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Effect of Process Parameters on the Quality of Bio-Coal Briquette Produced from *Prosopis Africana* Pods

Usaka, E., Edeoja, A. O.*, Ibrahim, J. S.
Mechanical Engineering Department,
Joseph Sarwuan Tarka University, Makurdi, Nigeria

ABSTRACT

Briquette quality varies due to the variations in production methods and parameters; the knowledge of optimal compaction pressure, binder composition and particle size for production of high-quality briquette is important. In this study, the effect of varying compaction pressure (5, 10 and 15 MPa), briquette geometry (solid and hollow) and particle size (425, 600 and 1000 μm) on the properties of *Prosopis Africana* pods bio-coal briquette was investigated. The investigation involved the collection, crushing, milling and compaction of the samples into briquettes with cassava starch as binder. The formed briquettes were subjected to several standard methods to verify their suitability as fuels. Results showed that compaction pressure and particle size had significant effect on thermo-physical properties of briquettes. Compaction pressure increase increased the briquette density, water resistance, compressive strength, impact resistance, ignition time and reduced burning rate. Particle size increase reduced the density, impact resistance, water resistance, compressive strength, ignition time and increased the burning rate of briquettes. Results also showed that hollow briquettes had superior combustion characteristics compared to solid briquettes but lower physical and mechanical properties. Based on this study, the best quality bio-coal briquette was produced from optimum processing variables of 0.6 mm particle size and 10 MPa compaction pressure. Bio-coal briquettes from produced *Prosopis Africana* pods can serve as an alternative energy source, which can be used for heating and cooking applications in Nigeria.

Keywords: Binder composition, Bio-coal briquette, Briquette quality, Combustion Properties, Compaction Pressure, *Prosopis Africana* pods

INTRODUCTION

The continuous supply of energy resources is essential for the development of any nation. However, access to clean, affordable and reliable energy services is an enormous challenge in Nigeria (Bisu *et al.*, 2016; Usaka *et al.*, 2019). Acute shortage, high cost and irregular supply of clean energy sources has caused rural dwellers in Nigeria to depend on traditional energy sources such as wood and agricultural residue which has personal health and environmental implications (Bisu *et al*., 2016; Usaka *et al.*, 2019). The necessity into investigation of cleaner fuel to meet domestic heating application needs is imperative to minimize household health risk and ensuring environmental sustainability.

Briquettes from agricultural waste have received considerable interest because of their potential to utilize low-grade combustible material and availability in large quantities. Several studies have been carried out on the combustion properties of briquettes for various agricultural waste products such as groundnut shell and maize cob (Onuegbu *et al*., 2012), hazelnut shell (Haykiri-Acma & Yaman, 2010), melon shell and corn cob (Oyelaran & Tudunwada, 2015), elephant grass and spear grass (Onuegbu *et al*., 2010), wastepaper and groundnut shell (Oyelaran *et al*., 2015), rice bran and palm kernel shell (Mohammed & Olugbade 2015). To improve the quality of biomass briquettes, biomass is blended with other materials with high

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[*] Corresponding Author: edeoja.alex@uam.edu.ng

fixed carbon content such as coal. Literature studies reported that the combination of coal and biomass (bio-coal briquette) exhibited improved burning properties (Anggraeni *et al*., 2021).

The quality of briquette varies due to the variations in method of production and production parameters. Knowledge of optimal binder ratio, compaction pressure, and particle size for production of high-quality briquette is important. The quality of a briquette can be measured from its heating value, density, compressive strength, impact resistance, ash content, volatile matter content, fixed carbon content, and moisture content among others (Manbo *et al*., 2017).

The effect of variation of process parameters such as particle size, binder level, briquette shape, dwell time and compaction pressure has been observed to influence the mechanical and combustion properties of briquettes by several researchers such as Emerhi (2011), Tokan *et al*. (2014), Mohammed and Olugbade (2015), Mambo *et al*. (2017), Huko *et al*. (2015), Davies and Abolude (2013), and Sunardi *et al*. (2019).

This study is aimed at investigating the effect of varying compaction pressure and particle size on thermo-physical properties of both solid and hollow bio-coal briquettes produced from *Prosopis Africana* pods.

MATERIALS AND METHODS

This study was conducted in Joseph Sarwuan Tarka University Makurdi, in Makurdi Local Government Area of Benue State Nigeria. Makurdi is the capital of the Benue state of Nigeria. The materials/equipment used for this study includes; Okaba coal sample, *Prosopis Africana* pods, hydraulic press, mild steel mould, stop watch, cassava starch, hydraulic press, digital weighing balance, water, briquette stove, milling machine, platinum crucible, oven, 600μm standard sieve, cooking pot, thermometer, muffle furnace, meter rule, venier caliper.

