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Research Article

Development of a variance model for the prediction of water absorption and thickness swelling for an experimental design PVC reinforced composite pipes

Orhorhoro Ejiroghne Kelly[1*], Tamuno Rogers Ibunemisam[2], Azuka Joses Chukwuedo[3]

[1]*Department of Mechanical Engineering, General Abdulsalami Abubakar College of Engineering, Igbinedion University, Okada, Edo State, Nigeria*

[2]*School of Technical Services, Power Equipment and Electrical Machinery Development Institute, National Agency for Science and Engineering Infrastructure (NASENI), Okene, Kogi State, Nigeria*

[3]*Department of Chemical Engineering, Delta State Polytechnic, Ogwashi Uku, Delta State, Nigeria*

*Corresponding author: ejiroghene.orhorhoro@iuokada.edu.ng

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ABSTRACT

Water absorption is a significant constraint encountered when NFs reinforce polymer matrices. It is the primary cause of the breakdown of the fibre-matrix interface, resulting in swelling of the fibres, loss in the efficiency of load transfer between the matrix and the fibres, and ultimately, a reduction in the strength and stiffness of the composites. This study investigated the development of a variance model for predicting water absorption and thickness swelling for an experimental design of Polyvinyl chloride (PVC) reinforced composite pipes. The quadratic model was used to model the influence of the process factors (independent variables) on the responses (i.e., water absorption and thickness swelling). Statistical analysis of the experimental data was carried out by fitting the chosen quadratic model to the data to estimate the unknown model parameters. The results revealed that the model was characterised by a high R^2 value, indicating a perfect fit between the experimental observations and model predictions. The value of the variation coefficient was 3.320, which means the high precision and reliability of the model. The results of water absorption tests as a function of independent process factors showed that increasing the level of PVC in the composite material resulted in a decrease in the water absorption capacity of the material. This is desirable since an excellent composite pipe material should resist moisture intrusion.

1. INTRODUCTION

Polyvinyl chloride (PVC) is a polymer generally produced by extrusion. It has widespread usage in the industry due to its low cost and desirable physical and mechanical properties. Furthermore, the two main reasons that make PVC appealing are its nearly limitless range of applications and its unending production capabilities to meet market demand and challenges [1]. The application of PVC materials by the building industry represents the second biggest market globally for polymers. For pipe production, this amounted to a total market demand of nearly 3 million tonnes in Europe in the 2000s [2]. In Nigeria, the application of PVC is numerous, ranging from household to industrial use. It is increasingly replacing metals, glass, ceramics, and wood in many products. An estimated million tonnes of polyvinyl chlorides are used in Nigeria yearly [3].

Despite the essential and widespread usage of PVC, their inability to replace steel pipes due to their strength and toughness is a major concern. As mentioned earlier, there is a need to reinforce PVC pipes to overcome the limitation. Reinforced PVC pipes refer to composite combinations of the PVC matrix and reinforcing materials, predominantly in chopped and continuous fibre forms such as woven and non-woven. Furthermore, the properties of natural fibre (NF) reinforced polymer matrix composites depend on those of the individual components and their interfacial compatibility. Besides, stress transfer and load distribution efficiency at the interface are evaluated and determined by the degree of adhesion between the components [4].

Moreover, water absorption is a significant challenge posed when NFs are used to reinforce polymer matrices. It is the primary cause of the breakdown of the fibre-matrix interface, resulting in swelling of the fibres, loss in the efficiency of load transfer between the matrix and the fibres, and, ultimately, a reduction in the strength and stiffness of the composites [5]. Thus, the challenge posed by water absorption must be addressed so that NFs may be considered viable reinforcement in composite PVC [6].

However, studying the long-term water absorption capacity and thickness swelling of PVC-reinforced composite pipes using experimental methods is challenging due to the long working hours and high laboratory costs [7]. Several methodologies have been investigated to study mixture design experiment models where experimentation can be daunting [8-11]. Among all the methods, Response Surface Methodology (RSM) has been widely used to study mixture design experiments, such as long-term water absorption capacity and thickness swelling of a PVC-reinforced composite pipe. RSM incorporates improvement methodology for the settings of factorial factors, with the end goal that the reaction arrives at an ideal greatest or least worth [12]. Factorial strategies and ANOVA actively demonstrate the response, yet these are reached out for more point-by-point displaying of the impacts. RSM depends on the factorial review results (screening, then three-level factorial) and is a sort of increase where additional treatments are added to concentrate the impacts and work on the prescient force of the model [12]. The extra treatments are situated inside and out of the factorial space (focus point) (star focuses). The improved model is created on examination by various multiple regressions, and the condition can be utilised to plot the reaction surface [12].

