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# Some Moisture-Dependent Physical and Thermal Properties of Bambara Groundnut

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**Abstract:** *This study was carried out to investigate the effect of the moisture content on some physical and thermal properties of bambara groundnut (BBG) seeds. The properties were evaluated at five levels of moisture from11. 23 % to 28.11 % (wet basis). The average length, width and thickness were 12.10, 10.71 and 11.36 mm, at a moisture content of 11.23 %w.b., respectively. In the moisture range from 11.23% to 28.11% w.b., studies on rewetted BBG seeds showed that the unit seed mass increased from 1.115 to 1.634 g, the bulk density decreased from 795.25 to 781.87 kg/m$^3$, the true density increased from 1193.00 to1226.11 kg/m$^3$ and the porosity from 34.53 to 43.07 %. The geometric mean diameter increased from 11.37 to 13.35 mm, the sphericity decreased from 0.97 to 0.93 % and surface area increased from 407.25 to 562.10 mm$^2$. The coefficient of friction on mild steel, plywood and aluminum sheet surfaces increased from 0.087 to 0.277, 0.09 to 0.0.407 and 0.078 to 0.384, respectively; the emptying angle of repose from 19.98 to 29.12, 23.00 to 32.89 and 24.39 to 39.29, respectively. The specific heat, thermal diffusivity and thermal conductivity increased from 1.70 to 2.17 kJ/kgK, 0.19 to 0.205 x 10-7 m2/s and .253 to 0.31 W/mK, respectively with increase in moisture content from11. 23 % to 28.11 % (wet basis). Empirical models were developed for all the parameters measured and their respective high correlation coefficients indicate that they can be used to simulate these parameters within the moisture domain investigated.*
**Keywords:** *Bambara groundnut, Physical properties, Thermal properties, Empirical models.*

## I. Introduction

Bambara Groundnut (BBG) (*Vigna subterranea (L.) verdc*) seed is becoming an important food crops in African countries such as Nigeria, Senegal, Kenya and South Africa where it is grown and constitute a key source of proteins that is consumed in different forms to complement cereals and other starchy staples. For instance, it is usually fried or boiled with salt and eating as snack or pounded into flour and used in preparation of soup, porridge and various fried or steamed food products such as 'akara', 'moi-moi' and 'okpa' in Nigeria. It also finds a use in the preparation of local food drink 'kunu' and such dish as 'tuwo' (Linnemann, 1988). Linnemann, (1990) reported that BBG flour has been used in making bread in Zambia. Brough *et al.* (1993) noted that the milk prepared from BBG gave a preferred flavour to that of milk from cowpea, pigeon pea and soy bean. It is now prominent in diet of many rural household where it grown to the extent of being referred to as the third most important food legume after cowpea *(Vigna unguiculata)* and groundnut (Mkandawire, 2007).
Despite its high and balanced protein content, BBG remains under-utilised probably due to its content anti-nutrutional factors and its long time of cooking on one side and lack of adequate processing techniques to overcome the hard-to-cook phenomenon which is a major drawback limiting its utilization and thus discourage farmers from producing it for industrial purposes (Barimala & Anoghalu, 1997).

Physical properties of food and agricultural materials such as mass, size, shape, surface area, volume, aspect ratio, sphericity, true density, bulk density, porosity and angle of repose are those morphological attributes which when investigated are relevant to the design and development of harvesting, handling, processing and storage equipment for that particular material (Burubai & Amber, 2014).These properties describe the physical state of the material at any given condition and time. The mass, size and shape are essential for sorting, grading and various separation operations (Chandrasekar & Viswanathan, 1999; Zare *et al*.,2013). Pressure loads on storage structures is also dependent on angle of repose and frictional coefficients on bin wall materials (Burubai & Amber, 2014).