Sample Collection and Preparation

The coal sample used in this experimental study was obtained from Okaba deposit (Sub-bituminous Coal) in Kogi State, Nigeria. The biomass sample used in this experimental study is the pods of *Prosopis Africana* which was collected at local farms, markets and dump sites in Makurdi local government in Benue State, Nigeria. The collected coal and biomass samples were screened of impurities and sun dried to reduce the moisture content after which they were pulverized to obtain particle size reduction. The pulverized coal and biomass samples were passed through laboratory test sieves to achieve a uniform particle size of 0.425, 0.600 and 1.000 mm.

Briquette Sample Preparation

The pulverized coal sample was blended with biomass at composition of 60% coal and 40% biomass (composition with superior combustion properties from previous study on *Prosopis Africana* pods bio-coal briquette by same authors). The binder used in this experimental study was cassava starch, while calcium hydroxide acted as the desulphurizing agent. For each concentration, 5% calcium hydroxide based on the entire mass of coal was added as desulphurizing agent and 20% cassava starch based on the entire mass of mixture was used as binder for all samples (Kaliyan & Morey 2009; Guusu, 2021; Adekunle, 2015). The choice of cassava starch binder was due to its easy availability and cost effectiveness. Literature studies recommended composition of 20% or more for biological binders.

The briquettes were formed in a cylindrical mold with an inner diameter of 47.33 mm, a height of 83.26 and a rod with a 15.82 mm outer diameter placed in the center to create a hole in the middle of the briquette. The hole helps to increase porosity and oxygen supply, thereby improving briquette combustion. The different concentrations were loaded into the cylindrical mold and were compressed at various pressure values of 5, 10 and 15MPa using a manually operated hydraulic press at room temperature. The formed briquettes (solid and hollow) were extruded and labeled as shown in Table 1. The briquettes were transferred to an open space for sun drying to enhance solidification. After drying, the dimensions and mass of each briquette produced were measured.

Table 1: Briquette samples Nomenclature

Briquette samples		Compaction pressure (MPa)	Particle size (μm)
Solid Bio-coal briquettes	**A11**	5	425
	A12	10	425
	A13	15	425
	A21	5	600
	A22	10	600
	A23	15	600
	A31	5	1000
	A32	10	1000
	A33	15	1000
Hollow bio-coal briquettes	**B11**	5	425
	B12	10	425
	B13	15	425
	B21	5	600
	B22	10	600
	B23	15	600
	B31	5	1000
	B32	10	1000
	B33	15	1000

For convenience of discussion, the samples were coded for both solid and hollow briquettes samples as shown in Table 2. These codes were used to discuss of changes in particle size and compaction pressure and their effect on the various properties of the briquettes.

Table 2: Mean Sample Codes

Code	Mean of samples
5	A11, A21 and A31
10	A12, A22 and A32
15	A13, A23 and A33
425	A11, A12 and A13
600	A21, A22 and A23
1000	A31, A32 and A33

Analysis of Samples

Density determination

The density of the briquette samples was determined as the ratio of the average mass to the volume of the briquette. The mass of the briquettes was obtained by using a digital weighing scale, while the volume was calculated by measuring the dimensions of the cylindrical briquettes (radius and height) and applying the formula for the volume of a cylinder ($\pi R^2 H$ for solid briquettes and $\pi(R^2 - r^2)H$ for hollow briquettes)

$$Density = \frac{mass}{volume} \tag{1}$$

Compression strength, durability and water resistance test

The compressive strength and impact resistance analysis are methods of testing the quality and durability of a solid fuel. Compressive resistance (or crushing resistance) is the maximum crushing load a briquette can withstand before cracking or breaking, which simulates the compressive stress due to weight of the top pellets on the lower pellets during storage (Gonen, 2010). Compressive resistance of the briquette samples was determined by a test, in which a single briquette was placed between two flat, parallel plates with greater facial areas than the area of the briquette and an increasing load was applied at a constant rate until the briquette cracked. The load at fracture was reported as compressive force. The compressive strength of the samples was calculated using Equation (2) below.

$$\text{Compressive strength} = \frac{\text{Compressive force}}{\text{Cross sectional area of the sample}} \tag{2}$$

Cross sectional area = πR^2 for solid briquettes and $\pi(R^2 - r^2)$ for hollow briquettes.

Durability index determined by dropping the briquette samples repeatedly 4 times from a height of 1.50 m onto a solid base and the weight loss was recorded. The durability index (*DI*) of the briquette samples was expressed as

$$DI = \frac{mf}{mi} \times 100\% \tag{3}$$

Where *mi* is the briquette mass before the test (g) and *mf* is the briquette mass after the test (g).