Due to its flexibility, the quadratic model is the most used Response Surface Methodology (RSM) model. Moreover, the unknown model parameters can be estimated easily using the least squares method algorithm in the Design Expert software [13]. Furthermore, most of the work in previous work established the fact that most real-life processes are modelled using the quadratic model [14-16]. Therefore, this study investigated the development of a variance model for predicting water absorption and thickness swelling for an experimental design of PVC reinforced composite pipes. The quadratic model was used to model the influence of the process factors (independent variables) on the responses (i.e., water absorption and thickness swelling). Statistical analysis of the experimental data was carried out by fitting the chosen quadratic model to the data to estimate the unknown model parameters.

2. MATERIALS AND METHOD

In modelling the influence of the process factors (independent variables) on the responses (i.e., water absorption and thickness swelling), the quadratic (second order) model shown in Equation (1) was used.

$$Y = b_o + \sum_{i=1}^{N} b_i X_i + \sum_{i,j=1}^{N} b_{ij} X_i X_j + \sum_{i=1}^{N} b_{ii} X_i^2 + \sum_{i=1}^{N} e_i \tag{1}$$

The statistical models representing the responses were first developed and then validated before they were used for optimising the responses. In the first-order models, the steepest ascent method was used for maximising applicable responses, while the steepest descent method was used for minimising applicable responses [17]. For the quadratic models, the method of ridge analysis was used for optimising the reactions. The optimum condition of the second-order model is the Hessian matrix obtained from the model (after incorporating the Lagrange multipliers) based on the independent variables (i.e., must be positive definite for a minimisation problem and negative definite for a maximisation problem) [18].

The goodness of fit of the models representing water absorption and thickness swelling was evaluated by analysing variance (ANOVA). The result of ANOVA was used to assess the statistical significance and fit of the models using statistical parameters like F value, p-value, a sum of squares, mean square, lack of fit, standard deviation, coefficient of variation, coefficient of determination (R^2), adjusted R^2, adequate precision, Predicted Residual Sum of Squares (PRESS).

3. RESULTS AND DISCUSSION

3.1. Goodness of fit statistics of the models

Tables 1 - 4 show the model summary and lack of fit test results for water absorption and thickness swelling. Statistical analysis of the experimental data was carried out by fitting the chosen quadratic model to the data to estimate the unknown model parameters. This process was accomplished by applying multiple regression analyses to the data. At the end of the process, the estimated model parameters were incorporated into the general quadratic model equation to obtain the final statistical model for each response. Equations (2) and (3) present the equations representing the models' water absorption and thickness swelling in terms of the independent variables (PVC (X_1), rattan (X_2), plantain peduncle (X_3), temperature (X_4), and pressure (X_5).

Table 1. Model fit results for water absorption.

Source	Standard deviation	R^2	Adjusted R^2	Predicted R^2	PRESS	Remark
Linear	0.13	0.7015	0.6642	0.5992	0.94	
2FI	0.14	0.7643	0.6464	0.4000	1.41	
Quadratic	0.030	0.9901	0.9823	0.9722	0.065	Suggested
Cubic	0.038	0.9938	0.9719	0.8865	0.27	Aliased

Table 2. Lack of fit test results for water absorption.

Source	Sum of square	degree of freedom	Mean square	F-value	p-value	Remark
Linear	0.69	35	0.020	9.20	0.0103	
2FI	0.54	25	0.022	10.13	0.0085	
Quadratic	0.012	20	6.23E-04	0.29	0.9792	Suggested
Cubic	3.93E-03	5	7.86E-04	0.37	0.8530	Aliased
Error	0.011	5	2.15E-03			

Table 3. Model fit results in thickness swelling.