For years, the physical properties of agricultural products have been of interest to many researchers. They have reported physical and mechanical properties of seeds, nuts, kernels and fruits such as maize (Bart-Plange *et al*.), arigo seeds (Davies, 2010), tef seed (Ozarslan), chick pea, wheat grains (Aydin, 2002) and lentil seeds (Ozturk *et al*., 2010), lentil seeds (Bagherpour *et al*., 2010), soybeans (Davies & El-Oken, 2009), ground nut (Davies, 2009), chia seeds (Ixtaina *et al*., 2008), rice (Correa *et al*., 2007), raw and parboiled paddy (Reddy & Chakraverty, 2004), and hemp seeds (Sacilik *et al*., 2003; flaxseed (Singh *et al*., 2012) and corn seed (Babic *et al*., 2013). Despite these efforts little has been done on the physical properties of BBG seeds talkless of developing simple empirical models for the relationships between these aforementioned properties and moisture content that may cause significant change in their magnitude. In the same vein, there is apparently no report in the scientific literature that gives the thermal properties of BBG seeds and/or their relationship with its moisture content. It is highly essential to have knowledge of the thermal properties of the BBG seeds in order to effectively develop the processes and equipment needed in the drying, storage and thermal processing of the seed. Thermal properties of various food and agricultural products have been studied by such researchers as Kazarian & Hall (1965), Suter, Agarwal & Clary (1975), Shepherd & Bhardwaj (1986) and Dutta *et al.* (1988). Knowledge of how thermal conductivity (k), specific heat capacity ($C_p$,) and thermal diffusivity $(\alpha)$ depend on factors like temperature and moisture-content is required in modeling, simulation and equipment design for various food processing operations such as drying, wetting, heating, cooling and freezing are important parts of food processing operation. Interest in transport properties of foods (thermal conductivity, heat capacity, density, mass and thermal diffusivity and heat and mass transfer coefficient) appears due to the importance to predict heat and mass transfer rates during processing, preservation and optimal design of processing equipment. Mariani *et al*., 2008).

During the processing, properties like density, thermal conductivity and heat capacity present substantial changes depending on the composition, the temperature and the physical structure of the food (Figura & Teixeira, 2007; Fikiin & Fikiin, 1999; Nesvadba, 2005; Sahin & Sumnu, 2006).These thermal properties of food materials can be determined in two ways, either by direct measurement or by determining the composition of the foodstuff and using predictive equations expressing these properties as a function of chemical composition (Nesvadba, 1982). In order to design equipment for the handling, conveying, separation, drying, aeration, storing and processing of BBG seeds, it is necessary to determine their physical and mechanical properties as a function of moisture content.Therefore, our aim in this study was to determine the physical and thermal properties of BBG seeds, and develop empirical models for their relationship with moisture contents which provide the basic information for designing grain handling and processing machinery.

## II. Materials and methods

### 2.1 Materials

Dry mature BBG seeds were used for the experiment. A bulk quantity of the grain legume seed used was purchased from Sabo market, Ogbomoso, Oyo State Nigeria. The variety was the common milked (cream) colored one, which is mainly grown in the North Eastern Nigeria. The bulk was manually cleaned to remove foreign matter, dust, dirt, broken and immature grains and then sampled for experiment. The chemical composition of the BBG were analyzed for moisture, crude protein (N × 6.25), total fat, crude fiber and ash content using AOAC [1995] standard methods 925.10, 920.87, 920.39, 925.08 and 923.03 respectively. Carbohydrate content was determined by difference 100 - (% moisture + % protein + % fat + % ash). Chemical composition of raw material is shown in Table 1. The samples of the desired moisture contents were prepared by adding the amount of distilled water as calculated from the following relation (Sacilik *et al*., 2003):

$$Q = \frac{W_i(M_f - M_i)}{(100 - M_f)} \qquad 1$$

where, $W_i$, is the initial mass of sample in kg; $M_i$, is the initial moisture content of sample in % w.b.; and $M_f$ , is the final moisture content of sample in % w.b. The samples were then poured into separate polyethylene bags and the bags sealed tightly. The samples were kept at 5$^o$C in a refrigerator for a week to enable the moisture to distribute uniformly throughout the sample. The required quantity of the seed was taken out of the refrigerator and allowed to equilibrate to the room temperature for about 2 h (Singh & Goswami, 1996; Coskun *et al*. 2006) before experiments.