The water resistance of the briquette samples was determined from the percentage of water absorbed by a briquette when immersed in water. The briquette samples were immersed in water at room temperature for 30 seconds. The resistance to water penetration is determined from equation (4) below in which *WR* = water resistance in percentage; $M_{\text{wet briquette}}$ = mass of wet briquette and M_{initial} = initial mass of briquette.

$$\%WR = 100 - \left[\frac{M_{wet\ briquette} - M_{initial}}{M_{initial}} \times 100\right] \tag{4}$$

Calorific value determination

Calorific value was determined using a Gallenkamp Ballistic Bomb Calorimeter in accordance with American Society of Testing and Materials (ASTM) standards at Pedagogic consulting, Ayodele Fanoiki Street, Lagos. 0.25g of each briquette sample was weighed into the steel capsule. A 10cm cotton thread was attached to the thermocouple to touch the capsule. The bomb was closed and charged in with oxygen up to 30 atm. The bomb was fixed up by depression the ignite switch to burn the sample in an excess of oxygen. The maximum temperature rise in the bomb was measured with the thermocouple and galvanometer system. The rise in temperature was compared with that obtained for 0.25g of Benzoic value of each sample was determined by the following stepwise calculations:

Calculations:

Mass of Benzoic Acid = W_1

Calorific value of 1gm Benzoic Acid = $6.32\ kcal/g$

Heat released from Benzoic Acid = $6.32 \times W_1\ kcal$

Galvonometer deflection without sample = T_1

Galvonometer deflection of Benzoic Acid = $T_2 - T_1$

Calibration constant = $\frac{6.32 \times W_1}{T_2 - T_1} = y$

The standardizing is repeated five times and average value calculated for y.

Mass of sample = $0.25g$

Galvonometer deflection with sample = T_3

Galvonometer deflection of sample = $T_3 - T_1$

Heat released from sample= $(T_3 - T_1)y\ kcal$

$$\text{Calorific value of sample} = \frac{(T_3 - T_1)y}{0.25}\ kcal/g \tag{5}$$

Performance test

The water boiling test using the briquette samples was carried out at the metallurgy and materials laboratory, Mechanical Engineering, Joseph Sarwuan Tarka University Makurdi. The test was done to obtain and compare ignition time, burning rate and water boiling time of each briquette sample that was produced. Each briquette sample was ignited at the base with a cigarette lighter in a drought free place. The time required for the flame to ignite the briquette was recorded as the ignition time using stopwatch. Water boiling test was carried out to compare the cooking efficiency of the briquettes. It measured the time taken for each set of briquettes to boil an equal volume of water under similar conditions.100g of each briquette sample was used to boil 100cm^3 of water using small stainless cup and domestic briquette stoves. During this test, the burning rate of the briquettes was determined as the ratio of the mass of the briquette (in grams) burned to the total time (in minute) taken.

RESULTS AND DISCUSSION

Density

The density values for this study ranged between 807 to 866 kg/m^3 for solid briquettes and 739 to 792 kg/m^3 for hollow briquettes. Figure 1 shows the effect of varying particle size on the density of both solid and hollow briquette samples, it can be seen that particle size increase resulted to reduction of the density values for both solid and hollow briquettes. Reduction in particle size eases compaction and allows more mass of material for a given volume which increases briquette density (Huko *et al*., 2015; Estiaty *et al*., 2018; Manbo *et al*., 2017; Sunardi *et al*., 2019; Guusu *et al*., 2021; Anggraenni *et al*., 2021). Figure 2 shows the effect of varying compaction pressure on the density of the briquette samples. It was observed that density increased with increase in compaction pressure. This is due to the decrease in inter-particle spacing experienced at higher compaction pressure, thereby reducing the volume and increasing the density. Huko *et al.* (2015) explained that high pressure brings about mechanical interlocking and increased adhesion between the particles, forming intermolecular bonds in the contact area.

