Predictive Models for some Densification Characteristics of Corncob Briquettes

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Abstract: Corncob is a renewable energy resource that has a considerable potential to meet the energy demand in rural areas in Nigeria, especially for domestic and small scale cottage applications. Corncobs utilized were sun-dried and their moisture content was determined using ASAE standard. The residues were subjected to size reduction process and three particle sizes S_1 (4.70 mm), S_2 (2.40 mm) and S_3 (0.60 mm) were selected. The bulk density of the unprocessed materials and relaxed briquettes were determined using ASAE standard. Starch mutillage (binder) was added to the residues at 20 (B_1), 25 (B_2), and 30 % (B_3) by weight of the residue. A briquetting machine was used to form briquettes at pressures of 2.40 (P_1), 4.40 (P_2) and 6.60 (P_3) MPa with observation of a dwell time of 120 seconds. The initial, maximum and the relaxed densities of the briquettes were determined using the mould dimension, the relaxed briquette's dimension and ASAE standard method of determining densities. Also determined were the compaction, density and relaxation ratios of the formed briquettes. Percentage axial and lateral expansions were also determined. The experimental data were subjected to regression analysis. A statistical package SPSS version 11.0 was used. The regression coefficients for the maximum density, relaxed density, compaction ratio, density ratio, relaxation ratio, axial expansion and lateral expansion are 0.72, 0.81, 0.85, 0.84, 0.77, 0.86 and 0.81 respectively. The study concluded that there is no significant difference between experimental and predicted results. Hence, all the developed models are reliable.

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1. Introduction

Corncob is a renewable energy resource that has a considerable potential to meet the energy demand in rural areas in Nigeria, especially for domestic and small scale cottage applications.

Corncob residues are abundantly available in Nigeria. This is because; Nigeria was the second largest producer of maize in Africa in the year 2006 with 7.5 million tons (FOS, 2006). In Nigeria alone, twenty eight different food items can be prepared from maize (BCOS, 2010). South Africa has the highest production of 11.04 million tons (Adesanya and Raheem, 2009). The bulk density of raw corncob is around 50 kg/m^3, whereas the highest bulk density of unprocessed wood is around 250 kg/m^3 (Demirbas, 2001; Oladeji, 2011). Therefore, these bulky residues can be densified into briquettes. Briquetting is a method of increasing the bulk density of biomass by mechanical pressure (Wilaipon, 2009). Briquettes have low moisture content (about 8% wet basis) for safe storage and high bulk density (more than 600 kg/m^3) for efficient transport and storage. The process of forming biomass into briquettes depends upon the physical properties of ground particles and process variables during briquetting. The compaction process is a complex interaction between particles, their constituents and forces. Mani et al. (2004) evaluated the compaction mechanism of straws, stover and switch grass using different compaction models.

In order to optimize briquetting process in term of processing parameters or briquetting machines, many researchers have carried out investigations into modelling of biomass briquetting. For example, Mandavgane and Venkatesh (2006) developed artificial neural networks for modelling of properties of bio-briquettes like ash, volatile matter, relative moisture and calorific value as a function of compositions of briquettes. Artificial Neural Networks (ANN) is part of black box modelling technique, which had been used for estimation of properties of bio-briquettes. In the work, multiplayer perception (MLP), ANN with Generalized Delta Rule (GDR) based learning was developed for estimation of properties of bio-briquettes as a function of composition. The most accurate ANN model was arrived at, after number of trials and errors as done in earlier attempts by Mandavgane et al. (2006). The biomass feed stocks used were cow dung, sawdust, rice and tree leaves. There was straight line relationship between the actual and predicted values of percentage ash content, relative moisture content, volatile matter and calorific values. This reveals the accuracy and success of the ANN models developed, which have high accuracy level of between 98-99.5%.

Hernandez et al. (2004) attempted to find the levels of factors that provide optimum responses in terms of quality of products and cost in the densification of a cattle feed diet based on corn crop residues (62%). The responses (dependent variables) defined according to the application were density and durability as those variables represent quality of product and specific energy consumption as a cost parameter. To attain this goal, an optimization procedure for multiple response problems was used. This procedure uses the response surface methodology (RSM) and the desirability function. The RSM is popular in the study of the food-extrusion processes (Mercier and Harper, 1999). RSM is a collection of statistical techniques that are useful for modelling and analysis of process (Myers and Mongomery, 1995). Through the use of optimization process, the optimum values arrived at were 13% moisture content, $102^{O}C$ die temperature, $28N/m^2$ compression pressure and particle size 9.5mm.