### 2.2 Axial dimensions

In order to determine the average size of the seeds, a sample of 100 seeds was randomly selected. For each individual seed, the three principal dimensions, namely length (L), width (W) and thickness (T), were measured using a micrometer screw gauge (least count 0.01 mm)as described by de Figueiredo *et al.* (2011) .

### 2.3 Geometric properties

The geometric mean ($D_g$), the sphericity ϕ), and surface area (S) defined as the ratio between the surface area of the sphere having the same volume as that of the seed and the surface area of the seed were determined using the following expressions by Mohsenin (1986), Jain & Bal (1997) & Varnamkhasti *et al*. (2008), respectively:

$$D_e = (LWT)^{1/3} \qquad 2$$

$$\phi = \frac{D_e}{L} \qquad (3)$$

$$S = \frac{\pi BL}{(2L - B)} \qquad (4)$$

where, $B = \sqrt{(WT)}$ (5)

## 2.4 Angle of repose

The dynamic angle of repose ($\theta_r$) was evaluated on three structural surfaces namely; mild steel plate (MS), unsanded plywood (PW) and aluminum surface (AL). The angle of repose was determined by using an empty cylindrical mold of 15 mm diameter and 25 mm height. The cylinder was placed at the centre of surfaces afore-mentioned, filled with BBG and raised gradually until it forms a cone of grain. The angle of repose was calculated from the measurements of the height (H) of the free surface of the seeds and the diameter (D) of the heap formed using the following relationship (Dutta *et al*., 1988; Olaoye, 2000):

$$\theta_r = \tan^{-1}\left(\frac{2\pi H}{D}\right) \qquad (6)$$

## 2.5 Static coefficient of friction

The static coefficient friction (μ) for BBG was measured against the three different surfaces by using a cylinder of diameter 75 mm and depth 50 mm filled with BBG, respectively. While the cylinder resting on the surface, it was raised gradually until the filled cylinder just started to slide down (Seyed & Elnaz, 2006). Static coefficient of friction was then calculated from $\mu = \tan\beta$ where, β is the angle of tilt (degree).

## 2.6 Gravimetric properties

The true density ($\rho_t$), defined as the ratio of the mass of the sample to its true volume, was determined according to the method of de Figueiredo *et al.* (2011) using an electronic balance reading 0.001 g and a pycnometer (water displacement method). The bulk density ($\rho_b$) was determined by using the mass/volume relationship (Fraser *et al*., 1978) by filling an empty plastic container of predetermined volume and tare weight with the grains by pouring from a constant height, striking off the top level and weighing. The porosity value (ε), defined as the fraction of space in the bulk grain which is not occupied by the grain, was calculated from the following relationship according to Mohsenin (1986):

$$\varepsilon = \left(1 - \frac{\rho_b}{\rho_t}\right) \times 100 \qquad (7)$$

The unit mass of the seed ($m_u$) was evaluated from the samples used to calculate the true density, dividing the mass of the sample by the number of seeds (de Figueiredo *et al*., 2011).

## 2.7 Thermal properties

### 2.7.1 Specific heat

Specific heat of the seeds was determined in triplicate using a copper calorimeter placed inside a lagged flask by the method of mixtures. The specific heat capacity of the BBG seeds was determined in an adiabatic drop calorimeter using the method of mixtures described by McProud and Lund (1983). 5g of the BBG seeds, tightly wrapped in a thin polythene foil was dropped in calorimeter containing water at $80^{O}$C temperature. The temperature of the water and sample were recorded over time. The data was used to plot the heat loss curve and the specific heat capacity was calculated from the heat balance equation;

$$C_s = \frac{1}{M_s}\left[M_w C_w \left(\frac{G_w}{G_s}\right) - M_c C_c\right] \qquad (8)$$

where, Cw and Cc are the specific heat capacity of water and calorimeter respectively (kJ/kgK); Ms, Mw and Mc are the mass of sample, water and calorimeter, respectively (kg); Gw and Gs are the slopes of cooling for water and sample, respectively ($^{O}$C/s)