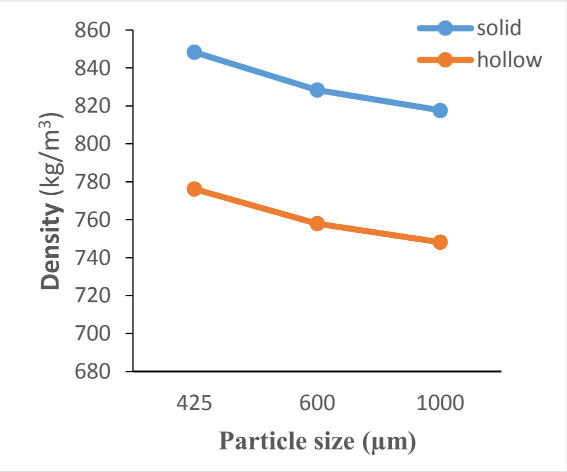

Figure 1: Density as a function of particle size

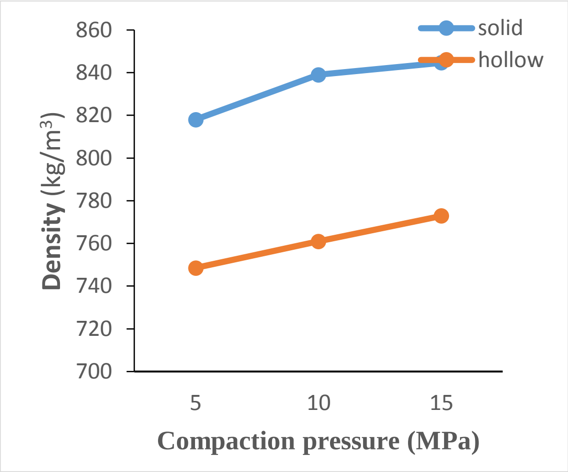

Figure 2: Density as a function of compaction pressure

Compressive Strength

Figure 3 and 4 shows the effect of varying particle size and compaction pressure on the compressive strength of the briquette samples with the values ranging from 4.32 to 5.58N/mm^2 for solid briquette and 3.67 to 4.74N/mm^2. It can be seen that particle size increase resulted in reduction of the compressive strength values while the compressive strength values increased with increase in compaction pressure.

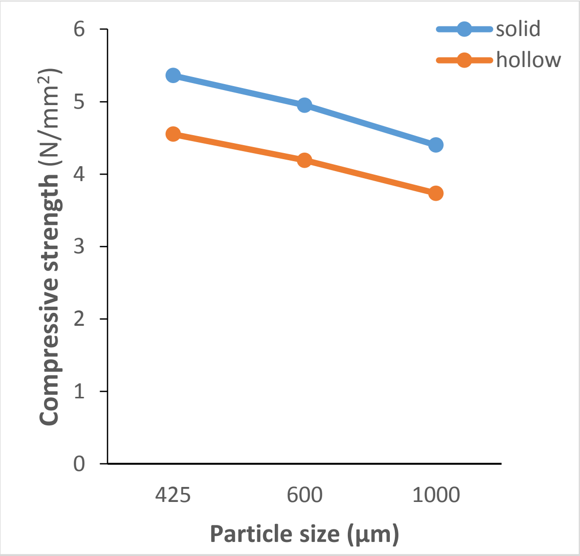

Figure 3: Compressive strength as a function of particle size

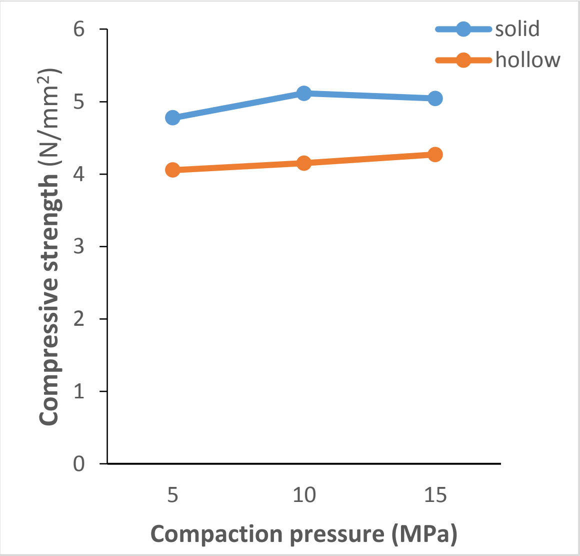

Figure 4: Compressive strength as a function of compaction pressure

Impact Resistance

The impact resistance values for this study varied from 95.05 to 98.23% for solid briquettes and from 87.73 to 90.67% for hollow briquettes. Figure 5 and 6 shows the effect of varying particle size and compaction pressure on the impact resistance of the briquette samples. These results revealed that decrease in particle size increased the impact resistance the briquette samples while the impact resistance increased with increase in compaction pressure. Huko *et al*. (2015) highlighted that smaller particles have greater surface area resulting in increased gelatinization and better binding. Results also revealed that the hollow briquettes had lower impact resistance value compared to the solid briquette samples.

