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Physico-mechanical Characteristics of High Density Briquettes produced from Composite Sawdust

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ABSTRACT: Physico-mechanical characteristics of briquettes produced from composite sawdust admixture using a screw press briquetting machine was investigated. Sample feedstock materials collected has particle sizes varying between 6-8mm with 10-20% powdery components (< 4 mesh). Briquette's physical characteristics investigated using standard test apparatus and procedures include dimensional stability immediately, 1 hour and 30 days after production, effects of particle moisture and particle size on briquette compressed and relaxed densities. Mechanical characteristics include resistance to gravity and impact, effects of densities on impact resistance index (IRI) and effects of briquette durability in water. Statistical models were used to establish empirical relationships between the feedstock materials (independent variables) and briquette characteristics (independent variables). The physical characteristics of briquettes produced at 12% are loose and brittle with poor dimensional stability, at 10% they are bonded but weak in strength with good dimensional stability while briquettes produced at 8% are well-formed, good colouration with char carbonation, excellent dimensional stability. The compressed density of the briquettes ranges of 490-820 kg/m^3. The lower moisture briquettes have high resistance to water dispersion, high impact resistance and excellent storability.

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Composite sawdust admixture are material wastes generated directly from primary and secondary wood processing machines without separation of its components into materials such as bark, dust, shaves, chips and other particulate matters. These materials are produced in large volumes from timber industries and they constitute nuisance to both public health and the environment when not properly managed (Elinwa and Abdulkadir, 2011). This has been affirmed by the increasing number of sawmills springing up in Nigeria today, particularly in the South west Nigeria (Bello and Onilude, 2013). The presence of these wastes in large quantity poses disposal problems for the industries. Taking advantage of the energy potentials wasted in burning of these massive wastes in open dump sites, their efficient use to meet part of energy demand for heating and gas emissions reduction through conversion processes has become imperative. These wastes can be briquetted in various forms, either as pellets, or briquettes through low or high temperatures and pressure applications and be utilized as high-grade solid briquette fuels by improving the calorific value and ensuring a clean smoke-free flame suitable for small scale industrial and domestic applications. A number of locally available materials have been briquetted for energy production according to (Faborode, 1988; Adekoya 1989; Ajayi and Lawal 1995; Olorunnisola 1998, 1999). Several research efforts have equally been extensively made to study compression characteristics of different types of biomass. For instance, alfalfa (Adapa *et al.*, 2006; Hall and Hall 1968), straws/grasses (Demirbaş 1999; Kaliyan and Morey 2006; Mani *et al.*, 2006a; Mani *et al.*, 2006b; Ndiema *et al.*, 2002; Shaw *et al.*, 2006; Wamukonya and Jenkins 1995), palm fiber/shell (Husain *et al.* 2002), olive cake/refuse (Yaman *et al.*, 2000), wood and wood waste (Chin and Siddiqui 2000; Li and Liu 2000) as well as sawdust/charred palm kernel shell (Kuti, 2009) among other studies. However, in many of the foregoing studies, the briquettes were produced as low/medium density, mostly with the aid of binders such as cassava starch and palm oil sludge which tend to produce smoky briquettes. This work presents studies on the physico-mechanical characteristics of briquettes produced in binderless high temperature operation using composite sawdust from mill sites in the south-western Nigeria. In order to achieve this research objective, a screw press extruder developed at the University of Ibadan, Nigeria was used to produce the briquettes.

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MATERIALS AND METHOD

Experimental machine setup: The experimental machine (figure 1) used in this test was an electrically powered screw type extruder developed at the University of Ibadan, Nigeria. The machine is in four segments; the power unit, the speed reducer gear assembly, extrusion assembly and the control panel. The power unit comprising of an induction motor and a three-grooved belt-pulley power transmission system. The motor is mounted on an adjustable base joined to the main frame. The speed reducer gear assembly which serves dual functions of speed reducer and steady power transmission to the extruder. The extrusion assembly comprising of the extrusion barrel, the screw shaft, the die and heater. The barrel is mounted on the main frame with bolts while the screw shaft is supported (cantilever support) by a large double roller thrust bearing fitly fixed into the extruder barrel. The screw shaft is connected to the reducer gear output shaft through a detachable universal joint. The die comprises of a ring bracket attaching it to the barrel, the bored conical extrusion chamber that necked into a cylindrical bore which produces the final briquette.