### 2.7.2Thermal diffusivity

The temperature history of BBG was determined by using three different probes. Each probe was connected by K-type thermocouple wires to a digital multimeter (AldaAvd 890C-1JENWAY, England). Each probe was fixed at different points, one being at the surface of the calorimeter, one being at the centre of the powder while the other measures the temperature of the water. The calorimeter (with BBG ) was placed in hot water at 30$^{o}$C with a digital multimeter used to monitor the heating medium temperature via a probe and thermocouple wire at 4 min interval until the temperature of the water reached the desired temperature (Dickerson, 1965; Adekunle *et al*., 2013). The thermal diffusivity was calculated using the equation:

$$\alpha = \left(\frac{Mr^2}{4(T_j - T_s)}\right) \qquad (9)$$

where, α is the thermal diffusivity(m$^2$/sec), M, is the slope of $T_o$ against time i.e slope of heat curve ($^{o}$C/s), r is the radius of container, $T_j$ is the temperature of the surface at any time t, $^{o}$C and $T_c$ is the temperature at the center of the food at time t, $^{o}$C

**2.7.3Thermal conductivity**

The thermal conductivity was calculated using experimental values of specific heat, thermal diffusivity and bulk density as follows (Heldman & Singh, 2009):

$$k = \alpha \rho C_p \qquad 10$$

**2.8 Statistical analysis**

The data were analyzed statistically using SPSS software SPSS 14 (SPSS Inc., USA ) and the means were separated using the Duncan's multiple range test ($p \leq 0.05$). All the data were presented as the mean with the standard deviation. The coefficients of determination between the properties evaluated and the moisture content were determined using the Microsoft Excel 2003 (Microsoft Corp., USA).

## III. Results and Discussion

**3.1 Physical dimensions**

The mean length, width and thickness, and their dependence on moisture content are shown in Table 2. The mean values of 100 measurements were: 12.10 mm for length, 10.71 mm for width and 11.36 mm for thickness of BBG at a moisture level of 11.23 % w.b. Analysis of variance showed that moisture content had a significant effect on all dimensions of BBG ($p \leq 0.05$) in the ranges of moisture content evaluated. The mean values of the length, width and thickness measured within moisture contents investigated ranged from 12.10 to 14.35, 10.71 to 12.31 and 11.36 to 13.35 mm respectively as shown in Table 1. The coefficient of correlation (Table 1) shows that moisture has significance positive linear effect on both the length and thickness and, quadratic effect on the width of BBG at $p \leq 0.05$. With $R^2$ -value ≥ 0.922 the regression equations can be used to describe the relationships between the moisture and the dimensions of BBG as shown in Table 1. When soaked in water, the absorbed moisture, only after saturating the inter-space available between the cotyledons and coat diffused into the cotyledons and effect increases all dimensions of the BBG seeds (Balasubramanian, 2001). The values of these physical dimensions would be an important consideration in the development of seed sizing, grading machines, and in their separation from undesirable materials (Ogunjimi *et al*., 2002) and decorticating equipment.

