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Production of particle boards from corn cobs and cassava stalks: Optimisation of mechanical properties using response surface methodology

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Abstract
The aim of this work was to optimise the production of particle boards from corn cobs and cassava stalks, two abundantly available and inexpensive agricultural residues in Nigeria. The mechanical properties investigated were the modulus of rupture (MOR) and modulus of elasticity (MOE). The production of particle boards was investigated under the following conditions: board density (1000-1200 kg/m^3), resin loading (386-463 g) and amount of agro residue (154-185 g) using Box-Behnken design. Statistically significant models ($p<0.05$) were developed to represent the relationship between the responses (MOR and MOE) and the production variables. Both models showed significant fit with experimental data with R^2 values of 0.96 and 0.91 respectively. Analysis of variance (ANOVA) results showed that MOR and MOE were influenced by the amount of resin and agro residue used. The board density did not have any significant effect on the MOR and MOE of the boards produced. Response surface methodology (RSM) was used to optimise the MOR and MOE and the optimisation results showed that the maximum MOR and MOE values of 4.9 N/mm^2 and 910.03 N/mm^2 were respectively obtained at the optimum production conditions of board density, resin loading and amount of agro residue (i.e. 1200 kg/m^3, 463 g and 155.99 g respectively). The particle board produced at the optimised conditions satisfied the American National Standard ANSI/A208.1-1999 specification for general purpose particle boards.

Keywords: Particle board; Urea formaldehyde; Phenol formaldehyde; Corn cobs; Cassava stalks

1. Introduction
In developing countries such as Nigeria, the construction industry is considered as an important part of the economy [1]. This sector is heavily dependent on forest resources for the purpose of roofing, ceiling construction, panelling, furniture manufacture and other fabrication works that require the use of wood. In particular, the panel/board industry in Nigeria has experienced continuous growth in recent years and Sotannde et al. [2] recently estimated the demand for wood and wood derived panels/boards to be 4.704 and 0.688 million m^3 respectively. This has placed a lot of strain on forest resources leading to deforestation and its attendant adverse effect on the environment as well as increase in the price of wood [3].

Particleboard is a composite panel product typically produced from wood products such as shavings, flakes, wafers, chips, sawdust, strands etc [4]. It is commonly applied as material for flooring, wall bracing, ceiling boarding, furniture, partitioning, cladding etc [5]. The particles of the composite material are held together by synthetic resins and other additives may be added to enhance the properties of the final composite material. Several types of resins are commonly used with urea formaldehyde and phenol formaldehyde resin being the cheapest and easiest to use.

The need to reduce the dependence on wood and forest resources has resulted in a great interest in the utilisation of agricultural residues and wastes for particle board production [6]. These agricultural residues such as the stalks of most cereal crops, rice husks, coconut coir, bagasse, corn cobs, peanut shells etc are cheap and abundantly available in many developing countries such as Nigeria, Philippines, Indonesia, Sri Lanka, and India [7,8]. These materials are often disposed of inappropriately or openly incinerated thereby contributing to environmental pollution [9]. Bio-based composites have been reported as potential replacement for polymer and wood based composites as a result of their attractive qualities such as low technology requirement, environmental friendliness, low production cost, ease of recycling etc [10].

Several researchers have reported work on the usage of agricultural residues for the production of particle boards. Bekalo and Reinhardt [11] investigated the production of particle boards from coffee husk and hull fibres using thermosetting resins. Mendes et al. [5] produced particle boards from sugarcane bagasse. They investigated the effect of adhesive type and loading on the quality of particle board produced. They reported that the best particle board was produced using urea formaldehyde at a loading of 6%. Boquillon et al. [12] studied the properties of wheat straw and its potential for particle board production. Sekaluvu et al. [6] investigated the factors that affected the production of particle boards from maize cobs. Their results revealed that the properties of the particle boards produced were significantly affected by the resin content and particle size. Other studies have investigated the use of other agro residues such as rice husk [13], rattan [14], pine [4], cotton straws [15], sunflower stalks [16], and date palm leaves [17].

