EXPERIMENTAL DESIGN METHOD FOR THE PRODUCTION OF BONDED PARTICLEBOARDS WITH OPTIMUM MECHANICAL PROPERTIES USING SAWDUST

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Abstract
In this study, design of experiment (DOE) was used to generate an experimental design for the production of bonded particleboards from sawdust. A three variable Box-Behnken design was used to study the effect of amount of sawdust, amount of binder and acclimatisation time on the modulus of rupture (MOR) and modulus of elasticity (MOE) of the boards. Statistically significant quadratic models ($p<0.0001$) were developed to predict the MOR and MOE of the boards. The models exhibited insignificant lack of fit ($R^2=0.98$ for MOR and $R^2=0.99$ for MOE) and low standard deviation. The three factors investigated (amount of sawdust, amount of binder and acclimatisation time) were statistically significant ($p<0.05$) showing that they influenced the production of the particleboards. All three factor however affected the MOR and MOE positively. Optimisation results obtained from response surface methodology (RSM) showed that particleboards with maximum MOR and MOE of 9.35 N/mm^2 and 1116 N/mm^2 respectively can be produced by using 185 g of sawdust and 463 g of binder and allowing 21 days for acclimatisation. The boards produced at these conditions satisfied the American National Standard Institute ANSI/A208.1-1999 specification for general purpose particleboards.
Keywords: Particleboard, RSM, Box-Behnken design, Sawdust, Binder, Modulus of rupture

1. Introduction

The production of particleboards typically requires the use of wood as raw material. With the growth in population, particularly in developing countries such as Nigeria, it is projected that the strain on available wood resources will increase as a result of the increase in the demand for wood based products (Amenaghawon et al., 2015). Further dependence on wood could potentially result in an increase in the rate of deforestation as well as its attendant negative consequences (Kayode, 2007). This has shifted the focus away from wood resources as a means of satisfying the demand.

A viable and sustainable alternative is the use of agricultural wastes for the manufacture of particleboards. The boards can be made from essentially any lignocellulosic material that gives them high strength and a predetermined density since the chemical composition of the lignocellulosic material is similar to that of wood (Mendes et al., 2009). These agricultural residues such as the stalks of most cereal crops, rice husks, coconut coir, bagasse, corn cobs, peanut shells, sawdust etc are cheap and abundantly available in many developing countries such as Nigeria, Philippines, Indonesia, Sri Lanka and India (Aisien et al., 2013; Amenaghawon et al., 2013a). Burning these materials or discarding them as it is done in most developing countries does not add value to them rather this action contributes to increasing the greenhouse gases in the environment and consequently global warming *(Fiorelli et al., 2013).* Production of particleboards provides an alternative usage for these otherwise useless materials. It also helps to mitigate negative environmental impacts through the production of new materials aimed at sustainability (*Chamma and Leao, 2008*).

In recent years, research efforts have been focussed on the potential utilisation of lignocellulosic wastes for the production of value added products such as particleboards. *Boquillon et al. (2004) studied the properties of wheat straw and its potential for particle board production.* Xu et al. (2009) evaluated sugarcane bagasse for the purpose of producing particleboards. The effect of wax emulsion as a stabilising agent was investigated and their results showed that wax improved the properties of the boards produced. Furthermore, the properties of the boards were found to meet the ANSI A208.1 standard for commercial grade boards. In another study, *Sekaluvu et al. (2014*) investigated the factors that affected the production of particle boards from maize cobs. Their results showed that the properties of the particle boards produced were significantly affected by the resin content and particle size. Aisien et al. (2013) investigated the potential use of corn cobs and cassava stalk for composite panel production and the results of the study established the factors that affected the production of particleboards.

Despite the volume of studies done on this subject, very little attempt has been made to optimise the factors that affect the production process. In a previous study, Amenaghawon et al. (2015) produced particleboards from corncobs and cassava stalks and established the best ratio of feedstock to binder for producing boards with optimum properties. Following from that, the present study was aimed at producing particleboards from sawdust with a view to optimising the properties of the boards produced as well as establishing the optimum conditions for producing the boards. The boards were produced using statistically designed experiments and the properties were optimised using RSM. RSM is a very useful tool for optimising multivariate processes and it has a lot of advantages over the traditional one factor at a time method (Montgomery 2005).