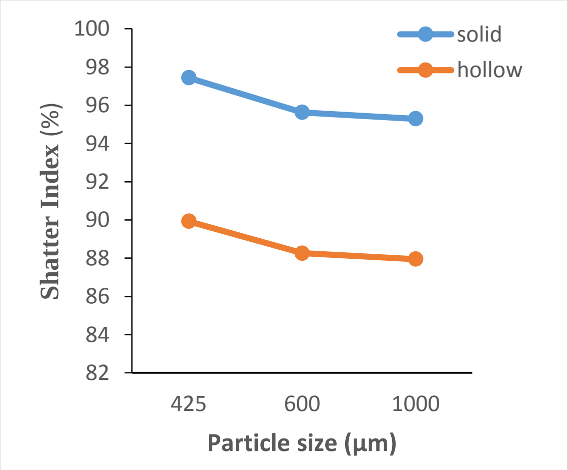

Figure 5: Impact resistance as a function of particle size

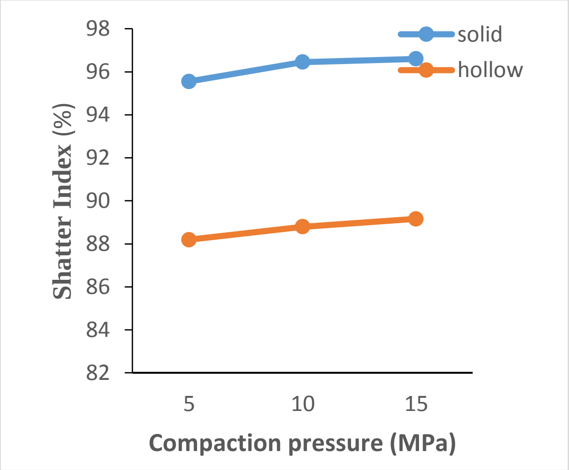

Figure 6: Impact resistance as a function of compaction pressure

Water Resistance

Water resistance refers to a materials ability to resist the penetration of water. Results showed that water resistance of the briquette samples varied from 82.05 to 89.86% for solid briquettes and varied from 72.61 to 79.53%. Figure 7 and 8 shows the effect of varying particle size and compaction pressure on the water resistance of the briquette samples. These results revealed that decrease in particle size increased the water resistance the briquette samples while the water resistance increased with increase in compaction pressure. Orisalaye *et al.* (2019) explained that better bonding occurs with smaller particle sizes which results from the increase in the contact points for inter-particle bonding. For briquettes produced with larger particle sized materials, there are wider inter particle voids which limits the bonding of the particles, thereby reducing the water resistance of the briquettes. Zanjani *et al.* (2014) and Guusu (2021) also stated that the increase of briquetting pressure showed positive results but insignificant effects on water resistance index. Mitchual (2015) and Anggraeni *et al.* (2021) stated that compacting pressure between 20 and 50 MPa had significant effect on quality of briquettes due to reduction in pore spaces achieved at elevated compaction pressure.

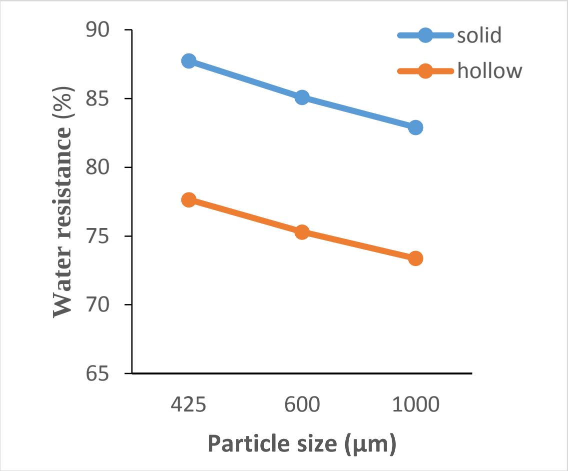

Figure 7: Water resistance as a function of particle size

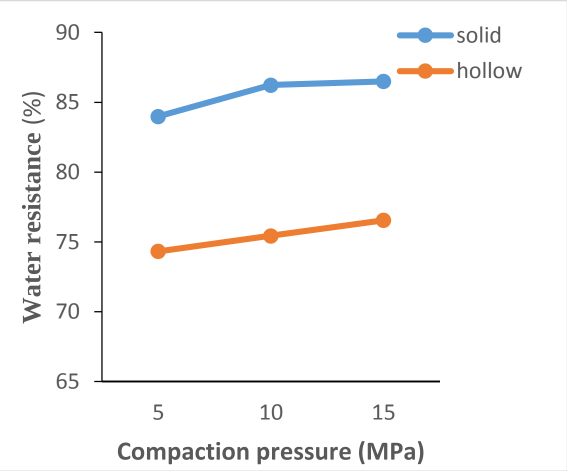

Figure 8: Water resistance as a function of compaction pressure

Calorific Value

Calorific value determines the energy content of the briquette samples, and its values depend on the briquette’s chemical composition and moisture content (Oyelaran &Tudunwada, 2015). The calorific value for the briquette samples for this study ranged between 18.85 - 18.97 MJ/kg. Calorific values reported by Adekunle *et al.* (2015) for sawdust bio-coal briquette varied between 17.68 – 33.30 MJ/kg, rice husk bio-coal briquette varied between 9.00 – 16.40 MJ/kg (Ikelle *et al.*, 2014), elephant grass bio-coal briquette varied between 15.98 – 20.39 MJ/kg (Onuegbu *et al.*, 2010), corn cob bio-coal briquette varied between 8.25 – 15.69 MJ/kg (Ikelle & Ogah, 2014), cassava stalk bio-coal briquette varied between 22.50 – 25.40 MJ/kg (Ikelle *et al.*, 2017), groundnut shell bio-coal briquette varied between 8.85 – 14.85 MJ/kg (Oji and Monday, 2017) and sesame seed stalk bio-coal briquette varied between 19.98 – 24.17 MJ/kg (Guusu *et al.*, 2021).

