weighed using an analytical balance (accuracy of 10^{-4} g). For every measurement, the specimens were wiped to remove surface condensation. In addition, the weighting process was carried out in a very short time period to minimize the effects of discontinuity in the moisture absorption process. The weight of moisture absorbed M_t(g) was calculated using Eqn. 1

$$M_t(\text{g}) = \frac{W_t - W_o}{W_o} \qquad \text{Eqn. 1}$$

Where, W_t is the total weight at time (t) and W_o is the reference dry weight of the specimen. The experiments were terminated at 11 days for both composites because equilibrium was achieved. At equilibrium, there was no observable weight gain with time.

2.4. Response surface modeling.

Response surface methodology (RSM) was used to analyze the data on Design-Expert v10.0.1 software (Stat Ease Inc., Minneapolis, USA). RSM is a group of statistical techniques used for modeling and optimization [25]. Historical data design (HDD) was used in this study as it affords the researcher the flexibility to obtain the frequency of data collection needed to obtain accurate results. HDD has been previously utilized for the optimization of biodiesel production [26], solvent extraction [27], machining condition [28], photocatalytic degradation [29], and a host of others. HDD was used in this study to model the results obtained. The specific data inputted into the software can be obtained in the supplementary material. The designation of factors and responses for the study is shown in Table 1.

Table 1. Designation of factors and response

Designation	Data	Unit	Data band
Factor 1	Time	Days	0 < x < 11
Factor 2	Filler content	Wt%	10 < x < 40
Response 1	Moisture absorbed PPC	Grams	
Response 2	Moisture absorbed BFC	Grams	

3. Results and Discussion

3.1. Determination of best-fit model.

In RSM, the best fit model firstly needs to be determined. In RSM, this is done by the sequential sum of squares. The best model is usually selected by choosing the highest order polynomial whose p-value is significant and whose model terms are not aliased. A model is said to be aliased when the estimate of an effect includes the influence of one or more other effects. The results of the computed sequential sum of the sum of squares for PPC and BFC are shown in Tables 2 and 4, respectively. The model summary statistics for PPC and BFC are shown in Tables 3 and 5, respectively. Looking at Tables 2-3 for PPC, it can be deduced that the most suitable model for the data is the quadratic model. For BFC (Tables 4-5), the best fit model for the moisture absorption data is also the cubic model. This decision is made by careful consideration of the p-value and the coefficient of determination.

Table 2. The sequential model sum of squares for PPC.

Source	Sum of Squares	Df	Mean Square	F Value	p-value	Verdict
Mean vs Total	23880.63	1	23880.63			
Linear vs Mean	4463.35	2	2231.67	82.80	< 0.0001	
2FI vs Linear	0.44	1	0.44	0.016	0.9006	
Quadratic vs 2FI	623.29	2	311.65	22.22	< 0.0001	
Cubic vs Quadratic	202.66	4	50.67	4.98	0.0025	Suggested
Quartic vs Cubic	224.13	4	56.03	11.74	< 0.0001	Aliased
Residual	162.34	34	4.77			
Total	29556.84	48	615.77			

Table 3. Model summary statistics for PPC.

Source	Standard dev	R^2	Adjusted R^2	Predicted R^2	PRESS	Verdict
Linear	5.19	0.7863	0.7768	0.7444	1451.12	
2FI	5.25	0.7864	0.7718	0.7135	1626.32	
Quadratic	3.75	0.8962	0.8839	0.8322	952.31	
Cubic	3.19	0.9319	0.9158	0.8347	938.00	Suggested

Quartic	2.19	0.9714	0.9605	0.8931	607.07	Aliased

Table 4. The sequential model sum of squares for BFC.

Source	Sum of Squares	Df	Mean Square	F Value	p-value	Verdict
Mean vs Total	13631.31	1	13631.31			
Linear vs Mean	2551.53	2	1275.77	86.60	< 0.0001	
2FI vs Linear	0.83	1	0.83	0.055	0.8152	
Quadratic vs 2FI	329.54	2	164.77	20.81	< 0.0001	Suggested
Cubic vs Quadratic	111.60	4	27.90	4.80	0.0031	Suggested
Quartic vs Cubic	128.64	4	32.16	11.85	< 0.0001	Aliased
Residual	92.29	34	2.71			
Total	16845.75	48	350.95			

Table 5. Model summary statistics for BFC.