**Table 1:** Principal dimensions and geometric properties of 100 seed count of BBG at different moisture content and regression parameters *.

| Moisture content (% w.b.) | Length (mm) | Width (mm) | Thickness (mm) | Geometric mean diameter(mm) | Sphericity (%) | Surface area ($mm^2$) |
|---|---|---|---|---|---|---|
| 11.23 | 12.10(0.77)$^a$ | 10.71(0.78)$^a$ | 11.36(0.72)$^a$ | 11.37(0.66)$^a$ | 0.94( 0.032)$^a$ | 407.25(46.95)$^a$ |
| 14.09 | 12.34(0.83)$^a$ | 10.96(0.85)$^a$ | 11.56(0.85)$^a$ | 11.60(0.76)$^b$ | 0.95(0.032)$^{ab}$ | 424.41(55.52)$^b$ |
| 16.93 | 12.68(0.96)$^b$ | 11.96(0.90)$^b$ | 12.08(0.94)$^b$ | 12.22(0.72)$^c$ | 0.97(0.023)$^b$ | 470.90(61.15)$^c$ |
| 22.09 | 13.61(1.16)$^c$ | 12.18(0.89)$^{bc}$ | 13.11(1.14)$^c$ | 12.94(0.46)$^d$ | 0.95(0.042)$^{ab}$ | 528.61(75.52)$^d$ |
| 28.11 | 14.35(1.06)$^d$ | 12.31(0.90)$^c$ | 13.52(1.07)$^d$ | 13.35(0.83)$^d$ | 0.93(0.034)$^a$ | 562.10(70.69)$^e$ |
| Regression | 0.14M+10.44 | $0.083M^2+0.43M+6.86$ | 0.14M+9.75 | 0.12M+9.99 | $-0.0003M^2+0.013M+0.84$ | 9.73M+298.72 |
| $R^2$ | 0.990 | 0.932 | 0.965 | 0.967 | 0.922 | 0.971 |

* Mean of 5 replicates with standard deviation in parentheses. Values in the same column followed by different superscript letters indicate significant differences with the moisture content ($p < 0.05$).M : moisture content, (% w.b.).

**3.2 Geometric properties**

Geometric properties of grains are fundamental because they determine interactions between and among particles, and with the surrounding air. These interactions influence almost all the engineering properties of grains that must be considered in the design and evaluation of grain storage and handling systems (de Figueiredo *et al.*, 2011).The geometric mean diameter (GMD), sphericity and surface area of the BBG nuts varied from 11.37 – 13.35 mm, 0.94 – 0. 97mm, and 407.25 – 562.10 $mm^2$ respectively as moisture content increased from 11.23 to 28.11 % as detailed in Table 2. The increase in the values of GMD might be attributed to its dependence on the three principal dimensions of the seed. For moisture range considered, all geometric properties presented significant differences ($p \leq 0.05$) with moisture content of the seed except sphericity. Their dependencies on moisture content are expressed as regression equations with their respective high $R^2$ values (≥ 0.922) as shown in Table 2. The geometric mean diameter insignificantly ($p \leq 0.05$) increased from 11.37 to 13.35 mm with increase in moisture content. The geometric mean diameter is useful for the evaluation of the projected area of a particle moving in the turbulent or near-turbulent area of an air stream. Hence, it is a useful parameter in design of separation systems for the seeds from extraneous materials (Gharibzahedi *et al.*, 2010).
Sphericity is an expression of a solid shape relative to that of a sphere of the same volume while the aspect ratio relates the width to the length of the seed which is an indicative of its tendency toward being spherical in shape (Gharibzahedi *et al*., 2010). The values of sphericity show that the seed are nearly spherical in shape and it will roll easily on surfaces especially in hoppers and dehulling equipment. High sphericity and aspect ratio is an

indication of the seeds tending to a spherical shape. These properties are useful in the design of dehulling equipment (Mohsenin, 1986).

### 3.3. Gravimetric properties

The variation of gravimetric properties with moisture content is shown in Table 2. Unit mass, bulk density, true density and porosity were found to vary from 1.115 to 1.634 g, 698.15 to 795.25 kg/m$^3$, 1193.00 to 1226.11 kg/ m$^3$ and 34.53 to 43.07 % within the moisture content investigated. Analysis of variance showed that moisture content had a significant positive effect ($p < 0.05$) on all the gravimetric properties considered for BBG in this study except for bulk density which decreases with increase in moisture. The results of the fit regression curves for unit weight, bulk density, true density and porosity are given in Table 2.