2. Materials and Methods

2.1 Materials collection and preparation

The sawdust used in this study was obtained from a wood mill in Benin City, Nigeria. Urea formaldehyde (UF) used as binder was procured from a local vendor in Benin City. The sawdust was screened using standard sieves to obtain 2 mm particles. It was then pretreated using hot water at a temperature of 85°C to extract inhibitory compounds which could affect the setting of the boards (Aisien et al., 2013). The sawdust was subsequently oven dried at 60 °C to a constant weight moisture content of about 12%.

2.2 Design of Experiment

A three variable Box-Behnken design was used for the production of the boards with the variables studied as well as their levels shown in Table 1.

Table 1: Coded and actual levels of the factors for three factor Box-Behnken design for particle

Independent Variables	Symbols	Coded and Actual Levels		
		-1	0	+1
Amount of saw dust (g)	X_1	154	154.0	185
Amount of binder (g)	X_2	386	424.5	463
Acclimatisation time (days)	X_3	14	17.5	21

The Box-Behnken design has been established to be suitable for fitting quadratic response surfaces and this design generates a second degree polynomial model which can be used for optimisation purposes (Amenaghawon et al., 2013b). The experimental design was developed using Design Expert® 7.0.0 (Stat-ease, Inc. Minneapolis, USA). Equation (1) is a second order polynomial equation which was fitted to the experimental data in order to predict the responses (Amenaghawon et al., 2014).

$$Y_i \quad b_o + \sum b_i X_j + \sum b_{ij} X_i X_j + \sum b_{ii} X_i^{R} + e_i \tag{1}$$

where Y_i is the dependent variable or predicted response which represented the mechanical properties that were investigated. These were the MOR and MOE. X_i and X_j are the independent variables, b_o is offset term, b_i and b_{ij} are the single and interaction effect coefficients and e_i is the error term. The Design Expert software was used for regression and graphical analysis of the experimental data. The goodness of fit of the models for MOR and MOE was evaluated by the coefficient of determination (R^2) and analysis of variance (ANOVA). The optimum values of the variables tested were obtained by numerical optimisation based on the criterion of desirability (*Jargalsaikhan and Saracoğlu, 2008*).

2.3 Production of particleboard

The pretreated sawdust was mixed thoroughly with the binder in proportions recommended by the experimental design. After mixing, the material was put in a mould of dimension 35 cm×35 cm×0.6 cm and then inserted in a hydraulic press and pressed for 8 minutes under a pressure of 3.92 N/mm^2 (Mendes et al., 2009). Prior to board formation, the mould was covered with a sheet of polythene to prevent the board from sticking to it. About 2 cm was trimmed off the edge of each board produced using a buzz saw and the boards were subsequently put in a climatisation chamber at a temperature of 20 ± 2 °C and a relative humidity of 65 ±2 %. The acclimatisation period was as prescribed by the experimental design.

2.4 Testing of particleboard

The performance of the particleboards was evaluated by mechanical and physical tests carried out according to standard methods of ASTM D1037 and DIN 52362 (ASTM 1995; *Normen 1982*). The mechanical tests included MOR and MOE while the physical tests included thickness swelling (TS) and water absorption (WA). In this work, only the mechanical properties were presented.

3. Results and Discussion

3.1 Statistical Modelling and Analysis

The experimental data obtained in the course of the study was fitted to the second order regression model shown in Equation (1). The coefficients of the model variables were estimated by the Design Expert software using multiple regression analysis. The final response models used to predict the MOR and MOE at a confidence level of 95% are given in Equations (2) and (3) respectively. These equations were then used to predict the MOR and MOE of the boards and the results are presented in Table 2 alongside the experimental data.

$$Y \quad 384.57 - 2.29X_Q - 1.00X_2 + 2.22X_3 + 0.0029X_1X_2 - 0.021X_1X_3 + 0.0039X_2X_3 + 0.0040X_1^2 - 0.00056X_2^2 \qquad (2)$$

$$Y \quad 45476.13 - 247.13X_Q - 109.86X_2 - 94.01X_3 + 0.40X_1X_2 - 1.97X_1X_3 + 0.68X_2X_3 + 0.32X_1^2 + 0.037X_2^2 + 4.74X_3^2 \qquad (3)$$