To the best of our knowledge, none of these studies have attempted to optimise the properties of the particle board produced from these agro residues. In our previous work, the potential use of corn cobs and cassava stalk for composite panel production was investigated and the factors that affected the production of particle boards were established [7]. However, in this work, the objective is to optimise the mechanical properties of particle boards produced from corn cobs and cassava bagasse using urea formaldehyde and phenol formaldehyde as binder. The mechanical properties will be optimised using design of experiment for response surface methodology. It is important to optimise these factors in order to maximise the mechanical properties. Response surface methodology based on statistically designed experiments has been found to be very useful in optimising multivariable processes. According to Montgomery [18], it is employed for multiple regression analysis of quantitative data obtained from statistically designed experiments.

2. **Materials and methods**

2.1. *Materials collection and preparation*

The agro residues used in this study, corn cobs and cassava stalks were obtained from the Faculty of Agriculture model farm in the University of Benin, Benin City, Nigeria. Urea formaldehyde (UF) and phenol formaldehyde used as binder were obtained from the Chemical Engineering Laboratory, University of Benin. The residues were milled using a hammer mill and then screened using standard sieves to obtain 2 mm particles. The milled residues were transferred into hot water at a constant temperature of 85^{o}C to extract inhibitory compounds such as glucose, hemicelluloses and lignin [19]. This was done in order to ensure proper setting of the boards. The extracted materials were separately air dried to attain approximately 12% moisture content before use.

2.2 *Design of experiment*

A three variable Box-Behnken design for response surface methodology was used to study the combined effect of board density, resin loading and amount of agro residue on the mechanical properties of the particle boards produced. The range and levels of the independent variables are shown in Table 1.

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

Independent Variables	Symbols	Coded and Actual Levels		
		-1	0	+1
Board density (kg/m^3)	X_1	1000	1100	1200
Resin loading (g)	X_2	386	424	463
Amount of agro residue (g)	X_3	154	170	185

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The Box-Behnken design has been established to be suitable for the exploration of quadratic response surfaces and this design generates a second degree polynomial model which can be used for optimisation purposes [20]. The number of experimental run for this design was obtained from Equation (1).

$$N= k^2 + k + c_p \tag{1}$$

Where k is the number of factors and c_p is the number of replications at the center point. The design for the production of particle boards was developed using Design Expert® 7.0.0 (Stat-ease, Inc. Minneapolis, USA). The coded and actual values of the independent variables were calculated using Equation (2).

$$x_i = \frac{X_i - X_o}{\Delta X_i} \tag{2}$$

Where x_i and X_i are the coded and actual values of the independent variable respectively. X_o is the actual value of the independent variable at the center point and ΔX_i is the step change of X_i. The following generalised second degree polynomial equation was used to estimate the response of the dependent variable [21].

$$Y_i = b_o + \sum b_i X_j + \sum b_{ij} X_i X_j + \sum b_{ii} X_i^2 + e_i \tag{3}$$

where Y_i is the dependent variable or predicted response, 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 [22].

2.3 *Particle board production and testing*

Corn cobs and cassava stalks were mixed together in a 1:1 ratio. The same was done for the resins (urea formaldehyde and phenol formaldehyde). After milling, the mixture of corn cobs and cassava stalks was thoroughly mixed with the resin (in the ratio 2:5) to obtain a lump free matrix. The resulting material was then put in a mat forming box with dimensions 35 cm×35 cm×0.6 cm. A manual press machine was used to make a pre-pressing at 0.78 N/mm^2. The box was then put in a hydraulic press and the boards were made by using an 8-minute press closing time at a pressure of 1.23 N/mm^2 [5]. The mat forming box was covered with polythene sheet prior to board formation to prevent the sticking of the boards onto the box. About 2 cm was trimmed off the edge of each board produced using a buzz saw and the boards were subsequently put in an acclimatisation chamber at a temperature of 20 ± 2 ºC and a relative humidity of 65 ±2 % for a period of 3 days. Mechanical tests (modulus of rupture (MOR) and modulus of elasticity (MOE)) as well as physical tests (thickness swelling (TS), water absorption (WA) and linear expansivity) were carried out on the boards according to standard methods of ASTM D1037 and DIN 52362 [23,24]. In this work, only the mechanical properties were presented.