Fig 1: Experimental machine

Feedstock material preparation: Sawdust from sawn wood of different species (Figure 2) were collected from sawmill industries around Ibadan metropolis, sun dried to three moisture contents of 8%, 10% and 12%. The feedstock material is composed of different particle sizes which are known to improve the packing dynamics and also contribute to high static strength (Ludwig, 1994). However, it is also desirable to have a randomly distributed particle sizes so that an adequate amount of sufficiently small particles is present for embedding into the larger particles. The materials were subjected to particle size analysis following ASAE Standard S319.4 test procedure according to Adapa *et al*, (2009) to determine its physical characteristics. These materials were sorted for foreign materials and other particulate matters and stored at room temperature conditions in readiness for briquetting.

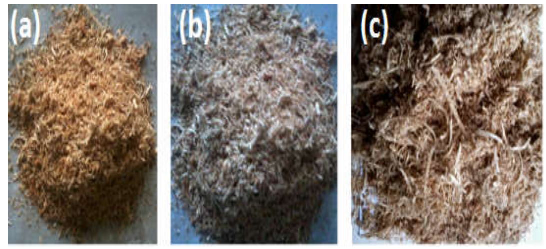

Fig 2: Sample feedstocks showing variations in particle sizes; a) 2-5mm, 3-6mm and 8-10mm

Methodology: The experimental machine at start-up was allowed to run at idle speed for five minutes to check for irregularities. Before the commencement of production, the heating elements was energized and subsequent die heating. The estimated start-up time for die heating was 15 minutes to allow enough time for the heaters to raise the temperature of the die to briquetting temperature of about 300°C. The extruder induction motor is then powered and feedstocks loading commenced. The die heater element was set at a temperature of 270 °C and allowed to beat the die gradually to briquetting operating temperature of 300 °C over a period of 10-15minutes. The machine was then loaded with feedstock material intermittently with sawdust. From the point of loading to the time densified briquettes appeared from the die-end was regarded as the start-up time and progressively, the length of extrusion at intervals were measured until the machine stopped or the briquette break off.

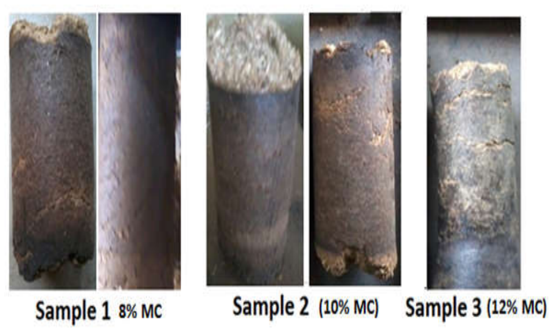

Fig 3: Briquette samples produced

Briquette performance test characteristics: The following physical characteristics were determined for sample briquettes produced.

Briquette physical characteristics: Briquette dimensional characteristics: The dimensional properties (diameter and unit lengths) of briquettes produced were consistently measured by a Vernier caliper at extrusion determine briquette stability and their durability tested according to test standards

(Yogesh, 2016). Briquettes were tested for dimensional stability, immediately, 1 hour and 30 days after production. The percentage elongation in length, or relaxation in length, is expressed as

$$\% \, elongation = \frac{L_1}{L_2 - L_3} \qquad 1$$

Where; L_1 = Total average elongation of samples along axial dimensions; L_2 = Longest elongation measured moments after extrusion; L_3 = Longest elongation measured after 1hour

Dimensional stability of the products was tested immediately after the briquettes were produced and an hour after the product has fully been cooled (Figure 4).

Fig 4: Measuring sample briquettes for dimensional stability and weight

Weight measurement: Samples of carefully cut briquettes were dressed and measured on electronic weighing balance as shown in figure 4 while the representative weights of samples were recorded.