Run	Factors						Response			
	Coded values			Actual values			MOR (N/mm²)		MOE (N/mm²)	
	X_1	X_2	X_3	X_1	X_2	X_3	Actual	Predicted	Actual	Predicted
1	0	0	0	169.5	424.5	17.5	4.66	4.63	589.12	600.94
2	0	0	0	169.5	424.5	17.5	4.66	4.63	589.12	600.94
3	0	1	-1	169.5	463.0	14.0	5.47	5.23	562.13	550.15
4	0	0	0	169.5	424.5	17.5	4.50	4.63	598.14	600.94
5	0	-1	-1	169.5	386.0	14.0	3.64	3.51	654.17	645.74
6	0	1	1	169.5	463.0	21.0	8.49	8.51	969.62	971.64
7	-1	1	1	154.0	463.0	21.0	9.44	9.59	976.92	982.60
8	-1	0	0	154.0	424.5	17.5	7.12	6.32	754.62	740.62
9	-1	0	-1	154.0	424.5	14.0	3.63	4.07	553.02	574.83
10	1	-1	-1	185.0	386.0	14.0	3.21	3.14	534.45	533.05
11	1	0	1	185.0	424.5	21.0	5.21	4.84	702.10	684.56
12	0	-1	0	169.5	386.0	21.0	4.46	4.66	681.15	690.99
13	1	1	0	185.0	463.0	17.5	8.79	8.86	950.50	954.78
14	0	-1	0	169.5	386.0	17.5	3.96	3.96	610.21	610.21
15	0	0	0	169.5	424.5	17.5	4.57	4.63	618.81	600.94
16	-1	0	0	154.0	424.5	17.5	6.12	6.32	754.12	740.62
17	1	0	0	185.0	424.5	17.5	4.50	4.87	602.31	616.98

Tables 3 to 5 show the results of analysis of variance (ANOVA) carried out to determine the fit of the statistical models representing the MOR and MOE of the particleboards. Tables 3 and 4 respectively shows that the models for MOR and MOE were significant with very low p values (<0.0001). The models also did not show lack of fit. All the model terms were also significant indicating changes in the values of these variables could affect the MOR and MOE of the boards. Table 5 shows that the models for MOR and MOE had very high R^2 values of 0.98 and 0.99 respectively. The R^2 value indicates the degree to which the model is able to predict the response. The closer the R^2 value is to unity, the better the model can predict the response (Qi et al., 2009). The R^2 values obtained in this study for both models show that there was significant fit between the observed and predicted values of MOR and MOE. The standard deviations were observed to be relatively small compared to the mean values of MOR and MOE showing that there was very little dispersion about the mean for the data predicted by both models. This further corroborates the significant fit of the models. The relatively low values of coefficient of variation (CV) obtained for MOR and MOE (6.50 and 2.66) shows that the runs were carried out with precision and the results thus reliable (Montgomery 2005). The Adequate precision for both models indicate adequate signals meaning that the models can be used to navigate the design space (Cao et al., 2009).

Table 3: ANOVA results for model representing MOR

Sources	Sum of Squares	df	Mean Squares	F value	p value
Model	56.91	8	7.11	42.73	< 0.0001
X_1	3.55	1	3.55	21.30	0.0017
X_2	12.37	1	12.37	74.29	< 0.0001
X_3	9.02	1	9.02	54.19	< 0.0001
X_1X_2	4.26	1	4.26	25.61	0.0010
X_1X_3	2.47	1	2.47	14.85	0.0049
X_2X_3	1.17	1	1.17	7.01	0.0293
X_1^2	3.33	1	3.33	20.03	0.0021
X_2^2	1.97	1	1.97	11.86	0.0088
Residual	1.33	8	0.17		
Lack of Fit	0.81	4	0.20	1.57	0.3362
Pure Error	0.52	4	0.13		
Cor Total	58.24	16			

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3Øµ≤£•≥	Sum of Squares	df	Mean Squares	F value	p value
Model	342989.81	9	38109.98	113.46	< 0.0001
X_1	25573.76	1	25573.76	76.14	< 0.0001
X_2	11187.73	1	11187.73	33.31	0.0007
X_3	99412.84	1	99412.84	295.97	< 0.0001
X_1X_2	23157.80	1	23157.80	68.94	< 0.0001
X_1X_3	6133.00	1	6133.00	18.26	0.0037
X_2X_3	36477.36	1	36477.36	108.60	< 0.0001
X_1^2	21373.65	1	21373.65	63.63	< 0.0001
X_2^2	2247.76	1	2247.76	6.69	0.0361
X_3^2	2331.38	1	2331.38	6.94	0.0337
Residual	2351.22	7	335.89		
Lack of Fit	1762.86	3	587.62	3.99	0.1071
Pure Error	588.37	4	147.09		
Cor Total	345341.03	16			