3. **Results and discussion**

3.1. *Statistical analysis*

The Box-Behnken design resulted in 17 experimental runs as shown in Table 2. Equations (4) and (5) were obtained after applying multiple regression analysis to the experimental data. These second degree polynomial equations were used to estimate the responses, MOR and MOE respectively.

$$\begin{aligned} Y = &-173.988 - 0.125X_1 + 0.249X_2 + 2.117X_3 + 0.000026X_1X_2 - 0.000153X_1X_3 \\ &+0.000587X_2X_3 + 0.000064X_1^2 - 0.000221X_2^2 - 0.0051X_3^2 \end{aligned} \tag{4}$$

$$\begin{aligned} Y = &-173.988 - 0.125X_1 + 0.249X_2 + 2.117X_3 + 0.000026X_1X_2 - 0.000153X_1X_3 \\ &+0.000587X_2X_3 + 0.000064X_1^2 - 0.000221X_2^2 - 0.0051X_3^2 \end{aligned} \tag{5}$$

The values of MOR and MOE predicted by Equations (4) and (5) are given in Table 2 along with the experimental data. The significance of the fit of the equations representing MOR and MOE was assessed by carrying out analysis of variance (ANOVA). ANOVA results show that the models for MOR and MOE were statistically significant with p values of 0.0004 and 0.0066 respectively as shown in Tables 3 and 4. Both models did not show lack of fit as seen from their "lack of fit" p values (0.7234 and 0.0997 respectively). For both models, the terms representing resin loading and amount of agro residues were significant while the term representing board density was not significant indicating that it did not significantly influence the MOR and MOE of the boards produced.

Table 2: Box-Behnken design for the production of particle boards

Run	Factors						Response			
	Coded values			Actual values			MOR (N/mm^2)		MOE (N/mm^2)	
	X_1	X_2	X_3	X_1	X_2	X_3	Actual	Predicted	Actual	Predicted
1	1	-1	0	1200	386.0	169.5	2.20	2.19	578.0	604.69
2	0	1	-1	1100	463.0	154.0	3.50	3.71	932.4	945.83
3	0	0	0	1100	424.5	169.5	2.42	3.19	734.2	823.80
4	0	1	1	1100	463.0	185.0	2.14	2.10	324.0	401.60
5	0	-1	-1	1100	386.0	154.0	0.43	0.47	492.0	414.40
6	1	0	1	1200	424.5	185.0	1.74	1.96	680.2	666.94
7	-1	0	-1	1000	424.5	154.0	2.99	2.77	764.7	777.96
8	-1	0	1	1000	424.5	185.0	2.30	2.33	678.0	627.09
9	-1	-1	0	1000	386.0	169.5	2.10	2.28	494.2	558.54
10	1	0	-1	1200	424.5	154.0	3.38	3.35	760.1	811.01
11	0	0	0	1100	424.5	169.5	3.38	3.19	845.0	823.80
12	0	0	0	1100	424.5	169.5	3.38	3.19	844.0	823.80
13	0	-1	1	1100	386.0	185.0	0.47	0.26	677.1	663.68
14	0	0	0	1100	424.5	169.5	3.38	3.19	845.0	823.80
15	1	1	0	1200	463.0.	169.5	5.10	4.92	794.0	729.66
16	-1	1	0	1000	463.0	169.5	4.60	4.61	729.6	702.91
17	0	0	0	1100	424.5	169.5	3.38	3.19	845.0	823.80

Table 3: ANOVA results for model representing MOR

Sources	Sum of Squares	df	Mean Squares	F value	p value
Model	23.56	9	2.62	18.45	0.0004
X_1	0.023	1	0.023	0.16	0.6986
X_2	12.85	1	12.85	90.57	< 0.0001
X_3	1.67	1	1.67	11.74	0.0111
X_1X_2	0.040	1	0.040	0.28	0.6119
X_1X_3	0.23	1	0.23	1.59	0.2477
X_2X_3	0.49	1	0.49	3.45	0.1055
X_1^2	1.72	1	1.72	12.14	0.0102
X_2^2	0.45	1	0.45	3.19	0.1174
X_3^2	6.32	1	6.32	44.54	0.0003
Residual	0.99	7	0.14		
Lack of Fit	0.26	3	0.085	0.46	0.7234
Pure Error	0.74	4	0.18		
Cor Total	24.56	16			