Source	Standard deviation	R^2	Adjusted R^2	Predicted R^2	PRESS	Remark
Linear	0.083	0.8361	0.8156	0.7751	0.38	
2FI	0.087	0.8627	0.7940	0.6240	0.63	
Quadratic	0.021	0.9936	0.9885	0.9758	0.040	Suggested
Cubic	0.018	0.9980	0.9909	0.9020	0.16	Aliased

Table 4. Lack of fit test results for thickness swelling.

Source	Sum of square	degree of freedom	Mean square	F-value	p-value	Remark
Linear	0.27	35	7.80E-03	46.66	0.0002	
2FI	0.23	25	9.14E-03	54.69	0.0001	
Quadratic	9.81E-03	20	4.91E-04	2.93	0.1179	Suggested
Cubic	2.54E-03	5	5.08E-04	3.04	0.1240	Aliased
Error	8.36E-04	5	1.67E-04			

$$\begin{aligned} \text{Water absorption} = {} & -6.52 + 0.19X_1 + 0.23X_2 + 0.23X_3 + 0.00037X_4 - 0.0042X_5 + 0.00090X_1X_2 \\ & + 0.000029X_1X_3 + 0.000098X_1X_4 + 0.00016X_1X_5 - 0.0044X_2X_3 - 0.000067X_2X_4 \\ & + 0.00069X_2X_5 - 0.00016X_3X_4 - 0.0011X_3X_5 - 0.000052X_4X_5 - 0.0023X_1^2 - 0.0084X_2^2 \\ & - 0.0012X_3^2 + 0.0000021X_4^2 - 0.0000093X_5^2 \end{aligned} \tag{2}$$

$$\begin{aligned} \text{Thickness swelling} = {} & 1.60 + 0.046X_1 - 0.12X_2 + 0.16X_3 + 0.00049X_4 - 0.022X_5 + 0.0023X_1X_2 \\ & - 0.0030X_1X_3 + 0.000031X_1X_4 + 0.0000091X_1X_5 - 0.0040X_2X_3 - 0.00010X_2X_4 \\ & + 0.00047X_2X_5 - 0.00027X_3X_4 - 0.00022X_3X_5 - 0.000012X_4X_5 - 0.0010X_1^2 \\ & + 0.000092X_2^2 + 0.00011X_3^2 + 0.0000057X_4^2 + 0.00010X_5^2 \end{aligned} \tag{3}$$

A total of 46 experimental results were obtained for each response. The statistical models (Equations 2 and 3) which were obtained by fitting the general quadratic model to these experimental results, were then used to predict their corresponding responses. The goodness of fit statistics for the model representing water absorption is shown in Table 5. The R^2 value obtained was 0.9901. The results in Table 5 show that the model was characterised by a high R2 value, indicating a perfect fit between the experimental observations and model predictions. Furthermore, the adjusted R^2 value was within reasonable agreement with the corresponding R^2 value, further confirming the fit of the models [19].

Table 5. The goodness of fit statistics for water absorption model.

Parameter	Value
R^2	0.9901
Adjusted R^2	0.9823
Predicted R^2	0.9722
Mean	0.9200
Standard deviation	0.0300
CV %	3.3200
Adequate precision	43.939

As shown in Table 5, the standard deviation value was small compared to the mean of the observations. This shows a tiny deviation between the individual experimental results and the mean value [20]. This further confirms the perfect fit of the model to the experimental data. The value of the coefficient of variation was obtained as 3.320. This low value for the model representing water absorption indicates that the experiments were run with high precision and reliability; hence, the runs are repeatable [17]. Table 5 also shows that the adequate precision value was 43.939. A value of 43.939 obtained in this work indicates that the model for water absorption has a fair signal. Therefore, the models can navigate the design space [20].

The goodness of fit statistics for the model representing thickness swelling is shown in Table 6. The R^2 value obtained was 0.9936. As seen from the results in Table 6, the model was characterised by a high R2 value, indicating a perfect fit between the experimental observations and model predictions. Furthermore, the adjusted R^2 value obtained was within reasonable agreement with the corresponding R^2 value, further confirming the fit of the models [19]. As shown in Table 6, the standard deviation value was small compared to the mean of the observations. This shows the minimal deviation between the individual experimental results and the mean value [20]. This further confirms the perfect fit of the model to the experimental data.