Mechanical characteristics: Toughness test: The toughness of the briquettes defined through resistance to gravity drop was evaluated through the percentage of decrease in mass after dropping the briquettes at least three times from a height of 2.0m on to a cemented concrete platform. After each drop, the test piece was put through a sieve with openings smaller than the minimum dimension of the briquette. According to Borowski, (2010), the gravitational resistance to drop should attain a value higher than 90%. Briquette resistance to gravity is evaluated in the equation 5 below:

$$K = \frac{B_z}{B} x100 \qquad 2$$

Where: B = Briquette mass before dropping, B_z = Mass remaining in filled sieve

Briquette densities: Briquette density measured immediately after production are regarded as compressed density, while briquette densities determined 30 days after removal from the press in accordance with ISO 3131 (1975) is regarded as relaxed density (RD). The briquette compressed density was calculated by dividing the average mass of the briquette by its volume.

$$CD = \frac{Mass}{Volume} (g|cm^3) \qquad 3$$

The mass of briquettes was determined using a laboratory electronic balance with an accuracy of 0.01 g. The diameter and length of a briquette were measured at three points with a Vernier Caliper. Relaxed density was then computed adopting the relation used by Mitchual *et al.,* (2013):

$$RD(g|cm^3) = \frac{108{,}000 \, xM(g)}{\pi[d_1mm + d_2mm + d_3]^2 x[l_1mm + l_2mm + l_3mm]} \qquad 4$$

Where d_1, d_2 and d_3 are diameters (mm) measured at three different points on the briquettes and l_1, l_2 and l_3 are lengths (mm) measured at three different points on the briquettes. M (g) is the mass of briquette.

Compression test: Compressive strength is a criterion for determining briquette durability from the point of view of briquettes transportation, manipulation and storage. Briquettes' strength in cleft and axial pressure are two methods employed in compression tests. Since the briquettes shape is cylindrical, the compressive strength was determined in cleft failure for compressed and intact briquettes using an Instron universal testing machine in accordance to ASTM D 2166-85 (Adapa *et al.,* 2006 and Mani *et al.,* 2006b).

RESULTS AND DISCUSSIONS

Material particle distribution: The characteristics of sawdust particle sizes of sawdust produces by different sawing machines used in primary and secondary sawmill activities had been investigated by Bello (2017). Preliminary studies on sawdust samples collected showed that geometric mean particle size of feedstock particle varies between 6-8 mm with 10-20% (ASAE Standard S319.4) powdery component (< 4 mesh) which is known to give better products. It is also desirable to have a randomly distributed particle sizes so that an adequate amount of sufficiently small particles is present for embedding into the larger particles.

Physical characteristics of samples: The representative weight, extrusion diameter, length and other physical attributes of samples measured after extrusion. Average dimensional changes along the diametric and length axes are 0.23mm and 0.35mm respectively (Table 1). This could be as a result of higher axial compression in the direction of forward movement resulting from screw conveyor. This condition could be explained by inter-particle interactions during densification.

Table 1: Dimensional stability of briquette samples

Product sample	Dimensions			Dimensions		
	Diameter moments (mm)	**Diameter 1hr later (mm)**	**Elongation (mm)**	**Length moments (mm)**	**Length 1 hr later (mm)**	**Elongation (mm)**
1	50.1	50.3	0.2	160.0	160.0	0
2	50.0	50.2	0.2	200	200.2	0.2
3	50.0	50.3	0.3	140.5	141.3	0.8
4	50.2	50.2	0.2	120.7	121.1	0.4
Average	50.075	50.25	0.23	155.3	155.65	0.35
% diametric elongation			**0.77**	**% lengthwise elongation**		**0.45**

Briquettes dimensional changes in storage: A plot of dimensional changes in briquette samples at different moistures at extrusion, 1 hour and after 30 days in storage is shown in Figure 5. At higher moisture contents, the briquette experiences significant changes in dimension between extrusion time and 1 hour of production than after 30-days of storage, after which there are no significant changes in the product. This is largely explained by the moisture reduction over a period of time (30 days).