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0°≤°≠•¥•≤	Response	
	MOR	MOE
R-Squared	0.98	0.99
Mean	5.44	688.27
Standard Deviation	0.41	18.33
C.V %	7.50	2.66
Adeq. Precision	21.78	31.98

3.2 Effect of Independent Variables

Figures 1 and 2 are response surface plots showing the effect of acclimatisation time and amount of sawdust on the MOR and MOE of the particleboards respectively. The MOR was observed to increase with increase in time allowed for acclimatisation. A similar trend was observed for the MOE. This is expected as both MOR and MOE are properties that measure the mechanical strength of the boards. The trend observed suggests that the MOR and MOE of the particleboards could be enhanced by allowing the boards sufficient time to acclimatise before carrying out testing. Adequate acclimatisation ensures proper conditioning of the boards. It also ensures that the boards are able to reach equilibrium conditions of moisture content and humidity that will be suitable for storage. Figures 1 and 2 also show that the MOR and MOE of the boards increased with increase in the amount of sawdust used. This trend could be attributed to the structural and mechanical strength conferred on the boards as a result of the type of feedstock used. Wood based feedstocks are generally considered to be stronger than other lignocellulosic options (Bektas et al., 2005). Hence using sawdust obtained from wood residue could mean that boards produced from it will have enhanced mechanical properties.

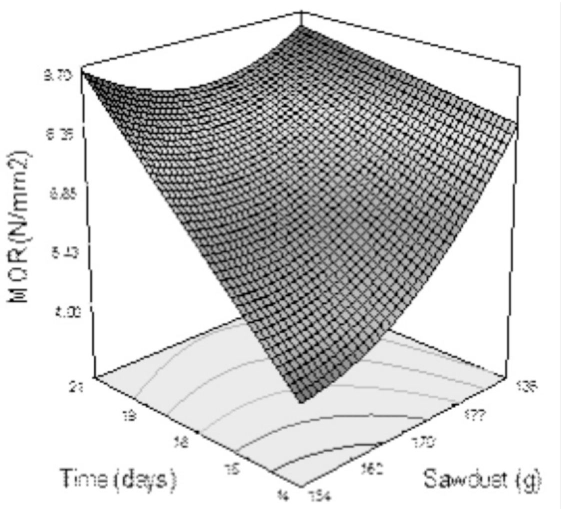

Figure 1: Effect of acclimatisation time and amount of sawdust on MOR

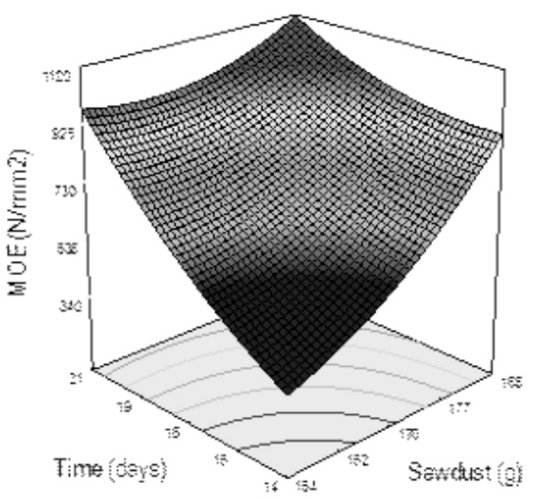

Figure 2: Effect of acclimatisation time and amount of sawdust on MOE

The MOR and MOE were observed to increase with increase in the amount of binder used as shown in Figures 3 and 4 respectively. The resin content determines the amount of void spaces within the particleboard matrix. When a small amount of binder is used, the binder serves to bind the particles of the sawdust together to form the composite material leaving behind some voids. However, when more of the binder is used, some of it serves to bind the sawdust particles together to form the composite material while the remainder fills up the void spaces which might have remained (*Sekaluvu et al., 2014*). The increased amount of binder used provides a large film of binder around each sawdust particle thus resulting in increased adhesion and bond contact between each particle (*Yimsamerjit et al., 2007*). This consequently results in an increase in the mechanical properties of the board. Similar observations have been reported previously (**Aisien et al., 2013; Amenaghawon et al., 2015; Mendes et al., 2009**).