Table 6. The goodness of fit statistics for thickness swelling model.

Parameter	Value
R2	0.9936
Adjusted R2	0.9885
Predicted R2	0.9758
Mean	0.8900
Standard deviation	0.0210
CV %	2.3300
Adequate precision	54.433

The value of the coefficient of variation was obtained as 2.330. This low value for the model representing thickness swelling indicates that the experiments were run with high precision and reliability. Hence, the runs are repeatable [20]. Table 6 also shows that the adequate precision value was 54.433. A value of 54.433 obtained in this work indicates that the model for thickness swelling has a sufficient signal. Therefore, the models can navigate the design space [20].

3.2 Model validation

The results predicted by the models were validated by comparing them with the actual experimental results. Figures 1a and 1b show the models' parity plots representing water absorption and thickness swelling, respectively. The parity plots are used to assess the level of fit between the model predictions and the experimental results. An excellent fit results when the data points for the plot clustered around the 45° diagonal line [21]. This means there is little deviation between the model predictions and the experimental results. The results presented in Figure 1 indeed show a good fit between the model predictions and the experimental results.

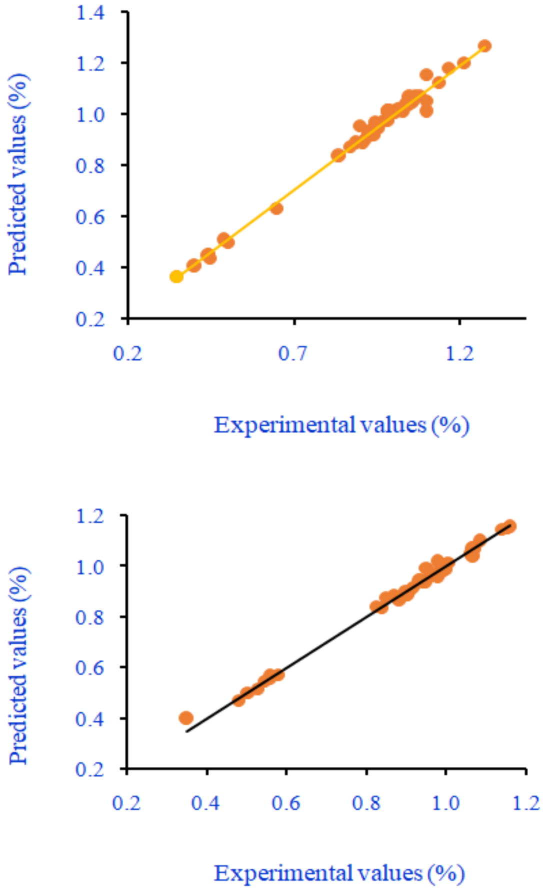
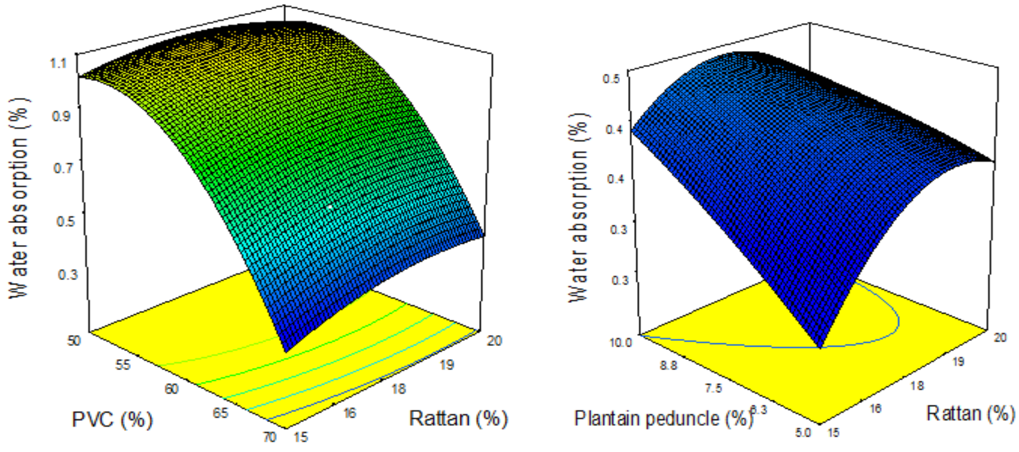


Figure 1. Parity plots of the predicted and experimental values of (a) Water absorption and (b) Thickness swelling.