Table 4: ANOVA results for model representing MOE

Sources	Sum of Squares	df	Mean Squares	F value	p value
Model	3.629E5	9	40321.45	7.75	0.0066
X_1	2657.21	1	2657.21	0.51	0.4980
X_2	36274.71	1	36274.71	6.97	0.0334
X_3	43497.75	1	43497.75	8.36	0.0233
X_1X_2	94.09	1	94.09	0.018	0.8968
X_1X_3	11.56	1	11.56	2.22E-3	0.9637
X_2X_3	1.574E5	1	1.574E5	30.25	0.0009
X_1^2	3849.71	1	3849.71	0.74	0.4182
X_2^2	88053.79	1	88053.79	16.92	0.0045
X_3^2	22322.78	1	22322.78	4.29	0.0771
Residual	36421.81	7	5203.12		
Lack of Fit	27643.01	3	9214.34	4.20	0.0997
Pure Error	8778.80	4	2194.70		
Cor Total	3.993E5	16			

Statistical information for ANOVA shows that the models describing MOR and MOE had high coefficient of determination (R^2) as shown in Table 5. This shows that the models were able to adequately represent the relationship between the chosen factors (board density, resin loading and amount of agro residue) and responses (MOR and MOE). R^2 values of 0.96 and 0.91 means that the models were able to explain 96% and 91% of the variability observed in the values of MOR and MOE respectively. The standard deviations were observed to be relatively small compared to the mean. The coefficient of variation was obtained for both models as 13.66 and 10.20 respectively. This parameter shows the degree of precision with which the runs were carried out. The values obtained show a high reliability as recommended by Montgomery [18]. The Adequate precision for both models indicate adequate signals meaning that the models can be used to navigate the design space [25].

Table 5: Statistical information for ANOVA

Parameter	Value	
	MOR	MOE
R-Squared	0.96	0.91
Mean	2.76	707.25
Standard Deviation	0.38	72.13
C.V %	13.66	10.20
Adeq. Precision	16.13	9.44

3.2. *Optimisation of particle board production*

Response surface methodology was used to optimise the particle board production variables. This was achieved by generating response surface plots showing the effects of board density, resin loading and amount of agro residue on the MOR and MOE of the boards produced. Figure 1 shows the effect of resin loading and amount of agro residue on the MOR of the particle boards. The trend observed shows that the MOR increased with increase in the amount of resin irrespective of the amount of agro residue used. This shows that there was adequate adhesion between the resin and the agro residue resulting in the increased MOR [10]. Previous reports have shown that to produce particle boards with high MOR, more of the resin has to be used [5,7,26]. Murakami et al. [27] reported that the mechanical and physical properties of particle boards could be enhanced by increasing the amount of resin used. The resin loading has been reported to determine the amount of voids present in the boards produced [6]. When a low resin loading is used, the resin is mixed up with the agro residue particles leaving some voids present. However, when the resin loading is increased, some of it is mixed with the agro residue particles to form the finish while the remainder fills up the voids that would otherwise be present in the finished product. Figure 1 also shows that intermediate amount of agro residue was needed to produce particle boards with high MOR values. Since a constant agro residue to resin ratio was used, intermediate amount of agro residue means that more resin could be used to produce the boards consequently resulting in the enhancement of the mechanical properties.

The effect of resin loading and board density on the MOR is shown in Figure 2. With respect to resin loading, a trend similar to that shown in Figure 1 was observed showing that the utilisation of high resin loadings enhanced the MOR of the boards produced. The density of the boards did not have any significant effect on the MOR irrespective of the amount of resin used. This corroborates the observation made in Table 3 that the model term representing board density had a p value greater than 0.05 showing that it was not significant.