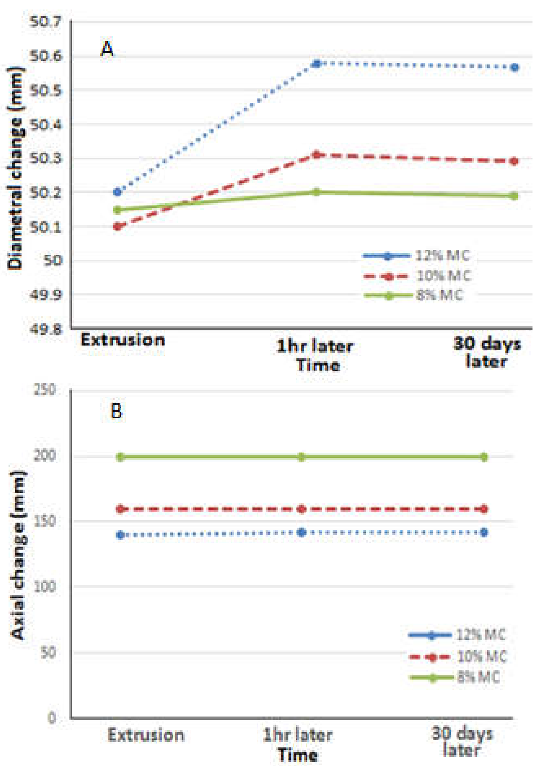

Fig 5: Diametral (A) and axial (B) changes of sample at different moisture contents

These characteristics indicates that briquettes are more dimensionally stable when produced at lower moistures than higher moistures. However, there are no significant changes in axial dimension in the briquettes at different moisture contents. This is explained by the lateral pressure applied in the direction of travel of the extruder and the inter-particle orientation in the direction of travel.

Effect of particle moisture on briquette compressed and relaxed densities: Figure 6 shows the effects of particle moisture on compressed and relaxed densities. At higher particle moisture contents, the compressed and relaxed densities increase up to 20% and 30% respectively while the densities are not significantly affected at lower moisture contents.

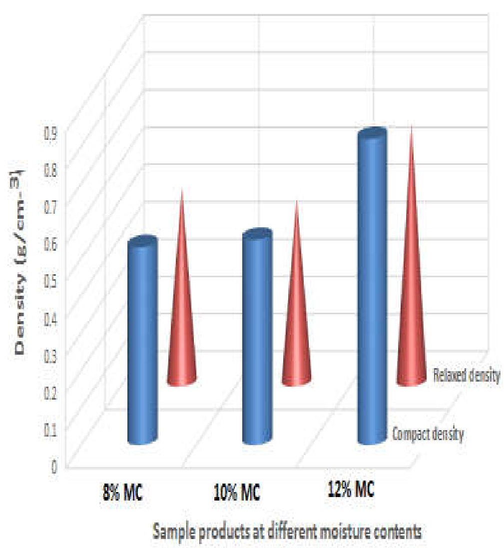

Fig 6: Compressed and relaxed densities at different moisture contents

A plot of multiple regression analysis using three models (linear, quadratic and exponential relations) to produce a curve of best fit between density and moisture contents was produced to validate this result. Among the three models, exponential multiple regression analysis provided a best fit curve (Figure 7) with the following regression equation predicting the compressed (CD) and relaxed (RD) density at any given particle moisture and size:

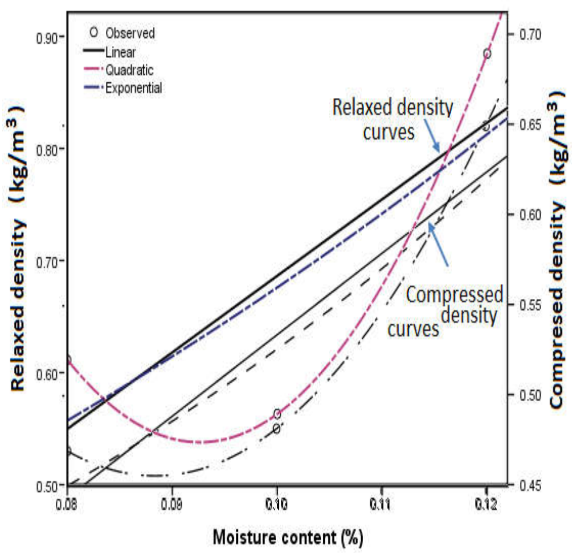

Fig 7: Regression relationship between densities and moisture contents

$$CD = 0.2084e^{10.912MC} \quad 5$$
$$RD = 0.2762e^{7.7016MC} \quad 6$$

These results suggest that the briquettes relaxed density increases with increasing compacting moisture level and that briquettes with lower moisture content are likely to have higher relaxed density than those with higher moisture content. A correlation analysis indicates a strong significant positive correlation between the Pearson's variables:

RD: $r = 0.902$, $r^2= 0.913$, adjusted $r^2=0.626$ and
CD: $r = 0.773$, $r^2= 0.598$, adjusted $r^2=0.196$.