Figure 9 shows the effect of varying particle size on the calorific value of the briquette samples. These results revealed that increase in particle size slightly increases the calorific value of the briquette samples. This could be as a result of higher moisture content of the smaller particle size briquette. Moisture content influences significantly the net calorific heating value; vaporising water requires energy from the burning process, thus reducing the net heating value of the fuel. Compaction pressure did not have significant effect on heating value of the briquette samples in this study because it only enhances the volumetric calorific value, but not heating value. This was consistent with findings from Tokan *et al.* (2014), Mambo *et al.* (2017), Sunardi *et al.* (2019) and Huko *et al.* (2015). Briquette geometry did not have effect on heating value of the briquette samples in this study since the heating values are dependent on briquette’s chemical composition and moisture content.

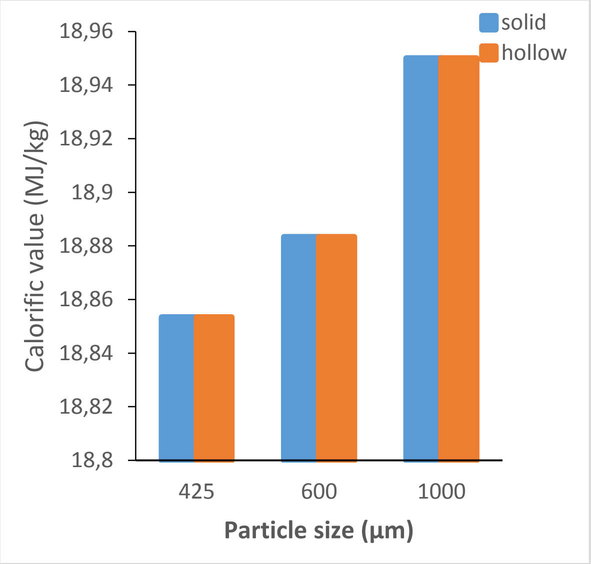

Figure 9: Calorific value as a function of particle size

Ignition Time

A combustible material should be easily ignitable particularly for household purposes, thus; lower ignition time values are preferred. Ignition time was taken as the average time taken to achieve steady glowing flame. For this study, ignition time values range from 135 to 195 seconds for solid briquettes while values ranged from 103 to 175 seconds for hollow briquettes. Ignition time values reported by Ikelle *et al.* (2014) for rice husk bio-coal briquette varied between 23.33 – 46.22 seconds, elephant grass bio-coal briquette varied between 19.20 – 186 seconds (Onuegbu *et al.*, 2010), corn cob bio-coal briquette varied between 27.20 – 37.00 seconds (Ikelle & Ogah, 2014), cassava stalk bio-coal briquette varied between 21.19 – 46.22 seconds (Ikelle *et al.*, 2017), melon shell bio-coal briquette varied between 32.00 – 68.00 seconds (Oyelaran & Tudunwada, 2015) and sesame seed stalk bio-coal briquette varied between 52 – 114 seconds (Guusu *et al.*, 2021).

It was observed that ignition time decreased with increase in particle size and increased with increase in pressure as shown in Figure 10 and 11 respectively. This observation is attributed to the fact that larger particle sizes have more pore spaces in between the particles than the finer particle sizes and increase in pressure improves compaction and consequently reducing porosity. Thus, increase in the porosity index of the briquettes causes reduction in time taken for the briquettes to be ignited. This was consistent with findings from Davies and Abolude (2013), Olugbade and Mohammed (2015), Estiaty *et al.* (2018) and Sunardi *et al.* (2019). Results revealed that the hollow briquette samples had lower ignition time compared to the solid briquette samples. This is due to more oxygen flow in the hole provided by the hollow briquettes which improves ignitability.

