JEAS

JOURNAL OF ENGINEERING AND APPLIED SCIENCES

Journal of Engineering and Applied Sciences 14 (2018), 26-39

DETERMINATION OF SELECTED PHYSICAL AND MECHANICAL PROPERTIES OF AFRICAN BREADFRUIT (var. *Inversa)* SEEDS

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Abstract

Some relevant physical, mechanical and aerodynamic properties of African Breadfruit (var. *Inversa)* were determined in relation to processing equipment design. The measured physical properties of breadfruit seeds are the principal dimensions (length, width, and thickness), technically known as major, intermediate and minor diameters. Surface area, sphericity, projected area, aspect ratio, volume, true density, bulk density and porosity were also determined at moisture content of 11.00% wb, 13% wb, 15.00% wb, 18% wb and 20% wb. The major, intermediate and minor diameters increased from 8.10$\pm$0.91cm to 10.05$\pm$0.6cm, 4.04$\pm$0.52cm to 5.00$\pm$0.10 and 2.96$\pm$0.43 to 4.60$\pm$0.40cm respectively for the range of moisture content of 11.00 to 20.00. Within the same moisture content, the surface area, sphericity and aspect ratio were 64.19$\pm$8.90cm, to 114.25$\pm$6.20cm, 56.00$\pm$8.00cm to 60.00$\pm$6.00cm and 50.10$\pm$0.04 respectively. Other physical properties determined were volume, true density, bulk density, 1000-grain weight and porosity. The volume varied from 50.6 to 121.05 cm^3, and the true density varied from 1.099 g/cm^3 to 1.11 g/cm^3 while bulk density, 100-grain weight and porosity varied from 0.8350 to 0.938 g/cm^3, 360 g to 610g and 15.01 to 5.60 respectively. The major Aerodynamic properties studied include, terminal velocity while the frictional properties of interest were angle of repose and coefficient of friction of the seeds on popular structural materials such as plywood, mild steel and galvanized steel sheets. The result of the study showed that the angle of repose of breadfruit seeds ranged from 44.85 to 63.12 deg., while coefficient of surface friction of the seeds on wood surface ranged from 0.3855 to 0.5754 while that of mild steel and galvanized steel surfaces were from 0.4217 to 0.5837 and 0.4131 to 0.7326 to 0.7326 respectively. The terminal velocities of the seeds, kernel and chaff/hull were from 10.44 to5.94 m/s, 5.267 to 2.18 m/s and 2.387 to 0.191 m/s respectively. The same trend was observed for sphericity (Ψ) and aspect ratio (Ra) of the breadfruit seeds. Regression equations were developed to predict the properties at different moisture content levels studied. The equation's goodness of fit, as shown in their coefficient of determination (R^2), is ranging from 0.8970 to 0.9999. The properties determined are very important factors in the design and development of cleaning and separation machine for shelled breadfruit seeds.

Keywords: physical, aerodynamics, properties, frictional, breadfruit, seeds

1.0. Introduction

1.1 Background of Study

African Breadfruit (*Treculia africana)*, popularly known in Nigeria as “Ukwa” in Igbo, “Afon” in Yoruba, “Bafafuta” in Hausa, “Ize” in Benin, “Izea” in Ijaw, “and Ediang” in Efik, is a monoecious dicotyledonous plant which belongs to the botanical family *Maraceae* and genus *Treculia*. The seeds are of particular interest because of their high nutritional value. Fresh seeds contain 38.3% carbohydrate, 17.7% crude protein and 15.9% fat (Ijeh *et al*., 2010).

It can be eaten as special delicacy in Nigeria (especially in the South-Eastern part of the country). As a result of the poor shelf life, most of the harvested seeds are eaten fresh. The seed is usually a good option for individuals with diabetes and is also roasted and eaten as snacks. It may be processed into flour from which several products like breadfruit, bread loaves, biscuits, cookies, dry-packs and soup-mixes could be made (Nwigbo *et al*., 2008). *Inversa variety are* found in Delta and Edo states and more abundantly in eastern states of Nigeria, while *Mollis variety* are usually found in some areas of Delta and Edo states of Nigeria. They can also be found in Cameroun, Democratic Republic of Congo, Gabon and are the most widely cultivated and consumed (Nwabueze, 2012). The first step in the unit operations involved in processing of African breadfruit seeds after pre-cleaning is parboiling. The parboiled seeds are cooled by sprinkling of cold water on it after draining the parboiling water. Subsequently, the seeds are shelled and separated from the outer seed coat (seeds and shell/husks) by aspiration.