It could be concluded that particle moisture content significantly increases the compressed density and reduces the relaxed density and consequently the quality for all briquettes

Effect of particle size on briquette compressed and relaxed densities: Briquette density increases with increase in proportion of smaller particles. Very fine particles have low void spaces and as such have low compressibility while coarse particle sizes have more tendencies of causing fissures that could cause cracks and fractures in compacted materials (MacBain, 1966). The finer the grind, the higher the quality of compact under low and medium density briquetting. At high particle moisture, fine particles materials merely grind and foul without binding while the coarse materials pulped. Fine particles readily absorb moisture than large particles, and therefore undergo a higher degree of grinding. Under high density briquetting, particle size has no significant impact on briquette quality because of high compacting pressure and simultaneous application of heat which melts the lignin to bind up the material particles. A correlation analysis between the relaxed density and particle size on one hand and compressed density and particle size on the other indicates a significant positive Pearson's correlation.

RD: $r = 0.576$, $r^2 = 0.332$, adjusted $r^2= -0.337$ and
CD: $r = 0.754$, $r^2= 0.568$, adjusted $r^2 = 0.136$)
respectively.

These results suggest that the material particle size has an exponential relationship with relaxed and compressed densities of the briquettes produced. An exponential multiple regression analysis provided a best fit curve (Figure 8) with the following exponential regression equation predicting the density at any given particle moisture and size:

$$CD = 0.380e^{0.064PS} \quad 7$$
$$RD = 0.422e^{0.037PS} \quad 8$$

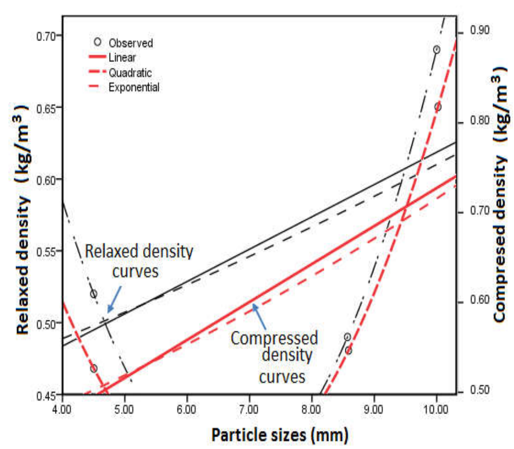

Fig 8: Regression curves for relationship between densities and particle size

Multiple effects of particle sizes and moisture content on densities: To establish the relative contributions of independent variables; moisture content and particle size in predicting the compressed and relaxed densities of briquettes and to establish the mathematical relationship between them, a partial multiple regression analysis was carried out using three models; linear, quadratic and exponential. A correlation analysis between dependent relaxed and compressed densities and independent particle moisture and particle size indicates strong significant positive correlations between moisture and particle size and weak positive correlations between relaxed density and particle size respectively (Pearson's r = 0.788, p value = 0.000; N = 3; two-tailed, α = 0.442 and Pearson's r = 0.915, p value = 0.000; N = 3; two-tailed, α = 0.284). These results suggest that the relaxed density of the briquettes increases with increasing particle size and that briquettes produced from smaller particle size sawdust are likely to have higher relaxed density than those with larger particle size. Compressed density was also found to have a very strong Pearson's correlation and weak positive non-significant correlation with the relaxed density of the briquettes (Pearson's r = 0.980, p value = 0.000; N = 3; 2-tailed, α = 0.128).

Effect of moisture content and material particle sizes on compressed and relaxed densities: ANOVA of the effect of moisture content and material particle size on compressed and relaxed densities outcomes in Tables 2 and 3 shows that at 5% level of significance and their interactions, particle size have more significant effects on the relaxed density than the compressed density of briquettes produced.