3.3 Modelling results

Three-dimensional (3D) response surface and contour plots were generated to study the effect of the input variables (PVC, rattan, plantain peduncle, temperature, and pressure) on the responses (water absorption and thickness swelling). The response surface plots were produced by varying two variables within the experimental range and keeping the remaining three variables constant at their centre point values. The results of water absorption tests as a function of independent process factors are presented in Figure 2. Results in Figure 2 show that increasing the level of PVC in the composite material resulted in a decrease in the water absorption capacity of the material. This is desirable since an excellent composite pipe material should resist moisture intrusion. The lower water absorption capacity could be attributed to the hydrophobic nature of the PVC polymer material. In addition, the increase of interfacial bonding between the PVC polymer material, which acted as binder and filler particles, can lead to decreased porosity levels, resulting in lower water absorption capacity [22-23]. This means that the composite material was more resistant to the permeation of water. Hence, this material has the potential to perform better than others in very humid environments or when it encounters water or moisture. This is an indication of dimensional stability [24-25]. These findings agree with previous research [26] investigating the production of asbestos-free brake pads using watermelon peels. This study found that proper bonding was achieved when a 25 wt% pure-water sachet was used as a binder with the watermelon peel particles, and a reduction in the water absorption capacity was observed. Other research [27] also used palm ash to produce non-asbestos brake pads by varying the composition of polychlorinated biphenyl waste (PCB) and palm ash. Thermoset resin was employed as a binder. The results showed that as the palm ash content increased in composition, the water absorption capacity reduced, indicating a beneficial effect.

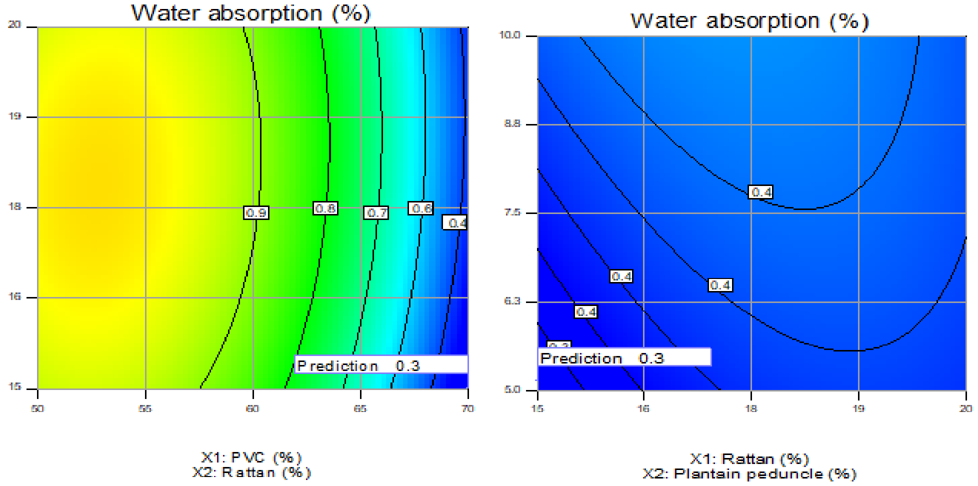
This study also found that increasing the level of rattan and plantain peduncle increased the water absorption capacity of the composite pipe, as shown in Figure 3. This is because the fibre materials are hydrophilic, unlike the PVC material. Moreover, the increase in temperature and pressure reduced water absorption, as shown in Figure 4. This result is probably contributed by better mobility and distribution of the plastic component among the fibre (rattan and plantain peduncle) particles [28], thus covering a larger surface area of the hydrophilic fibre component. Due to the ensuing better surface protection of lignocellulosic particles, water absorption levels are reduced, and the moisture resistance of the rattan-plantain peduncle-plastic composite pipes is improved.