Mani et al. (2003) developed a numerical model using Discrete Element Method (DEM) to study the compaction characteristics of biomass during densification. DEM is a numerical modelling method that makes use of contact mechanics between the particles and the wall to model the dynamics of assemblies of particles (Kremmer and Favier, 2000). In the work, DEM was used to model the compaction behaviour of corn stover grinds using particle flow code in 3D (PFC^{3D}) software. The specific properties of biomass particles such as particle size distribution, particle density, particle stiffness, particle-particle friction and particle-wall friction were incorporated into the model. A simple contact bond model was developed to produce the compacted mass.

The objective of this research was to develop predictive models by using regressive technique to establish the relationship between the particle sizes, briquetting pressures and percentage binder ratios by weight. The relationship developed was used to predict response parameters such as density, relaxed density, compaction and density as well as relaxation ratios. The relationship was also used to predict briquettes stability through the determination of percentage axial and lateral expansions.

2. Materials and Methods

Corncobs were obtained from farm dumps and those that were healthy and fungus free was selected. They were sun-dried and their moisture contents were determined using ASAE S269.4 (2003). The corncob residues were subjected to size reduction process through the use of hammer mill equipped with different screens in compliance with procedure described in ASAE 424.1 (2003). Three particle sizes S_1 (4.70 mm), S_2 (2.40 mm) and S_3 (0.60 mm) representing coarse, medium and fine series respectively were selected. The bulk density of the unprocessed materials and relaxed briquettes were determined using ASAE standard. Starch mutillage (binder) was added to the residues at 20 (B_1), 25 (B_2), and 30 % (B_3) by weight of the residue. A briquetting machine specially designed and fabricated for formation of briquettes was filled with a fixed charge of residue and compressed manually. Pressures of 2.40 (P_1), 4.40 (P_2) and 6.60 (P_3) MPa were separately applied for each briquette formation. A dwell time of 120 seconds was observed for the briquettes during formation. The initial, maximum and the relaxed densities of the briquettes were determined using the mould dimension, the relaxed briquette's dimension and ASAE standard method of determining densities. Also determined were the compaction, density and relaxation ratios of the formed briquettes. Briquette stability through the calculation of percentage axial and lateral expansions was also determined. These experimental data were subjected to regression analyses. Regression analysis provides a simple method for investigating functional relationships among variables. A statistical package SPSS version 11.0 was used for this analysis.

The process parameters examined in this work were % binder ratio (B), compaction pressure (P), and particle size (S). The output (response) variables are the physical properties of the briquettes. These output variables are as follows:

i) Maximum Density ii) Relaxed Density iii) Compaction Ratio iv) Density Ratio
v) Relaxation Ratio vi) Axial Expansion vii) Lateral Expansion

2.1 Model Development

Let the functional relationship between the output variable and the set of input parameters be as follows:-

i) Maximum Density = f [% Binder ratio (B), Compaction pressure (P), Particle size (S)] + C_1 (1)

ii) Relaxed Density = f [% Binder ratio (B), Compaction pressure (P), Particle size(S)] +C_2 (2)

iii) Compaction Ratio= f [% Binder ratio (B), Compaction pressure (P), Particle size (S)] + C_3 (3)

iv). Density Ratio = f [% Binder ratio (B), Compaction pressure (P), Particle size(S)] + C_4 (4)

v) Relaxation Ratio = f [% Binder ratio (B), Compaction pressure (P), Particle size(S)] + C_5 (5)

vi). Axial Expansion = f [% Binder ratio (B), Compaction pressure (P), Particle size(S)] + C_6 (6)

vii) Lateral Expansion = f [% Binder ratio (B), Compaction pressure (P), Particle size (S)] + C_7 (7)

Having established the different relationship of each input variable with the output variables, multiple regression analyses were done to estimate the coefficients of model factor.

After formulating equations 1 to 7, simulations of the equations were done and the results were compared with the experimental to show the practicability of the model. The simulation was conducted on Mat Lab 6.50 version of Mathworks Inc. NY, which is a mathematical simulator.

3. Results and Discussions

The estimated coefficients of the fitted models for output variables obtained from regression analyses of experimental data are presented in Table 1.