When air stream is used for the separation of seeds from the shells or husks it requires knowledge of aerodynamic characteristics of the particles and the associated shells or husks. It is therefore necessary to determine some relevant physical and aerodynamic properties of African breadfruit seeds (var. *Inversa)*, which are needed to determine the terminal velocity and other aerodynamic properties for effective pneumatic application. This will form the basis of design and development of machinery for the processing of the crop. The objective of this paper is therefore to determine some physical and aerodynamic properties of African breadfruit seeds.

2.0. Materials and Methods

2.1 Theoretical Background

Some very important physical characteristics of plants and animals frequently required for analysis and design of agricultural processing machines include the axial dimensions (length, width, thickness) which are subsequently used in determining geometric mean diameter, arithmetic mean diameter, equivalent diameter, surface area, sphericity, projected area, aspect ratio, volume, true and bulk densities and porosity. Aerodynamics can be simply defined as the study of how air interacts with moving bodies. It is primarily concerned with the forces of drag and lift, which are caused by air passing over and around solid bodies. The most important aerodynamic properties of solid materials in free fall in a column of air include terminal velocity and drag coefficient, which can be either skin drag or pressure drag.

2.1.1 Terminal velocity

An object moving under free fall attains its terminal velocity when the downward force of gravity acting on it equals the upward drag force. When this happens, the net force on the object is equal to zero, resulting in no further acceleration. As an object accelerates downwards due to gravity, the drag force acting on it increases, causing acceleration to decrease. At a particular speed, the drag force produced will equal the object's weight. At this point, the object ceases to accelerate altogether and continues falling at a constant speed known as terminal velocity. Terminal velocity varies directly with the ratio of weight to drag. More drag means a lower terminal velocity. Drag force also depends on the projected area of the object: this is why objects with large projected area have a lower terminal velocity than smaller ones.

2.2 Sample Preparation

Some quantity of the breadfruit seeds were procured and identified by a staff in botany department of Nnamdi Azikiwe University Awka, Nigeria. The samples were manually cleaned to ensure that the seeds were free of dirt and other foreign materials. One thousand seeds were randomly selected and weighed with a digital weighing balance (Mettler balance) with accuracy of ±0.001 g. Five batches of the seeds so sampled were subjected to different levels of moisture reconstitution for the experiments. The samples were soaked in water for 12hrs, 18hrs, 24hrs, 36 hrs, and 48 hours respectively, and then wrapped in black polythene bags for 48 hours The reconstituted samples' moisture content were determined using oven method. The moisture determination involved taking 100g of each sample and drying in the oven dried at 103^{o}C for 72 hours and cooled in a desiccators according to ASAE (1999) standards. The weight loss of each sample was recorded and the moisture content in percentage was calculated using the relationship given by Simonyan *et al*., (2009):

$$MC_{wb}\% = \frac{W_i - W_d}{W_i} \times 100 \quad (1)$$

Where, MC_{wb} = moisture content, wet basis, %.

W_i = initial mass of sample, kg.

W_d = dried mass of sample, kg.

The value of moisture content of fresh African breadfruit seeds was found to be 10.50% (w.b). The following moisture content levels were obtained: 10.6%, 12.8%, 15.2% , 17.4% and 20.00% wet bases (wb) were obtained.

The seeds were randomly selected from each of the samples and Veneer caliper (sensitivity 0.05mm) was used to measure the principal dimensions: length (L), width (W) and thickness (T) of the seeds which corresponds to major, intermediate and minor diameters respectively. An electronic scale (sensitivity 0.01g) was used to measure the weight (W_t) of each seed. The mean values of length, width and thickness were used to calculate the arithmetic mean diameter (D_a), geometric mean diameter (D_g), equivalent diameter (D_p), projected area (A_p), aspect ratio (R_a), surface area (A) and sphericity (Ψ) using the equations given by Moshenin, (1986), Jideani *et al.*, (2009) and Davies, (2009).

2.3 Determination of the Physical Properties

Thirty (30) seeds were randomly selected from each sample. Digital Veneer calipers (sensitivity 0.05mm) was used to measure axial dimensions: length (L), width (W) and thickness (T) of the seeds, while an electronic scale (sensitivity 0.01g) was used to measure the weight (W_t) of each seed. The mean values of length, width and thickness were used to calculate the arithmetic mean diameter (D_a), geometric mean diameter (D_g), equivalent diameter (D_p), projected area (A_p), aspect ratio (R_a), surface area (A) and sphericity (Ψ) using the equations given by Moshenin, (1986), Jideani *et al.*, (2009) and Davies, (2009).