Source	Standard dev	R^2	Adjusted R^2	Predicted R^2	PRESS	Verdict
Linear	3.84	0.7938	0.7846	0.7530	794.06	
2FI	3.88	0.7940	0.7800	0.7223	892.53	
Quadratic	2.81	0.8966	0.8842	0.8329	536.98	Suggested
Cubic	2.41	0.9313	0.9150	0.8317	540.96	Suggested
Quartic	1.65	0.9713	0.9603	0.8945	339.01	Aliased

3.2. Analysis of variance (ANOVA) and model reduction.

The analysis of variance (ANOVA) was conducted to evaluate the statistical significance of the model and the corresponding factors. From the ANOVA for PPC in Table 6, it can be observed that the RSM model is statistically significant (at a significance level of <0.05). It can also be observed that filler content is a significant factor but time is not. Significance in this sense refers to the observable effect/relationship between the specific factor and the response across the range of data. For BFC, however (Table 7), the model itself and both factors are statistically significant (at a significance level of <0.05). This informs that the models obtained are suitable for predicting the moisture absorbed (at a known filler content and time) for plantain peel and bamboo fiber reinforced polystyrene composites.

Table 6. Analysis of variance (ANOVA) for PPC (Partial sum of squares - Type III).

Source	Sum of Squares	df	Mean Square	F Value	p-value	Verdict
Model	5289.73	9	587.75	57.79	< 0.0001	significant
A-Time	39.07	1	39.07	3.84	0.0573	
B-Filler Content	265.39	1	265.39	26.09	< 0.0001	
AB	0.44	1	0.44	0.043	0.8372	
A^2	574.33	1	574.33	56.47	< 0.0001	
B^2	48.96	1	48.96	4.81	0.0344	
A^2B	59.06	1	59.06	5.81	0.0209	
AB^2	2.68	1	2.68	0.26	0.6110	
A^3	138.48	1	138.48	13.62	0.0007	
B^3	2.45	1	2.45	0.24	0.6265	
Residual	386.48	38	10.17			
Cor. Total	5676.21	47				

Table 7. Analysis of variance (ANOVA) for BFC (Partial sum of squares - Type III).

Source	Sum of Squares	df	Mean Square	F Value	p-value	Verdict
Model	2993.50	9	332.61	57.21	< 0.0001	significant
A-Time	30.18	1	30.18	5.19	0.0284	
B-Filler Content	123.61	1	123.61	21.26	< 0.0001	
AB	0.83	1	0.83	0.14	0.7074	
A^2	310.23	1	310.23	53.36	< 0.0001	
B^2	19.32	1	19.32	3.32	0.0762	
A^2B	35.11	1	35.11	6.04	0.0187	
AB^2	0.087	1	0.087	0.015	0.9035	
A^3	76.40	1	76.40	13.14	0.0008	
B^3	8.438E-004	1	8.438E-004	1.451E-004	0.9905	
Residual	220.93	38	5.81			

Cor. Total	3214.43	47				

Before the final expressions were selected, the model's accuracy was first improved through model reduction. Model reduction involves removing the non-significant model terms based on the ANOVA then recalculating the models. This was done for both PPC and BFC. The final equation for PPC moisture absorbed in terms of actual factors (after model reduction) is given in Eqn. 2.

$$PPC\ (g) = 0.5227 + 0.1366B + 0.7508A^2 + 0.0101B^2 - 8.82 \times 10^{-4}A^2B - 0.0549A^3 \quad \text{Eqn. 2}$$

The final equation for BFC moisture absorbed in terms of actual factors (after model reduction) is given in Eqn. 3.

$$BFC\ (g) = -10.07 + 7.008A + 0.4824B - 0.8909A^2 - 8.07 \times 10^{-4}A^2B + 0.0406A^3 \quad \text{Eqn. 3}$$

Where A is time (in days), and B is filler content (in wt%). The range of validity of the models is 0 < A < 11 and 10 < B < 40.

3.3. Model diagnostics.

For model diagnostics, the parity plot for both models is observed. This is done to compare the nearness of model predictions to experimental results. On the parity plots, the diagonal represents the point at which model predictions are exactly those of experiments. Points above the diagonal are model under-predictions, while those below are model over predictions [26]. Examining Figures 1-2 for PPC and BFC, respectively, it can be observed that most of the points lie quite close to the diagonal with no major outliers. This buttresses the suitability of the models over the studied range of data.