i. Effect of PVC and rattan composition on water absorption

ii. Effect of plantain peduncle and rattan composition on water absorption

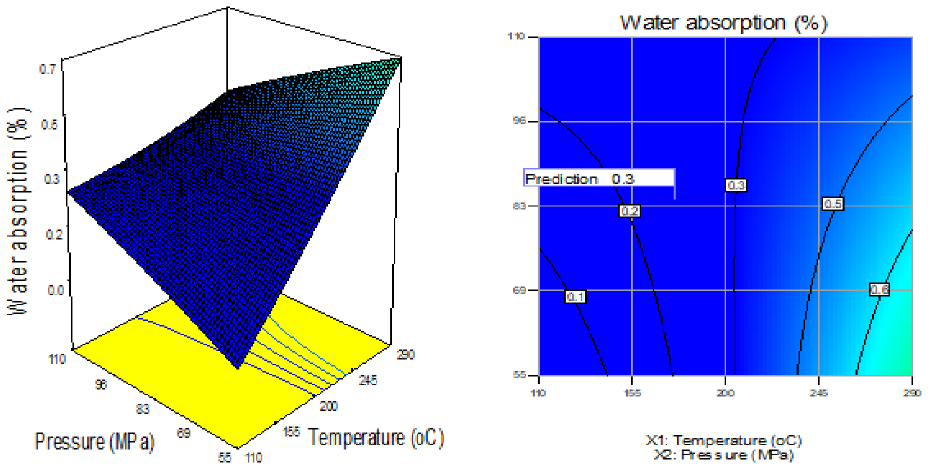
Figure 2. Response surface plot of water absorption.



i. Effect of PVC and rattan composition on water absorption

ii. Effect of plantain peduncle and rattan composition on

Figure 3. Contour plot of water absorption.

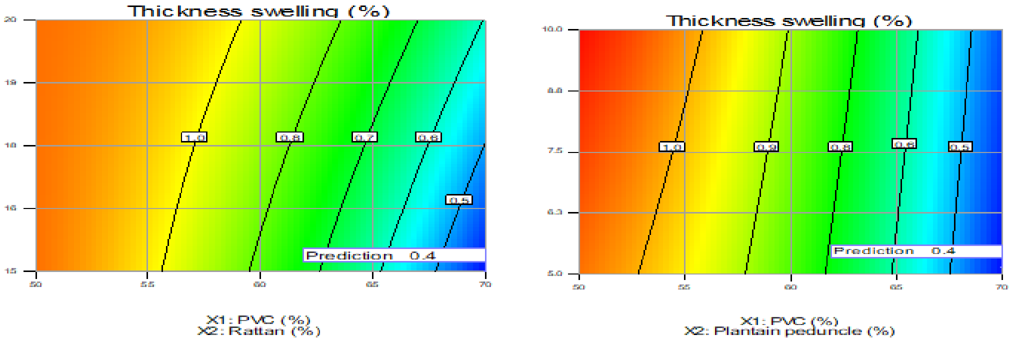


i. Response surface plot

ii. Contour plot

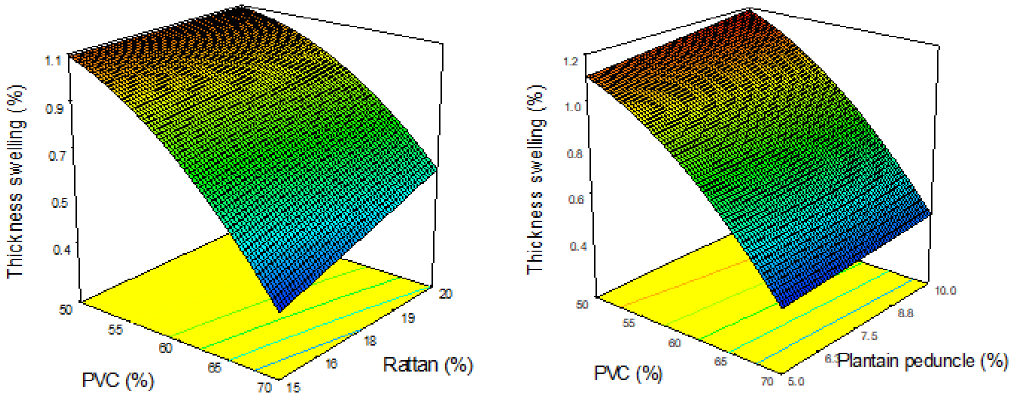
Figure 4. Effect of temperature and pressure on water absorption.