Unit mass of BBG increased significantly with the moisture content of the seed form (Tables 2). The mass of the seeds increased from 1.15 g to 1.634 g with increase in moisture content. The increase in mass may be attributed to the weight increase on moisture absorption.

The knowledge of bulk density is useful for the design of silos and hoppers for grain handling and storage (Nalladulai *et al*., 2002) to determine the weight of agricultural/food product that will be held by these containers. The decreasing trend for bulk density was also reported for different varieties of sunflower seeds (Gupta *&* Das, 1997; de Figueiredo *et al.,* 2011); lentil seeds (Carman, 1996); neem nuts (Visvanathan *et al*., 1996) and pigeon pea (Baryeh *&* Mangope, 2002). Within the moisture range studied, bulk density decrease with the increased in moisture level. Therefore, it could be attributed to the fact that increase in volume may be slightly high when compared with the net increase in mass of the bulk seed. This result is in agreement with the increase in porosity (Table 2) when the moisture content of the seed decreased.

A linear increase in true density was observed with moisture content. A similar Increasing trend in true density was reported by Gupta *&* Das (1998) for sunflower seeds, Aviara *et al.* (1999) for guna seeds, Chandrasekar *&* Visvanathan (1999) for coffee, and sweet corn (Coskun *et al.*, 2006). This may be due to higher mass increase of nut in comparison with its volume expansion on moisture gain.True density has practical application in determining separation of product from undesirable materials, and cleaning is an important unit operation in food processing (Fellows, 2000). The sinking and floating method is applicable for these samples because all of their densities were greater than that of density of water (1000 kg/m$^3$).

A linear increase in porosity as moisture content increase was also observed (Table 2). Similar trends were reported for lentil seeds (Çarman, 1996), traditional black hull sunflower (Gupta *&* Das, 1997), pigeon pea (Baryeh *&* Mangope, 2002), and safflower (Baümler *et al*., 2006), chickpea seeds (Konak *et al*., 2002), and green gram (Nimkar *&* Chattopadhyay, 2001) but a different behavior was reported for soybean (Sreenarayanan *et al*., 1985), safflower JSF-1 (Gupta *&* Prakash, 1992) and pumpkin seeds (Joshi *et al*., 1993).

**Table 2:** Gravimetric properties of BBG at different moisture content and regression parameters+.

| Moisture content (% w.b.) | unit seed mass* (g) | Bulk density (kg/m$^3$) | True density (kg/m$^3$) | Porosity (%) |
|---|---|---|---|---|
| 11.23 | 1.115(0.246)$^a$ | 781.87(3.78)$^{ab}$ | 1193.00(4.76)$^a$ | 34.53(0.96)$^a$ |
| 14.09 | 1.115(0.246)$^a$ | 795.25(5.29)$^b$ | 1203.76(4.12)$^b$ | 33.96(0.89)$^a$ |
| 16.93 | 1.222(0.203)$^b$ | 772.19(4.32)$^a$ | 1212.64(4.43)$^c$ | 36.34(1.05)$^b$ |
| 22.09 | 1.451(0.304)$^c$ | 702.22(4.17)$^c$ | 1219.19(5.79)$^d$ | 42.45(1.11)$^c$ |
| 28.11 | 1.634(0.294)$^d$ | 698.15(3.93)$^d$ | 1226.11(3.88)$^d$ | 43.07(1.56)$^c$ |
| Regression | 0.034M+0.69 | -6.28M+865.72 | 1.87M+1176.40 | 0.61M+26.73 |
| $R^2$ | 0.970 | 0.837 | 0.921 | 0.883 |

* Mean of 5 replicates with standard deviation in parentheses

Values in the same column followed by different superscript letters indicate significant differences with the moisture content ($p < 0.05$).

M : moisture content, (% w.b.).