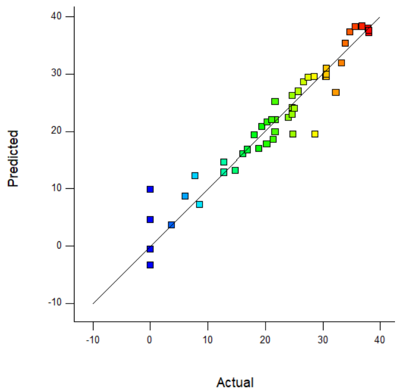

Figure 1. Parity plot of model predictions against actual results for PPC.

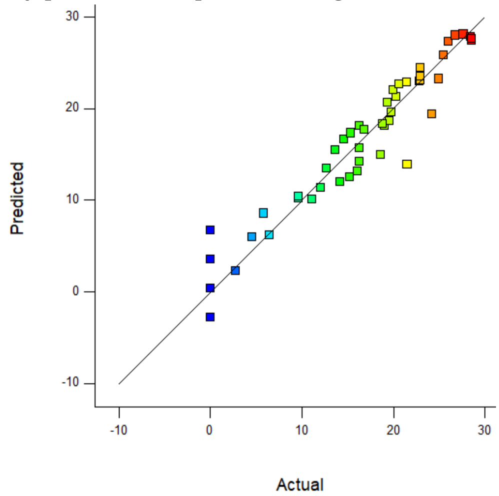

Figure 2. Parity plot of model predictions against actual results for BFC.

3.4. Parametric studies.

In this section, the ways in which the parameters related to the factors are discussed. The response surface plot for PPC and BFC are shown in Figures 3-4, respectively. Both plots can be observed to be similar. This informs that PPC and BFC have similar moisture absorption behavior, and differences only exist in their specific numerical values. It can be observed that moisture absorption increases with time, which holds overall filler content domains. The rapidity of the moisture absorption was observed to be quite high in the initial 5 days before slowing down over the course of the remaining 6 days. This is because concentration is the driving force in mass transfer. Initially, the moisture concentration gradient between the bulk of the composite and the liquid film around the composite leads to a greater rapidity. This advantage is reduced as more moisture gets into the composite until the equilibrium is achieved.

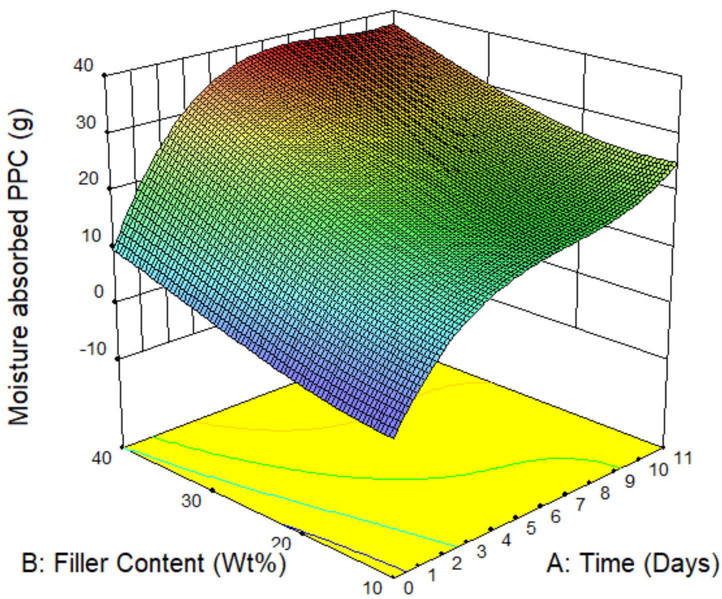

Figure 3. Effect of filler content and time on the moisture absorption behavior of PPC.

Moisture absorption can also be observed to increase with increasing filler content. This is due to the inherent susceptibility and affinity of biomass for moisture. Polymers are generally less susceptible to moisture absorption, but this property is gradually reduced by the proliferation of the more hydrophilic biomass within the polymer resin. At low fiber loading, moisture is absorbed by percolation, but it is absorbed by diffusion [30]. Percolation alone occurs within the fibers alone at low fiber content because plastic fully encapsulates them. At high fiber content, where there is a fiber-to-fiber contact within the composites, diffusion occurs. At equilibrium (11 days), the moisture absorbed for PPC was 21.72 g, 24.72 g, 30.60 g, and 38.04 g for 10 wt%, 20 wt%, 30 wt%, and 40 wt% filler content, respectively. At equilibrium (11 days), the moisture absorbed for BFC was 16.29 g, 20.25 g, 22.95 g, and 28.53 g at 10 wt%, 20 wt%, 30 wt%, and 40 wt% filler content, respectively. Comparing both results, it can be observed that the composites prepared from bamboo fibers fillers have lesser moisture absorption susceptibility than those prepared from plantain peel fillers. This informs that bamboo fibers will be preferable as fillers in applications where moisture absorption is a serious consideration.