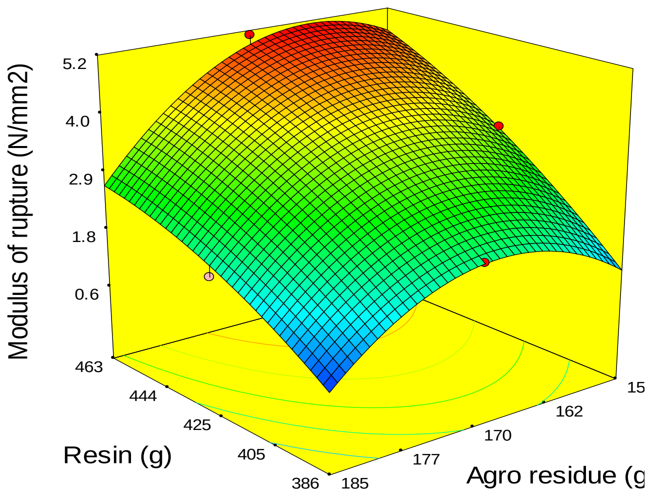

Figure 1: Effect of resin loading and amount of agro residue on MOR

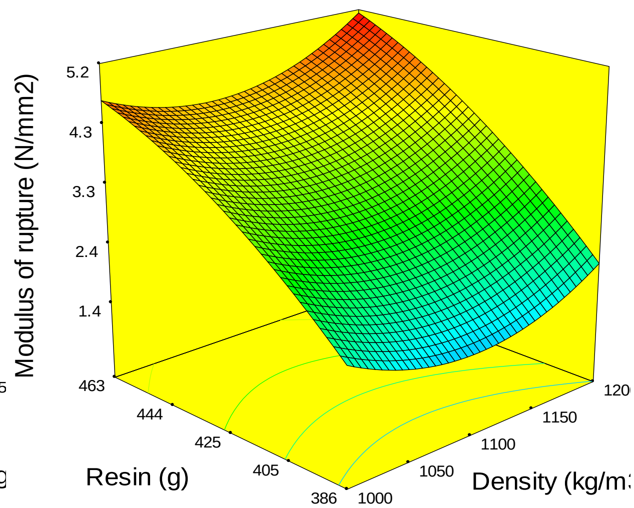

Figure 2: Effect of resin loading and board density on MOR

Figure 3 shows the effect of amount of agro residue and board density on MOR. The trend observed are similar to those presented in Figures 1 and 2 respectively. The MOE of the boards was observed to increase with increase in resin loading as shown in Figure 4. Good bond quality resulting from adequate contact between the resin and the agro residue particles has been cited as a reason for high MOE values [6]. This follows from the fact that high resin loadings increases the bond contact between the particles which in turn results in improved surface contact created when the particles are surrounded by a significant film of resin [28]. Since MOE and MOR are both mechanical properties, the trend observed for both would be expected to be similar. Both measures of mechanical strength of particle boards have been reported to be influenced by particle geometry and amount of resin [11,29].

The density of the boards did not significantly influence the MOE of the boards as shown in Figure 5. This is in agreement with results presented in Table 4. The requirement for agro residue-based particle boards is high MOR and MOE. Figure 5 shows that high MOE values were obtained when low levels of agro residue were used. Since a fixed ratio of agro residue to resin was utilised in producing the boards, a low level of agro residue translates to a high loading of resin. Therefore, reducing the amount of agro residue means increasing the amount of resin used which consequently increases the MOE of the boards.

The optimum levels of the independent variables and the responses (MOR and MOE) were determined from numerical optimisation of the statistical models (Equations 4 and 5) and the top five results are shown in Table 6. The results show that the maximum MOR and MOE were obtained at a board density of 1200 kg/m^3, a resin loading of 463 g and an agro residue loading of 155.99 g. The values of MOR and MOE obtain at these optimised conditions were 4.9 N/mm^2 and 910.03 N/mm^2 respectively. The American National Standard ANSI/A208.1-1999 specifies a minimum MOR and MOE of 3 N/mm^2 and 550 N/mm^2 respectively for general purpose particle boards [30]. The optimum MOR and MOE of the particle boards produced from the agro residues was found to satisfy this requirement as they had MOR and MOE values which were higher than the minimum standard.