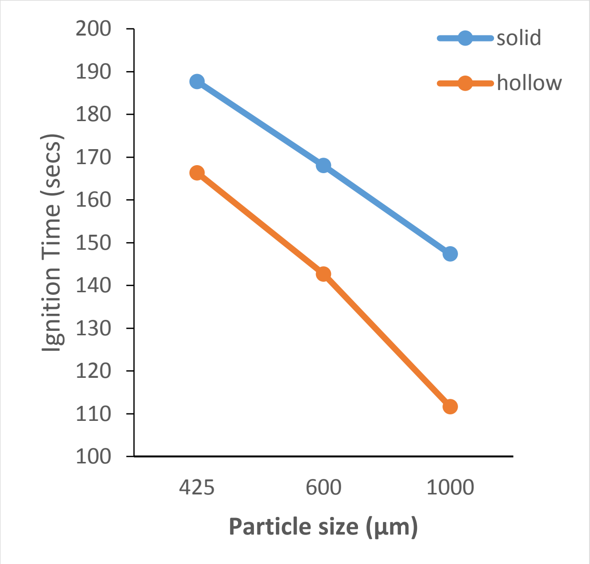

Figure 10: Ignition time as a function of particle size

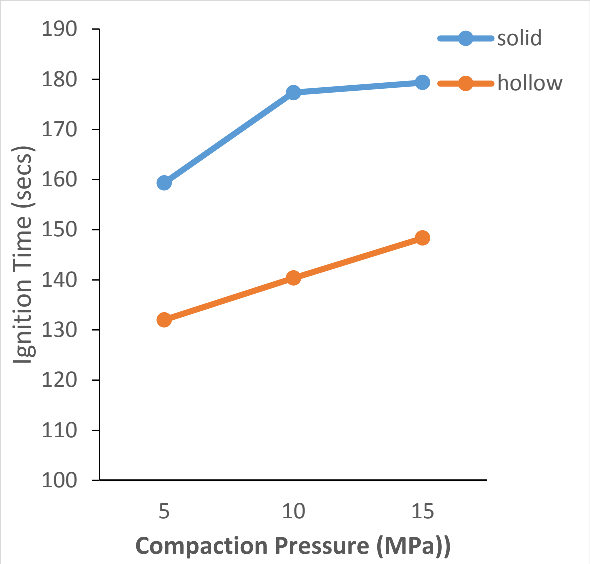

Figure 11: Ignition time as a function of compaction pressure

Burning Rate

Burning rate refers to the briquette mass that is consumed per unit time during combustion (the rate at which the briquette releases its energy). It is dependent on the chemical composition and geometry of the material (Adekunle, 2015). In this study, burning rate values range from 1.08 g/min to 5.85 g/min with its value increasing with increase in biomass content as shown in Figure 16. This increase is due to the high volatile matter possessed by the biomass. Burning rate of the briquette samples increased with increase in particle size and decreased with increase in pressure as shown in figure 12 and 13 respectively. This observation is attributed to the fact that larger particle sizes have more pore spaces in between the particles than the finer particle sizes and increase in pressure improves compaction and consequently reducing porosity. Thus, samples with larger pore spaces exhibited higher burning rates. This was consistent with findings from Olugbade and Mohammed (2015), Davies and Abolude (2013), Anggraeni *et al*. (2021), Estiaty *et al.* (2018) and Sunardi *et al*. (2019). High values for burning rate of briquettes are not desirable, as it implies that more quantity of the briquettes will be consumed over a relative time frame (Davies & Abolude, 2013). Results revealed that the hollow briquette samples had higher burning rate compared to the solid briquette samples. This is due to more oxygen flow in the hole provided by the hollow briquettes which improves burning.