The sphericity of African breadfruit seeds was calculated from the mean values of thirty (30) seeds using the equation given by Davies, (2009):

$$\Psi = \frac{(L \times W \times T)^{1/3}}{L} \times 100\% \qquad (2)$$

Where, Ψ = Sphericity (%); L = length (mm); W = width (mm); T = thickness (mm).

2.3.1 Aspect ratio (R_a)

The aspect ratio relates the width to the length of a seed which is indicative of its tendency toward being oblong in shape. Aspect ratio determines whether grains will slide or roll on their flat surfaces during handling and processing. The aspect ratio of the breadfruit seeds was calculated using the equation given by Kheiralipour *et al.*, (2008):

$$R_a = \frac{W}{L} \times 100 \qquad (3)$$

Where, R_a = Aspect ratio (%); W, L are mean values of width (mm) and length (mm).

2.3.2 Arithmetic mean diameter (D_a)

Arithmetic mean diameter was calculated using the formula given by Eke *et al.*, (2007) and Liny *et al*., (2013):

$$D_a = \frac{(L + W + T)}{3} \quad (4)$$

Where, L, W, T are mean values of length, width and thickness respectively (in mm).

2.3.3 Equivalent diameter (D_p)

Equivalent diameter is defined as the diameter of a sphere of equal volume. It was calculated using the equation given by Seifi and Alimardani, (2010a):

$$D_p = \frac{[L(W+T)^2]^{1/3}}{4} \quad (5)$$

Where: L, W and T are mean values of length, width and thickness (mm) as defined before.

2.3.4 Projected area (A_p)

The projected area of a particle is generally indicative of its pattern of behaviour in a flowing fluid such as air, as well as the ease of separating extraneous materials from the particle during cleaning by pneumatic means.

The projected area of the African breadfruit seeds var. *Inversa* was calculated using the formula given by Nalbandi *et al*., (2010):

$$A_p = \frac{\pi}{4} \times L \times W \quad (6)$$

Where, L and W are mean values of length and width (mm) as defined before.

2.3.5 Geometric mean diameter (D_g)

This was calculated using the formula (Davies, 2009):

$$D_g = (L \times W \times T)^{1/3} \quad (7)$$

Where: L = length (mm); W = width (mm) and T = thickness (mm).

2.3.6 Surface area (A)

Surface area was calculated using the formula given by Ismail *et al.*, (2009):

$$A = \pi {D_g}^2 \quad (8)$$

Where, A = Surface area (mm^2); $\boldsymbol{\pi}$ = 3.142; D_g = Geometric mean diameter (mm).

2.3.7 Bulk density (ρ_b)

The bulk density is the ratio of mass of a sample of the seeds to its total volume. It can also be defined as the mass of a group of individual particles divided by the space occupied by the entire mass, including the air space.

The method of Eke *et al*., (2007) was used to determine the bulk density of each sample. Thus, 360.7g of sample A was poured into a plastic, cylindrical container of known volume (V= $\pi r^2 h$: r = radius, h = height) to the brim. To determine the bulk density of sample A, the weight of the sample was divided by the volume of the cylinder. The same method was used to determine bulk density of different sub-samples at different moisture levels.

2.3.8 True Density (ρ_t)

The true density is defined as the ratio of mass of seeds to the true volume of seeds. True density was calculated by dividing the unit mass of the seed by its volume according to the formula given by Davies, (2009):

$$\rho_t = {}^{M}/_{V} \quad (9)$$

Where, $\boldsymbol{\rho_t}$ = true density (g/cm^3), M = unit mass (g), V = volume (cm^3).

2.3.9 Volume (V)

The liquid displacement method (Davies, 2011) was used to determine the volume of African breadfruit seeds, thus: 404.4g of clean water was poured into a cylindrical beaker calibrated 0 – 1200ml, the water level was observed to be at the 400ml mark. 285 fresh breadfruit seeds weighing 100g at 10.50% m.c (w.b) were coated with a thin layer of table gum and allowed to dry in order to prevent water absorption. The sample, which was lowered in a sinker made of mosquito wire netting into the beaker such that the seeds did not float during immersion in water, displaced 99.8g of water. The seed volume was obtained by dividing the mass of water displaced by the density of water at room temperature (≈ 1g/cm^3), which gave the seed volume as 99.8cm^3. Dividing the seed volume 99.8cm^3 by the number of breadfruit seeds in the 100g sample (i.e. 285) gives the volume of 1 breadfruit seed. This operation was replicated four times and the mean value was taken. The procedure was repeated for different samples at different moisture levels to determine the seed volume at that moisture levels.