From Table 1, the regression analyses for the seven models for briquettes produced from corncob had regression coefficients r = 0.72, 0.81, 0.85, 0.84, 0.77, 0.86 and 0.81 for the maximum density, relaxed density, compaction ratio, density ratio, relaxation ratio, axial expansion and lateral expansion respectively. All these values are significant at 95% level implying good model fit.

Table 1. Estimated coefficients of the fitted models for output variables based on t- statics for corncob briquettes

Maximum Density	**Model Factor**	**Coefficients**	**t-values**
(kg/m^3)	Constant C_1	797.50	11.57
	B	12.289	- 4.95
	P	23.121	4.20
	S	24.693	4.09
	R^2=0.72, s = 52.6		
Relaxed Density (kg/m^3)	Constant C_2	439	20.05
	B	1.922	- 2.44
	P	4.699	2.69
	S	17.940	- 9.36
	R^2 = 0.81 s = 16.70		
Compaction Ratio	Constant C_3	4.4447	7.92
	B	- 0.10989	- 5.44
	P	0.12874	2.87
	S	0.47391	9.65
	R^2 = 0.85 s = 0.4283		
Density Ratio	Constant C_4	0.57774	11.27
	B	0.006222	-3.37
	P	- 0.010804	- 2.64
	S	- 0.046532	-10.36
	R^2 = 0.84, s = 0.03915		
Relaxation Ratio R_{RW}	Constant C_5	1.8643	8.25
	B	- 0.024889	- 3.06
	P	0.03834	2.12
	S	0.15862	8.01
	R^2 = 0.77, s = 0.1726		
Axial Expansion A_{EW} (%)	Constant C_6	- 4.152	- 3.57
	B	0.29122	6.95
	P	- 0.50428	- 5.42
	S	- 0.8433	8.28
	R^2 = 0.86, s = 0.8883		
Lateral Expansion L_{EW} (%)	Constant C_7	- 0.7107	-1.64
	B	0.09778	6.29
	P	- 0.20367	-5.90
	S	0.18032	4.76
	R^2 = 0.81, s = 0.3300		

Following the regression analyses to estimate the response models and the accompanying statistics, the developed models for maximum density, relaxed density, compaction ratio, density ratio, relaxation ratio, axial expansion and lateral expansion are presented in equations 8 – 14. These are the empirical models obtained from multiple regression analyses.

i) Maximum density

$$= 797 - 12.3B + 23.1P + 24.7S \quad (8)$$

ii) Relaxed density

$$= 439 - 1.92B + 4.70P + 17.9S \quad (9)$$

iii) Compaction ratio

$$= 4.44 - 0.110.129P + 0.474S \quad (10)$$

iv)

$$\text{Density ratio} = 0.578 - 0.0062B + 0.0108P + 0.465S \quad (11)$$

v)

$$\text{Relaxation ratio} = 1.06 - 0.0249B + 0.0383P + 0.159S \quad (12)$$

vi)Axial Expansion

$$= -4.15 + 0.291B - 0.504P + 0.843S \quad (13)$$

vii) Lateral expansion

$$= -0.711 + 0.0978B - 0.204P + 0.100S \quad (14)$$

Where

B = Percentage binder ratio by weight (%)
P = Compaction pressure (MPa)
S = Particle size (mm)

3.1 Simulation and Validation of Models

The summary of the t-test for the simulated models for the seven physical properties examined in this study is presented in Table 2 at 95% significant level for briquettes formed.

Table 2. Summary of T-calculated and t-test for experimental and simulated models for briquettes produced from corncob

Source of Variation	T-value Calculated	t-value Critical	Remark
Maximum Density	0.499	1.675	No Significant Difference
Relaxed Density	0.499	1.675	No Significant Difference
Compaction Ratio	0.50	1.674	No Significant Difference
Density Ratio	0.50	1.674	No Significant Difference
Relaxation Ratio	0.499	1.675	No Significant Difference
Axial Expansion	0.499	1.674	No Significant Difference
Lateral Expansion	0.499	1.675	No Significant Difference

For all the physical properties examined in this work, the values of T-calculated are less than t-critical, implying there is no significant difference between the experimental and the simulated models (Table 2). Figures 1 - 7 showed the comparison between the experimental and simulated properties of the briquettes for three of the response parameters which are maximum and relaxed densities as well as compaction ratio.