### 3.4 Coefficient of friction

The effect of moisture content of the BBG seeds on friction coefficient against the various test surfaces, namely, mild steel, plywood and aluminum is given in Figure 1.The friction coefficient increased linearly with moisture content for all surfaces except mild steel that showed quadratic relationship. The equations showing these relationships existing between the angle of repose and moisture are as given in Fig. 1 and Table 3.

### 3.5Angle of repose

Figure 2 shows the variation the emptying angle of repose with seed moisture content on different surfaces. The positive linear regression equations showing the relationship existing between the angle of repose and moisture are as shown in Table 3. The high $R^2$ values are indications that these equations can be effective in predicting the angle of repose of BBG seeds within the moisture content domain investigated. The maximum angle of repose was offered by the aluminum surface, followed by plywood and mildsteel surfaces at all moisture contents as shown in Figure 2.

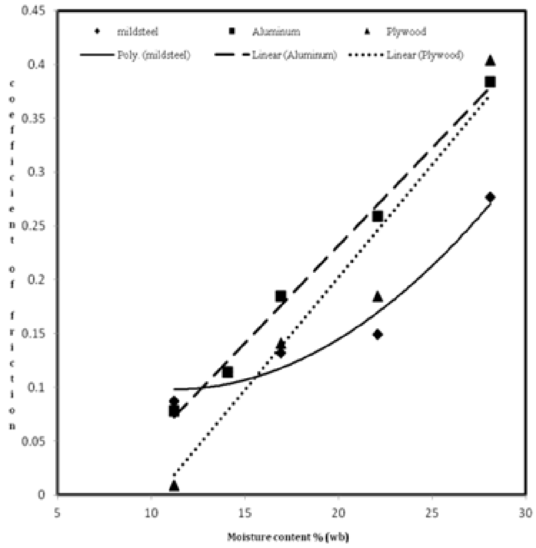


**Fig. 1:**Friction coefficients of BBG at different moisture contents

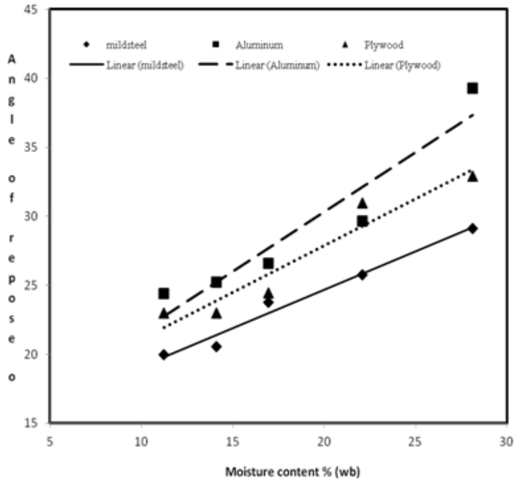


**Fig. 2:**Angle of repose of BBG at different on various surfaces moisture contents on various surfaces

**Table 3:** Regression equations as a function of moisture content for friction coefficient and angle of repose.

| Parameter | Material of construction | Regression | $R^2$ |
|---|---|---|---|
| Coefficient of static friction | MS | $0.0006M^2$-0.0136M+0.1742 | 0.958 |
| | PW | 0.0209M-0.22 | 0.928 |
| | AL | 0.0209M-0.22 | 0.994 |
| | | | |
| Angle of repose (°) | MS | 0.56M+13.53 | 0.977 |
| | PW | 0.68M+14.38 | 0.925 |
| | AL | 0.86M+14.38 | 0.906 |
| | | | |

M : moisture content, (% w.b.).

### 3.6 Thermal properties
#### 3.6.1 The specific heat

The specific heat of BBG seeds followed a positive linear relationship with moisture content with high $R^2$ values Fig. 3 and Table4. Other research workers (Tang *et al.*, 1991; Chakrabarty & Johnson, 1972 and Wang & Brennan, 1993) also observed linear relations of specific heat with moisture for other agricultural materials at high moisture contents. The relationship between the specific heat and moisture content within the domain investigated can be expressed by the regression equations given in Table 4.