2.3.10 Porosity (ε)

Porosity is the percentage of air space in particulate solids, which affects the resistance to air flow through the bulk solids; it can also be defined as the percentage voids of an unconsolidated mass of material. Porosity allows gases, such as air and liquids to flow through a mass of particles in aeration, drying, heating and cooling operations; it also indicates the amount of pores in a bulk material.

The porosity of African breadfruit seeds was calculated using the equation given by Moshenin (1986), Davies (2009) and Manuwa (2011):

$$\varepsilon = \frac{\rho_t - \rho_b}{\rho_t} \times 100 \quad (10)$$

Where: $\boldsymbol{\varepsilon}$ =porosity, (%); $\boldsymbol{\rho_b}$ = bulk density (g/cm^3); $\boldsymbol{\rho_t}$ = true density (g/cm^3).

2.3.11 Angle of repose ($\emptyset_r$)

Angle of repose also determines the maximum angle of a pile of grains in the horizontal plane, and it is important in the filling of a flat storage facility when grain is not piled at a uniform bed depth, but rather is peaked. The dynamic angle of repose ($\emptyset_r$) of raw African breadfruit seeds was determined by the emptying a box filled with the breadfruit inside which was mounted a platform of circular shape 0.15m diameter and 0.25m above the bottom of the box. With the height of the cone was measured and the diameter of the circular platform known, the angle of repose ($\emptyset_r$) was calculated using the formula given by Jideani *et al*., (2009) and Davies, (2009):

$$\theta_r = \tan^{-1}\left({2H}/{D}\right) \tag{11}$$

Where: $\emptyset_r$ = Dynamic angle of repose (^{o}); H = height of the heap (m); D = diameter of the heap (m).

2.4 Terminal Velocity

The terminal velocity of a free falling object is reached when the weight of the object is balanced by the upward buoyancy force and the drag force. This can be expressed as follows:

$$W = F_b + D \tag{12}$$

Where, W = Weight of object, kg; F_b = buoyancy force acting on the object,(N); D = drag force acting on the object, N.

If the falling object is spherical in shape, the expressions for the three forces are given as (Wikipedia, 2014):

$$W = \frac{\pi}{6} d^3 \rho_s g \tag{13}$$

$$F_b = \frac{\pi}{6} d^3 \rho g \tag{14}$$

$$D = C_d \frac{1}{2} \rho V^2 A \tag{15}$$

Where, d = diameter of the spherical object, m; g = gravitational constant, m/s; ρ = density of the fluid medium, kg/m^3; A = $\pi d^2/4$ = projected area of the sphere, m^2; C_d = drag coefficient.

V = characteristic velocity (taken as terminal velocity, V_t), m/s.

Terminal velocity – without considering the buoyancy effects – is given as:

$$V_t = \sqrt{\frac{2mg}{\rho A C_d}} \tag{16}$$

Where, V_t = terminal velocity, m/s.

m = mass of the falling object, kg.

g = acceleration due to gravity, 9.81 m/s; C_d = drag coefficient (dimensionless).

ρ = density of the fluid through which the object is falling, kg/m^3.

A = projected area of the object, m.

Usually, drag coefficient is unknown because of its dependence on speed. Therefore it is more convenient to obtain the value of the product of drag coefficient and square of the Reynolds number as follows:

$$C_d {R_e}^2 = \frac{mg D^2}{A\rho v^2} \tag{17}$$

Where, C_d = drag coefficient (dimensionless); R_e = Reynolds number (dimensionless)

m = mass, kg; g = gravitational constant, m/s

D = effective diameter of object, m.

v = kinematic viscosity of fluid = μ/ρ, m^2/s.

This product is a function of R_e, therefore, the value of terminal velocity is found by use of appropriate graph of C_d versus $R_{e,}$ and equation 16.

3.0 Results and Discussions

3.1 Physical Properties

The mean characteristic lengths of the breadfruit seeds are plotted against moisture content (% wet basis) with the view of establishing the functional relationships between these properties and their moisture content. The characteristic dimensions increased as the moisture content increased as shown in tables 1 and 2.