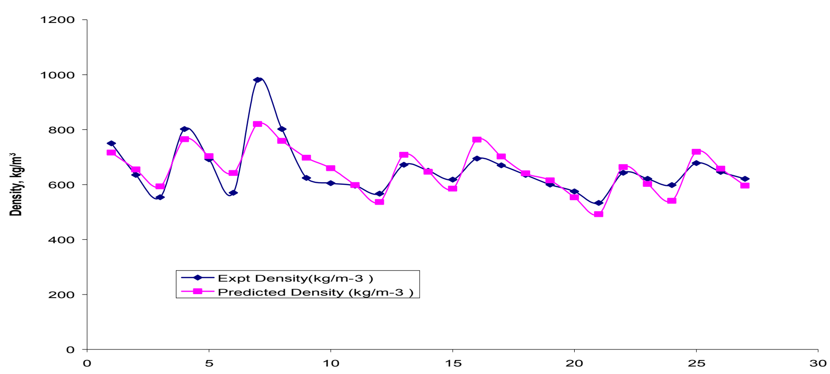

Figure 1. Comparison of experimental and simulated maximum density for briquettes formed

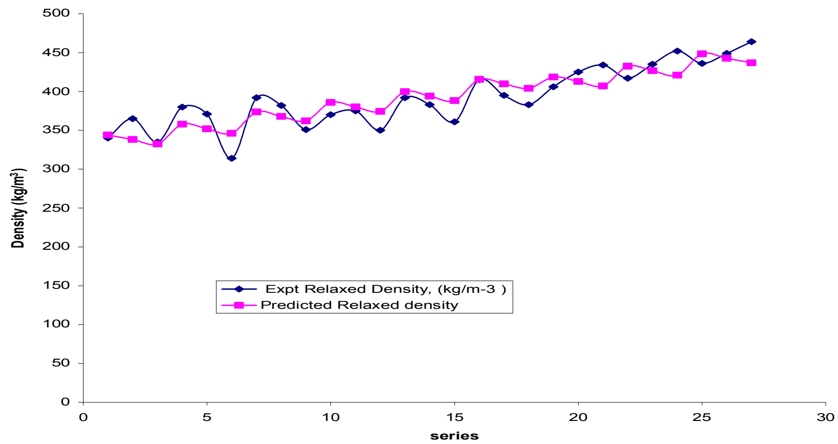

Figure 2. Comparison of experimental and simulated relaxed density for briquettes formed

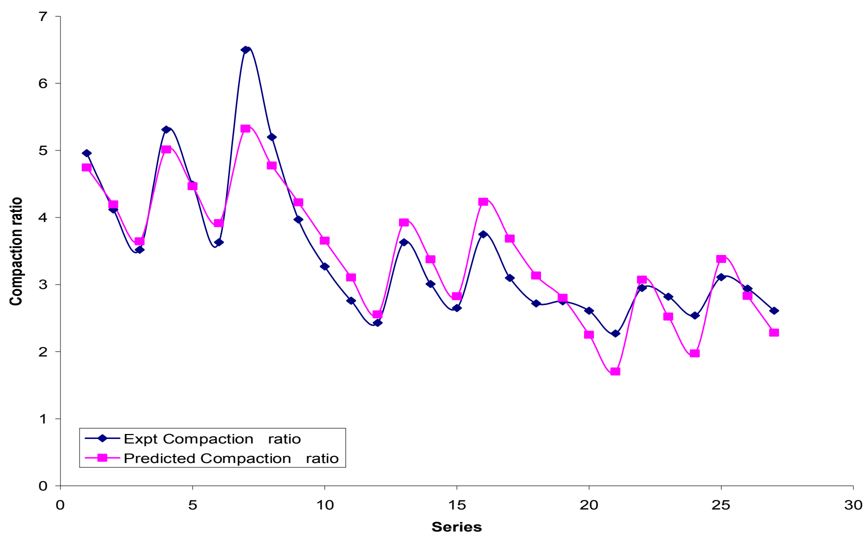

Figure 3. Comparison of experimental and simulated compaction ratio for briquettes formed

4. Conclusions

Seven (7) mathematical models were developed for briquettes produced from corncobs. The regression analyses for the seven models had regression coefficients r = 0.72, 0.81, 0.85, 0.84, 0.77, 0.86 and 0.81 for the maximum density, relaxed density, compaction ratio, density ratio, relaxation ratio, axial expansion and lateral expansion respectively.

Since t-statistics is less than t-critical both at one and two-tail with 95% confidence level for all the physical parameters examined in this study, it can be concluded that there is no significant difference between experimental and predicted results. Hence, all the developed models are reliable.

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