Table 2: ANOVA of effects of material properties on relaxed density

Source	Sum of squares	Df	Mean square	f	Sig.
MC	0.014	1	0.014	1.639	0.422
Residual	0.009	1	0.009		
Total	0.023	2			
PS	0.008	1	0.008	0.548	0.594
Residual	0.015	1	0.015		
Total	0.023	2			

Table 3: ANOVA of effects of material properties on compressed density

Source	Sum of squares	Df	Mean square	F	Sig.
MC	0.042	1	0.042	4.037	0.294
Residual	0.010	1	0.010		
Total	0.052	2			
PS	0.029	1	0.029	1.238	0.466
Residual	0.023	1	0.023		
Total	0.052	2			

The multiple coefficient of determination, R-value and the root mean square error for the ANOVA model were 0.9907 and 11.24, respectively. Thus, it could be deduced that particle size and moisture content, and their interactions explained about 99.07% of the variability in the relaxed density of the briquettes produced. Table 4 shows the unstandardized (β) and standardized (Beta) regression coefficients, the multiple correlation coefficient (R), adjusted R^2, the t value and its associated p value for each of the variables using a linear multiple regression analysis. From the table 4, particle size and moisture content collectively explained 70.9% (adjusted R^2 = 0.603 and 0.106) of the variance in the compressed density of briquette produced and 5.0% (adjusted R^2 = 0.242 and -0.292) of the variance in the relaxed density respectively. This suggests that the linear regression model is a good predictor of compressed density for high density briquettes (R^2 = 0.709, p value = 0.000) and poor predictor of relaxed density. Based on the Beta values, it could be inferred that the mathematical relationships between the dependent variables; compressed and relaxed density and the independent variables, moisture content (*MC*), and particle size (PS) are presented in equations 9 and 10.

Table 4: Regression analysis of moisture content and particle size on densities

Variables	B	Beta	R	R square	Adjusted R^2	T	p value
Compressed density							
Moisture content	7.250	0.895	0.895	0.801	0.603	2.009	0.294
Constant	-0.092					-0.251	0.102
Particle size	0.042	0.744	0.744	0.553	0.106	1.113	
Constant	0.309					1.013	
Relaxed density							
Moisture content	4.250	0.788	0.788	0.621	0.242	1.280	
Constant	0.142					0.421	
Particle size	0.022	0.595	0.595	0.354	-0.292	0.740	
Constant	0.394					1.613	

$$Compressed\ density\ (kg/m^3) = 0.309 + 7.250\,MC + 0.042\,PS \quad 9$$

$$Relaxed\ density\ kg/m^3 = 0.394 + 4.250\,MC + 0.022\,PS \quad 10$$

Mechanical characteristics: Briquette toughness: After repeatedly dropping each sample of the briquettes from a 2-m height to the laboratory concrete floor, the percentage of weight loss ratio between the loss in weight and the total weight was determined as shown in Table 5. From the tests conducted, after the repeated number of drops, observations revealed that all the briquettes studied did not shatter into pieces. From literatures, the gravitational resistance to drop should attained a maximum value of 93.09% and a minimum value of 89.55% which is in agreement with Borowski, (2010) that gravitational resistance to drop should attain a value higher than 90%.

Table 5: Briquette resistance to gravity and impact at 2-m drop height

Samples	Sample weights (g)	Final wt. after 5 drops (g)	Weight loss (g)	% wt. loss	Toughness (100%)
Light brown (1)	155	144.29	10.71	8.62	93.09
Char (black) (2)	206	188.03	17.97	8.72	91.28
Deep brown (3)	227	205.60	21.4	9.42	90.57
Deep brown (4)	101	90.45	10.55	10.45	89.56

Effect of densities on impact resistance index (IRI): The relationships between impact resistance index, compressed and relaxed densities for the treatments at 8% moisture ratio plotted on partial regression charts (Figure 9) on the two densities.