Table 1: summary of the physical dimensions and characteristics of breadfruit seeds

Moisture content (%)	Major diameter (cm)	intermediate diameter (cm)	Minor diameter, (cm)	Surface Area (cm^2)	Sphericity (ψ) (-)	Aspect Ratio(-)
11	8.10±0.91	4.04±0.53	2.96±0.43	64.19±8.90	56.00±8.00	50.10±0.04
13	8.16±1.01	4.08±0.40	3.66±0.60	75.40±7.40	57.00±7.00	50.00±0.08
15	9.02±1.22	4.11±0.52	3.89±0.80	83.70±9.60	57.40±7.00	46.10±0.90
18	9.50±0.50	4.40±0.60	4.00±0.71	92.30±8.60	58.00±2.10	50.00±0.01
20	10.05±0.60	5.00±0.10	4.60±0.40	114.25±6.20	60.00±6.00	50.00±0.01

Table 2: summary of other physical properties of breadfruit seeds

Moisture content (%)	Volume (mm^3)	True density, (ρ_t , g/cm^3)	Bulk density (ρ_b , g/cm^3)	1000-grain weight (g)	Porosity, (ε)
11	50.6	1.099	0.835	360	15.01
13	63.18	1.103	0.851	470	13.51

15	75.52	1.105	0.878	500	11.04
18	87.56	1.108	0.908	550	8.3
20	121.05	1.11	0.938	610	5.6

The regression equations and the coefficients of determination are presented in tables 3.

Table 3: Regression equations of physical properties and their coefficient of determination

Component	Regression equation	Coefficient of determination (R^2)
Major diameter (L_1)	L_1 =0.003M^2 + 0.113M + 6.513	R^2 = 0.970
Intermediate diameter (L_2)	L_2 = 0.01M^2 + 0.361M + 6.177	R^2 = 0.988
Minor diameter (L_3)	L_3 = -0.003M^2 + 0.248M + 0.956	R^2 = 0.927
Arithmetic mean diameter (D_a)	D_a =0.004M^2 + 0.025M + 4.348	R^2 = 0.997
Sphericity ($\boldsymbol{\Psi}$)	$\boldsymbol{\Psi}$ = 0.036M^2 - 0.083M + 61.74	R^2 = 0.8970
Projected area (A_p)	A_p =0.131M^2 - 0.2.55M + 37.93	R^2 = 0.999
Bulk density, ($\boldsymbol{\rho_b}$)	$\boldsymbol{\rho_b}$ =0.000M^2 + 0.004M + 0.771	R^2 = 0.994

The sphericity ($\boldsymbol{\Psi}$) and aspect ratio (Ra) of the breadfruit seeds show increases with increase in moisture content. Other physical properties such projected area, surface area, volume of seeds were regressed with moisture content. Their coefficients of determination as shown in the table 3 indicate strong relationship and good fit.

Bulk density and particle density increased with increase in moisture content, but the effect of moisture seems to be more noticeable in bulk density than in particle density. However, there are high correlations between them and moisture content as shown in table 3.

3.2 Terminal Velocity

The terminal velocities of the kernel, seeds and shell (hull) of African breadfruit were plotted and presented in figure 1. The terminal velocities decreased as moisture content of the three materials (seeds, kernel and shell) increased. The empirical models are presented in table 4.