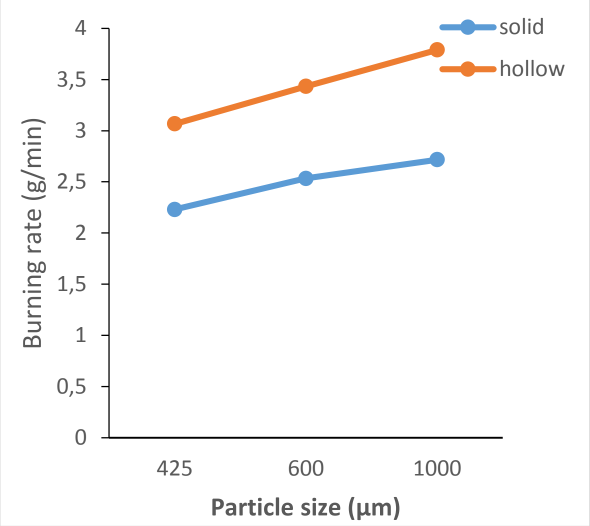

Figure 12: Burning rate as a function of particle size

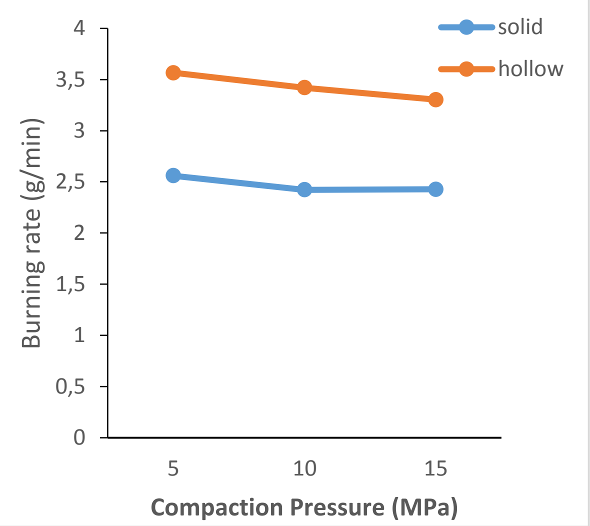

Figure 13: Burning rate as a function of compaction pressure

Water Boiling Time

Experimental results showed that the time required for briquette samples to boil an equal volume of water ranged from 4.25 to 10.97 minutes with its value decreasing with increase in biomass content as shown in Figure 18. Results also showed that the boiling time decreased with increase in particle size and decreased with increase in pressure as shown in Figure 14 and 15 respectively. Results also revealed that hollow briquette samples exhibited lower boiling time compared to the solid briquettes samples. Adekunle (2015) explained that boiling time is dependent on two factors: burning rate (how fast the fuel burns) and calorific value (how much heat is released). Water boiling time values reported by Ikelle *et al.* (2014) for rice husk bio-coal briquette varied between 1.42 – 4.12 minutes, elephant grass bio-coal briquette varied between 1.57 – 3.65 seconds (Onuegbu *et al.*, 2010), corn cob bio-coal briquette varied between 1.63 – 4.57 minutes (Ikelle & Ogah, 2014), cassava stalk bio-coal briquette varied between 1.56 – 4.94 minutes (Ikelle *et al.*, 2017), groundnut shell bio-coal briquette varied between 8.00 – 12.00 minutes (Oji and Monday, 2017) and sesame seed stalk bio-coal briquette varied between 6.15 – 6.38 minutes (Guusu *et al.*, 2021).

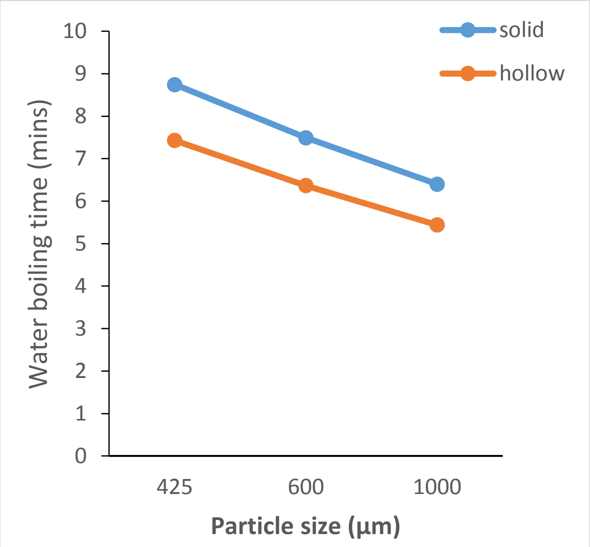

Figure 14: Boiling time as a function of particle size

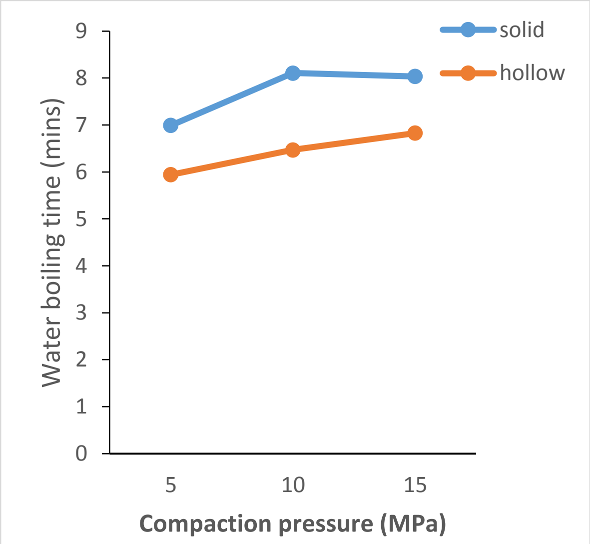

Figure 15: Boiling time as a function of compaction pressure

CONCLUSION

This experimental study focused on the effect of variable compaction pressure and particle size on the properties of solid and hollow bio-coal briquette samples produced *Prosopis Africana* pods. Results revealed that bio-coal briquettes from produced *Prosopis Africana* pods can serve as an alternative energy source, which can be used for heating and cooking applications in Nigeria. The study indicated that compaction pressure and particle size have a significant effect on thermo-physical properties of biomass briquettes. Increase in compaction pressure increased the briquette density, compressive strength, water resistance, impact resistance, ignition time and reduced the burning rate of the briquette samples. Particle size increase, reduced the density, impact resistance, ignition time and increased the burning rate. Results also showed that hollow briquettes had superior combustion characteristics compared to solid briquettes but lower physical and mechanical properties. Based on this study, the best quality bio-coal briquette was produced from optimum processing variables of 0.6mm particle size and 10 MPa compaction pressure. Briquettes produced from these parameters had overall superior physical, mechanical handling and combustion characteristics.

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