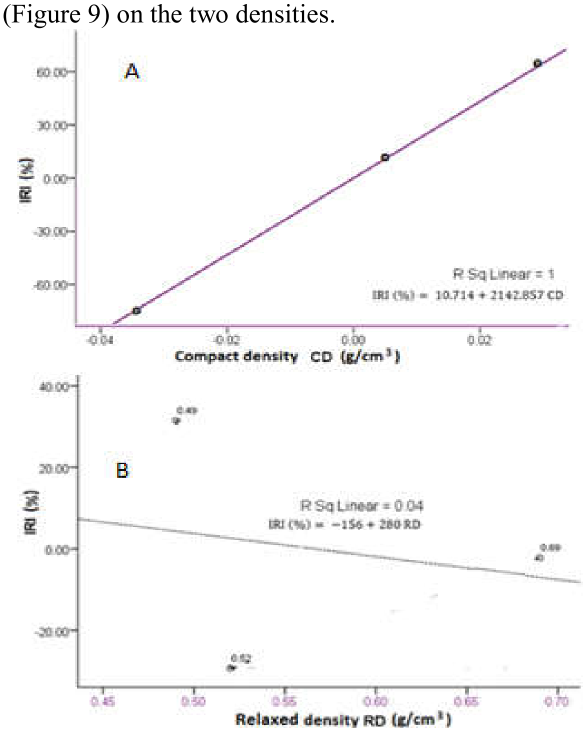

Fig 9: Partial regression curve for IRI briquette compressed density (a) and relaxed density (b)

The mathematical relationships obtained between impact resistance index, compressed and relaxed density are presented in the following expressions:

Compressed density:

$$\text{IRI}(\%) = 10.714 + 2142.857\,\text{CD} \quad (11)$$

Relaxed density:

$$\text{IRI}(\%) = -156.00 + 280.00\,\text{RD} \quad (12)$$

Owing to the weak nature of briquettes formed at 10% and 12% particle moistures, durability tests performed on them show high degree of shattering.

Effect of moisture content and particle size on impact resistance index (IRI): A multiple linear regression analysis was carried out to establish the relative contributions of independent variables; moisture content and particle size in predicting impact resistance of briquettes, and to establish the mathematical relationship between them (Table 6). The results indicate that at 5% level of significance and 95% confidence interval for β, the impact resistance index of briquettes were significantly affected by moisture and particle sizes. The mathematical relationship between impact resistance index, compressed and relaxed density is presented in Equation (13):

$$IRI\,\% = 650.137 - 1412.967\,RD + 2161.050\,CD \quad (13)$$

Table 6: Regression analysis of IRI on briquette' densities

Variables	B	Beta	R	R Square	Adjusted R^2		p value
Constant	650.137						
RD*	-1412.967	-.751	1.000	1.000	0.0	-	-
CD*	2161.050	1.724					

Effect of water on briquette durability in water: The onset dispersion time for each briquette when immersed was observed. The results indicate water resistance capacity of the briquettes varied from 25 ± 1.65% (B12) to 61 ± 3.12% (B10) to 94.21 ± 3.76% (B8) for the three studied moisture levels. It was observed that the briquette produced at 12%) had good hygroscopic properties as compared to the briquettes from the lower moisture levels. The briquette from 8% moisture level exhibits the least water absorption characteristics. This is an indication that hygroscopic property of briquettes at different moisture levels showed a linear relationship between water absorption capacity and moisture content.

Conclusions: Based on the physico-mechanical characteristics of briquettes produced, we conclude that, feedstock particle sizes and moisture content contributes to the quality of briquette. Sound briquettes with better physical attributes are produced at lower particle moisture contents. Particle size has no significant impact on briquette physical quality because of high compacting pressure and simultaneous application of heat which melts the lignin to bind up the material particles. Briquettes percentage elongations are significantly low along the diametral axial axes; but higher along the diametrical axis. High particle moisture significantly increases the compressed density and reduces the relaxed density and consequently the briquettes quality. The briquettes relaxed density increases with increasing particle size. The impact resistance index (IRI) of briquettes was significantly affected by moisture and particle sizes. Durability tests on 10% and 12% particle moisture briquettes show high degree of shattering. Briquette produced at 12% had good hygroscopic properties compared to those from lower moisture levels. Lower moisture briquettes exhibit the least water absorption characteristics, indicating hygroscopic property of briquettes and the linear relationship between water absorption capacity and moisture content.

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