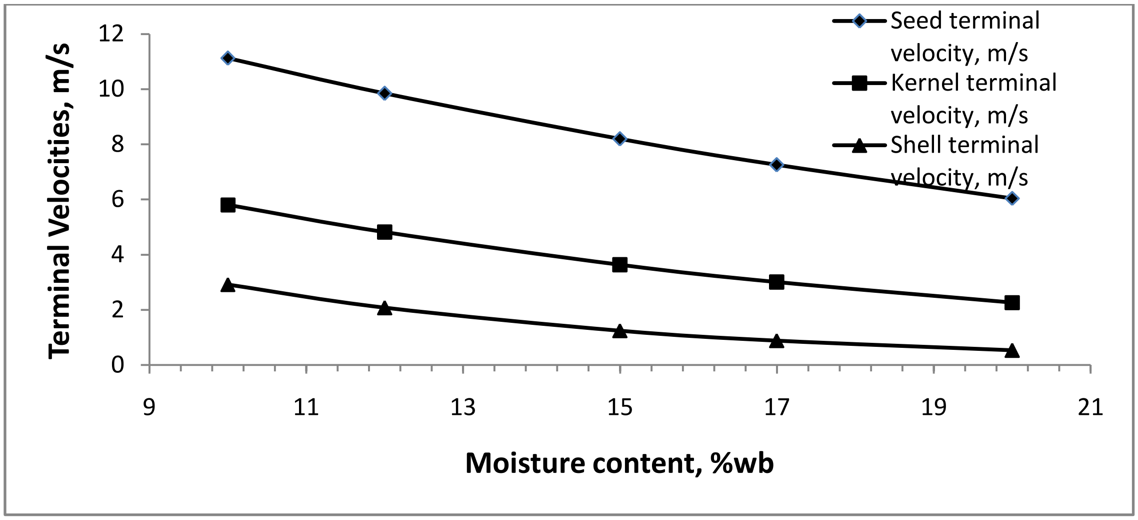

Fig.1 : Terminal velocities of breadfruit seeds, kernel and shells/hull against moisture content

3.3 Angle of Repose

The plot of angle of repose against moisture content is presented in figure 2. The equation relating angle of repose with moisture content and their coefficients of determination are presented in table 4. They all show good fit.

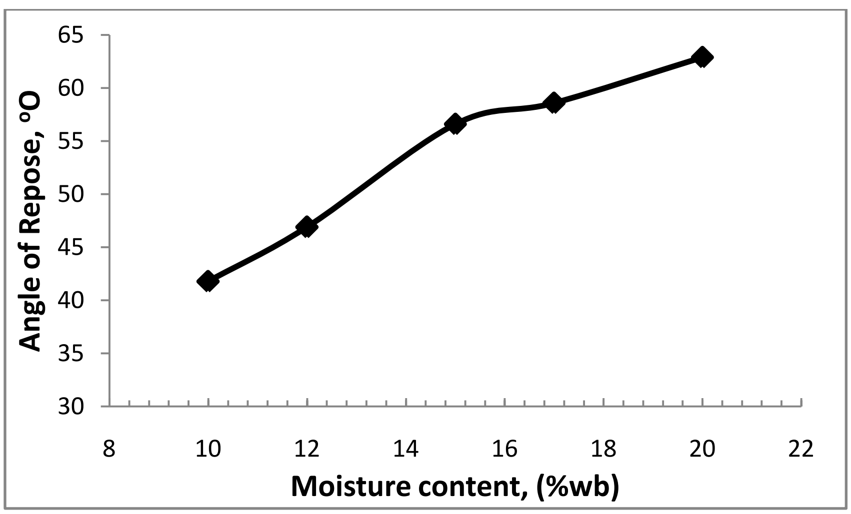

Fig. 3: Graph Angle of repose against moisture content

3.4 Coefficient if Friction on Three Surfaces

The plot of coefficients of friction on wood (plywood), mild steel and galvanized steel against moisture content are presented in figure 2. Within the range of the moisture content and ambient conditions of the experiments, the coefficient of friction increased with increase in moisture content. The regression equations shows high coefficient of determination and are presented in table 3.