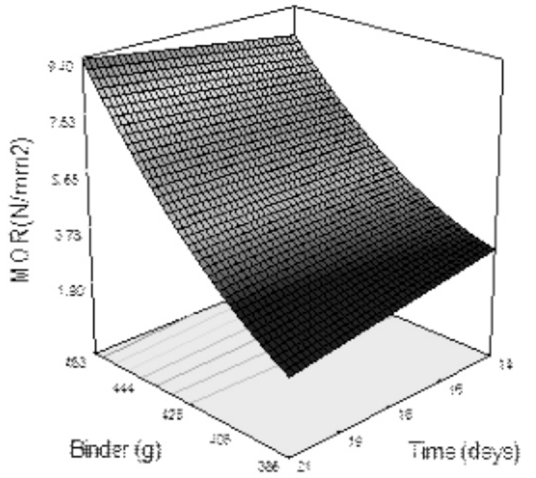

Figure 3: Effect of acclimatisation time and amount of binder on MOR

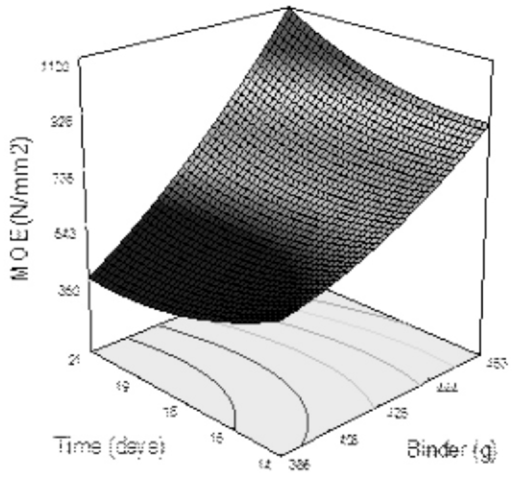

Figure 4: Effect of acclimatisation time and amount of binder on MOE

3.3 Numerical Optimisation

Numerical optimisation of the variables was carried out to maximise the MOR and MOE of the boards. The values of the independent variables during numerical optimisation were fixed in the range shown in Table 1. After evaluating the model graphs and the solutions suggested by the numerical optimisation package, the chosen conditions for producing particleboards with optimum mechanical properties was the one with the highest desirability value. These conditions were as follows: 185 g of sawdust, 463 g of binder and 21 days of acclimatisation time. Under these conditions, the maximum MOR and MOE of the boards were 9.35 N/mm^2 and 1116 N/mm^2 respectively. The maximum MOR and MOE were compared with the minimum specification of the American National Standard Institute ANSI/A208.1-1999 for general purpose particleboards (ANSI 1999) (i.e. 3 N/mm^2 and 550 N/mm^2 respectively for MOR and MOE). It can be seen from the optimisation results that the sawdust particleboards clearly satisfies the minimum MOR and MOE requirements established by the ANSI/A208.1-1999 standard. This shows that the sawdust particleboards can be used for general purposes.

3.4 Validation of Statistical Models

In order to confirm the validity of the statistical models used for predicting the MOR and MOE, three confirmation experimental runs were performed at the identified optimum conditions. The results showed that the maximum MOR and MOE (9.24 N/mm^2 and 1120 N/mm^2 respectively) obtained were close to the values predicted by the statistical models. The excellent correlation between the predicted and measured values shows the validity of statistical models.

Conclusion

Bonded particle boards were produced from sawdust using urea formaldehyde as binder. A three variable Box-Behnken design was found to be efficient in designing the experiments for the production of the boards. Statistically significant quadratic models ($p<0.0001$) were developed to predict the MOR and MOE of the boards produced. Both models showed a good fit with the experimental data as seen from the high R^2 values (0.98 and 0.99 respectively) and low standard deviation (0.41 and 18.33 respectively). The MOR and MOE were positively influenced by the amount of sawdust, amount of binder as well as the acclimatisation time and these variables were all significant at the 95% level. Optimisation results showed that particleboards with maximum MOR and MOE of 9.35 N/mm^2 and 1116 N/mm^2 respectively can be produced by using 185 g of sawdust and 463 g of binder and allowing 21 days for acclimatisation. The boards produced at these conditions **satisfied the** American National Standard Institute ANSI/A208.1-1999 specification for general purpose particleboards.

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