The characteristics of thickness swelling concerning the production variables (PVC, rattan, plantain peduncle, temperature, and pressure), as shown in Figures 5 to 7, were very similar to those of water absorption, as discussed above. An increase in PVC reduced the thickness swelling of the composite pipes produced, which was previously attributed to the hydrophobic nature of the PVC material. On the other hand, with higher fibre (rattan and plantain peduncle) content, thickness swelling tends to increase as a larger share of the particle surface is insufficiently bonded and protected by the plastic component, and the greater connectivity between particles allows for easier moisture intrusion [28]. Conversely, increasing temperature and pressure reduced the thickness swelling, and this was also attributed to better mobility and distribution of the plastic component among the fibre (rattan and plantain peduncle) particles, thus covering a larger surface area of the hydrophilic fibre component and the ensuing better surface protection of lignocellulosic particles.



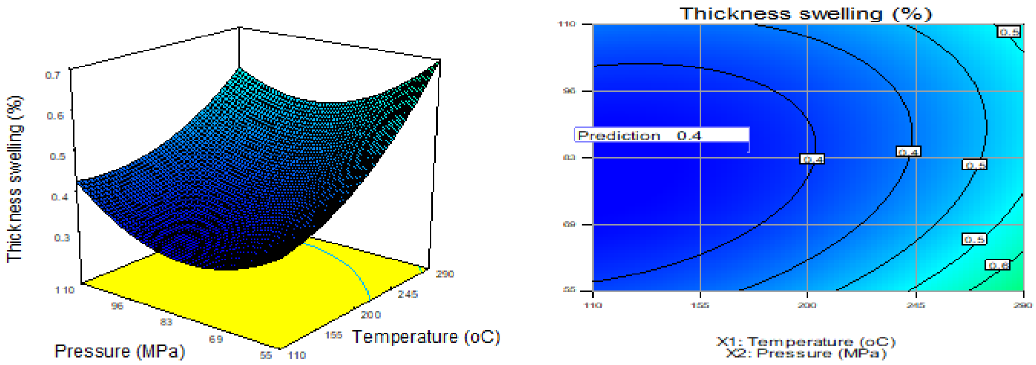
i. Effect of PVC and rattan on thickness swelling ii. Effect of PVC and plantain peduncle on thickness swelling

Figure 5. Contour plot of thickness swelling.



i. Effect of PVC and rattan on thickness swelling ii. Effect of PVC and plantain peduncle on thickness swelling

Figure 6. Response surface plot of thickness swelling.



i. Response surface plot ii. Contour plot

Figure 7. Effect temperature and pressure on thickness swelling.

4. CONCLUSION

The development of a variance model for predicting water absorption and thickness swelling for an experimental design reinforcing PVC composite pipes was successfully carried out. The results showed that the model had a high R2 value, indicating a perfect fit between the experimental observations and model predictions. Furthermore, the adjusted R^2 value was within reasonable agreement with the corresponding R^2 value, confirming the fit of the models. An adequate precision value of 43.939 was obtained, and this was an indication that the model for water absorption has a sufficient signal and that the models can be used to navigate the design space.

Increasing the level of rattan and plantain peduncle increased the water absorption capacity of the composite pipe. This is due to the hydrophilic fibre materials, unlike the PVC material. Also, an increase in temperature and pressure reduced water absorption. This is contributed by a better mobility and distribution of the plastic component among the fibre (rattan and plantain peduncle) particles, thus covering a larger surface area of the hydrophilic fibre component.

The characteristics of thickness swelling concerning the production variables (PVC, rattan, plantain peduncle, temperature, and pressure) showed that increased PVC resulted in reduced thickness swelling of the composite pipes. However, with higher fibre (rattan and plantain peduncle) content, thickness swelling tends to improve as a larger share of the particle surface is insufficiently bonded and protected by the plastic component, and the more excellent connectivity between particles allows for easier moisture intrusion.

CONFLICTS OF INTEREST

The authors declare no competing financial interests or personal relationships that could have appeared to impact the work reported in this paper.

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