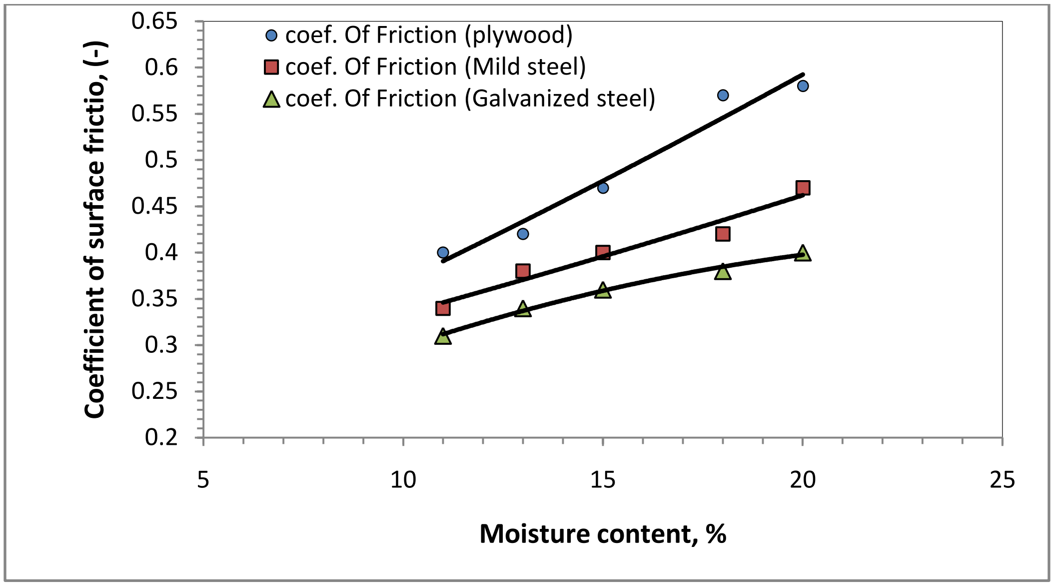

Fig. 4: graph of moisture content against coefficient of friction of breadfruit seeds on three structural surfaces

The empirical equations which were developed to predict the coefficient of friction of the seeds of breadfruit on the four surfaces are presented in table 4. They show strong relationships as indicated by their coefficient of determination (R^2)

Table 4: Regression models of Mechanical properties and their coefficients of determination

Component	Regression equation	R^2
Angle of repose	$\emptyset_r$ = -0.133M^2 + 6.153M - 6.740	R^2 = 0.9910
Coefficient of friction (plywood)	μ = 0.0001M^2 + 0.018M + 0.1754	R^2 = 0.9614
Coefficient of friction (mild steel)	μ = 9E-05M^2 + 0.0102M + 0.2237	R^2 = 0.9535
Coefficient of friction (galvanized steel)	μ = 4E-4M^2 + 0.0231M + 0.1106	R^2 = 0.9915
Terminal velocity of seed	$V_t = 0.015M^2 - 0.965M + 19.24$	$R^2 = 0.999$
Terminal velocity of kernel	$V_t = 0.016M^2 - 0.839M + 12.56$	$R^2 = 0.999$
Terminal velocity of hull/chaff	$V_t = 0.018M^2 - 0.802M + 9.031$	$R^2 = 0.998$
Terminal velocity (Seed)	V_t = -0.0225M^2 + 2.0395M + 9.6775	R^2 = 0.8173

The computations of the aerodynamic properties were based on the properties of the air at the conditions presented on table 5. These air properties were obtained from vaisala humidity calculator (psychrometric software) at the prevailing room temperature of the laboratory.

Table 5: Properties of air for aerodynamic experiment.

Specific Weight, w (N/m^3)	Specific gravity, S.G (-)	Specific Volume, V_g (m^3/kg)	Absolute Viscosity, (kg/m^3)	Kinematic Viscosity, v (m^2/s)	Fluidity, (rhe)	Relative humidity, R.H (%)
11.42	0.0012	0.8588	1.983×10^{-5}	1.70×10^{-5}	5.04×10^{4}	8

(Data from VAISALA psychrometric calculator)

4.0. Conclusion

The seeds of African breadfruit are of particular interest because of their high nutritional value. Fresh seeds contain up to 38.3% carbohydrate, 17.7% crude protein and 15.9% fat.

It is therefore necessary to determine some relevant physical and aerodynamic properties of these important seeds (var. *Inversa)*, which are needed to determine the parameters for effective pneumatic separation of shelled breadfruit seeds from hulls and foreign matter and also form the basis for design and development of machinery for their mechanized processes.

The characteristic dimensions were found to increase as the moisture content increased. The sphericity (Ψ) and aspect ratio (Ra) of the breadfruit seeds showed increase with increase in moisture content. Bulk density and particle density increased with increase in moisture content, but the effect of moisture was more noticeable in bulk density than in particle density.

The terminal velocities of the three materials studied decreased as moisture content of the materials (seeds, kernel and shell) increased.

The angle of repose and coefficient of friction on all the surfaces increased with increase in moisture content in the range of moisture tested.

The computations of the aerodynamic properties studied in this work were based on the properties of the air at the prevailing air conditions.

Bulk density and particle density increased with increase in moisture content, but the effect of moisture was more noticeable in bulk density than in particle density. The terminal velocities of the three materials studied decreased as moisture content of the materials (seeds, kernel and shell) increased. The angle of repose and coefficient of friction on all the surfaces increased with increase in moisture content in the range of moisture tested. The whole empirical equations developed have strong relationships among the variables as indicated by their high coefficient of determination (R^2) ranging from 0.0.8970 to 0.9990.

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