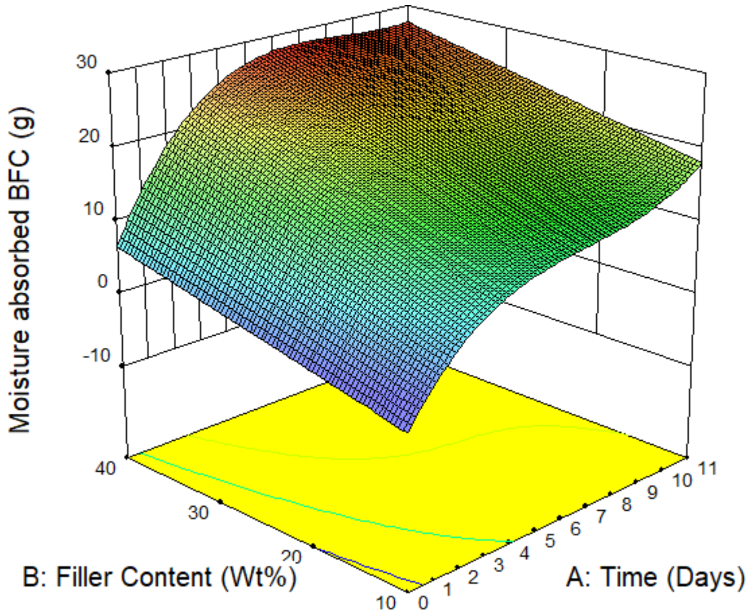

Figure 4. Effect of filler content and time on the moisture absorption behavior of BFC.

3.5. Practical implications of the study.

There is several importance of moisture absorption modeling in composite technology. The key importance is in developing a maintenance regime for materials obtained from this kind of composites. If a good understanding of moisture absorption is in place for a particular material, the contact time with water on maintenance will be adequately moderately. It is well known that moisture absorption leads to the rapid deterioration and even decay of biomass-reinforced plastic composites. Furthermore, those models can be applied as design equations. The filler loading that can achieve a specific moisture property at a set time can be predicted. Hence, considering other properties of the composites, moisture absorption will also be placed in a higher priority. This study also helps to provide a fundamental understanding of how the content of biomass filler and immersion time affects the absorption of moisture (for the case of plantain peel and bamboo fiber reinforcements. Considering that expanded polystyrene plantain peels and bamboo fiber are waste materials, this study also provides an important facet in solid waste management. The non-biodegradable expanded polystyrene can now be valorized in a more profitable application, simultaneously fostering environmental and economic sustainability.

4. Conclusions

In this study, the moisture absorption behavior of plantain peel (PPC) and bamboo fiber (BFC) reinforced composites were statistically modeled using response surface methodology – historical data design on Design-Expert v10.0.1 software (Stat Ease Inc., Minneapolis, USA). The most suitable model for the study results was found to be the cubic model. The ANOVA for PPC and BFC observed that the RSM model was statistically significant (at a significance level of <0.05). Filler content was statistically significant for both composites types but time was only significant for BFC. Final models were achieved to predict moisture absorbed for BFC and PPC at a specific time, and filler content after model reduction of the insignificant terms was conducted. Parametric studies revealed that moisture absorption increased with time and filler content for both BFC and PFC, and their behavior was quite similar. At equilibrium (11 days), the moisture absorbed for PPC was 21.72 g, 24.72 g, 30.60 g, and 38.04 g for 10 wt%, 20 wt%, 30 wt%, and 40 wt% filler content, respectively. At equilibrium (11 days), the moisture absorbed for BFC was 16.29 g, 20.25 g, 22.95 g, and 28.53 g at 10 wt%, 20 wt%, 30 wt%, and 40 wt% filler content, respectively.

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Conflicts of Interest

The authors declare no conflict of interest.

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