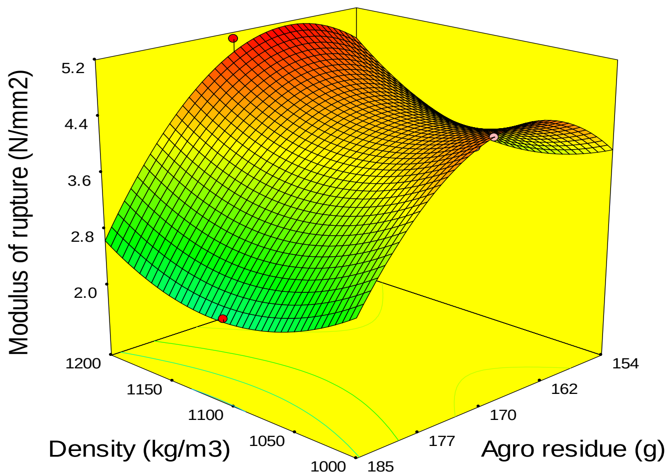

Figure 3: Effect of board density and amount of agro residue on MOR

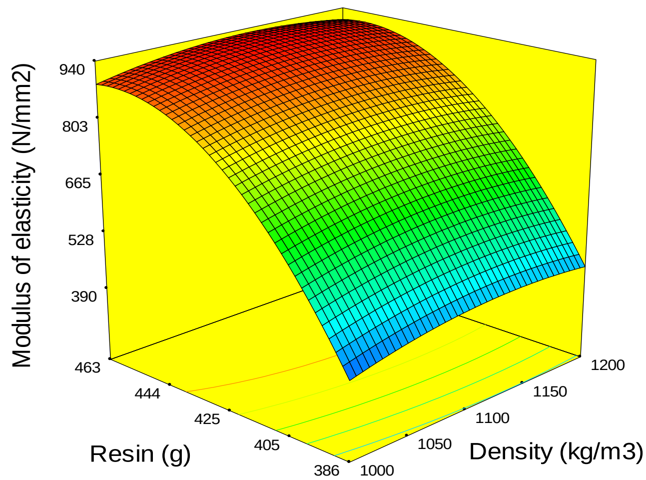

Figure 4: Effect of resin loading and board density on MOE

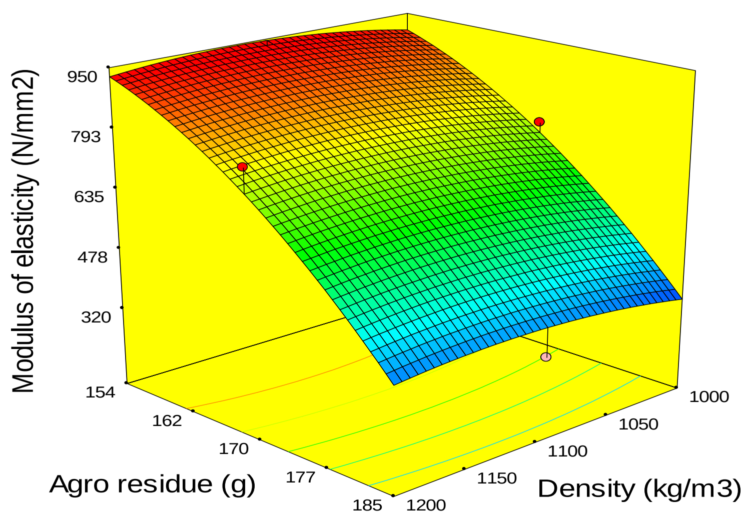

Figure 5: Effect of board density and amount of agro residue on MOE

Table 6: Solutions for optimum conditions

Solution	Board density	Resin loading	Agro residue	MOR	MOE	Desirability
1	1200	463.0	155.99	4.90	910.03	0.834
2	1200	463.0	156.26	4.92	907.49	0.834
3	1200	462.3	156.25	4.90	908.64	0.833
4	1200	463.0	154.02	4.74	927.07	0.831
5	1200	460.7	154.84	4.75	922.10	0.828

3.3. *Validation of statistical model*

Three validation experimental runs were performed at the chosen optimum conditions to validate the statistical models representing MOR and MOE. The result shows that the maximum MOR and MOE values of 4.91 N/mm^2 and 910.10 N/mm^2 respectively obtained were close to the predicted values of 4.90 N/mm^2 and 910.03 N/mm^2 respectively. The excellent correlation between the predicted and measured values of these experiments shows the validity of statistical models.

Conclusions

In this study, particle boards were produced from corn cobs and cassava stalks using urea formaldehyde and phenol formaldehyde as binder. Design of experiment for response surface methodology has been demonstrated to be useful in optimising the board production process. Mechanical properties of the board such as MOR and MOE were influenced by the amount of agro residue and resin used but they were not influenced by the board density. Quadratic statistical models developed to represent MOR and MOE showed a good fit with the experimental data with R^2 values of 0.96 and 0.91 respectively. The best particle board was produced at the optimised conditions and it had a MOR and MOE of 4.90 N/mm^2 and 910.03 N/mm^2. This was achieved at a board density of 1200 kg/m^3, a resin loading of 463 g and an agro residue loading of 155.99 g. The particle board produced at the optimised conditions satisfied the American National Standard ANSI/A208.1-1999 specification for general purpose particle boards.

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