**3.6.2 Thermal diffusivity**

The relationship between temperature and thermal diffusivity at different moisture contents is shown in Figure 4. The thermal diffusivity varied from $0.158 x 10^{-8}$ to $0.205 x 10^{-8}$ $m^2/s$ with increase in moisture content. The variation of thermal diffusivity with moisture content exhibited a positive linear relationship (Table 4). The increase in thermal diffusivity with moisture content may be due to fact that the value of bulk density decreased.

**3.6.3Thermal conductivity**

The variation of thermal conductivity with moisture contents is shown in Fig. 3. It can be observed that the thermal conductivity increased with moisture at a given temperature and followed positive linear relationship within the moisture contents understudy (Figure 5 and Table 4). Other research workers (Sharma & Thompson, 1973; Kazarian & Hall, 1965; Hsu *et al.*, 1991) reported the existence of a linear relationship of thermal conductivity with moisture content for other agricultural materials. The values of thermal conductivity varied from 0.253 to 0.31 W/mK in the range of moisture content understudy.

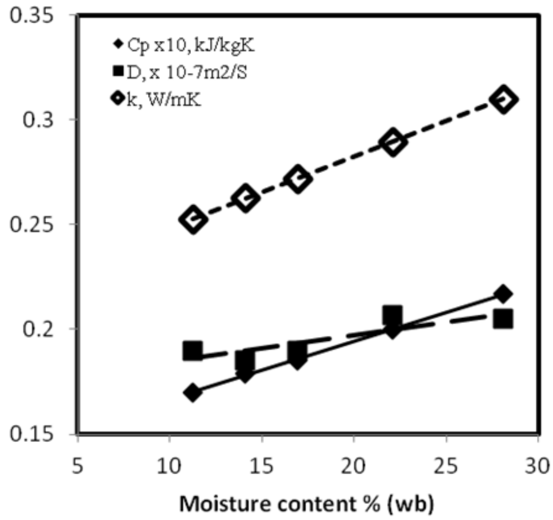


**Fig.3:** Variation of thermal properties of BBG with moisture

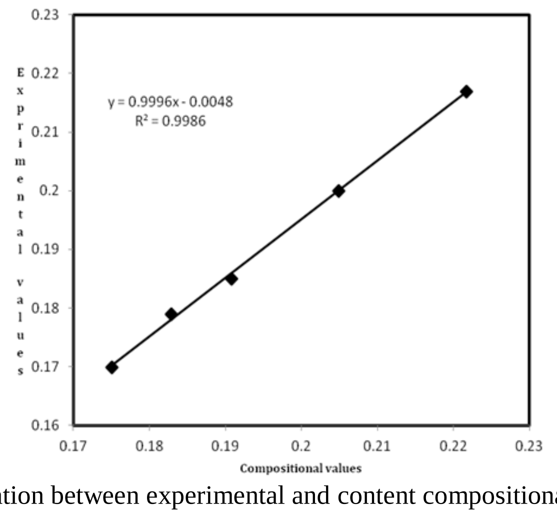


**Fig. 4:** Correlation between experimental and content compositional values for specific heat (x10kJ/kgK)

**Table 4:** Regression equations as a function of moisture content for thermal properties.

| Parameter | Regression | $R^2$ |
|---|---|---|
| Specific heat (kJ/kgK) | 0.028M+1.39 | 0.999 |
| Thermal diffusivity ($x10^{-8}m^2/s$) | 0.0013M+0.17 | 0.731 |
| Thermal conductivity (W/mK) | 0.0034M+0.22 | 1.00 |

M : moisture content, (% w.b.).

### 2.6.4 Experimental and computed thermal properties

Table 4 shows the egression equations of the experimental data. These data were compared with the computed thermal properties from equations 11 to 13 (Heldman & Singh, 2009). The correlations showed that there is good agreement between developed models and additive model for all the thermal properties considered in this study as shown on Fig. 4 to 6 with high $R^2$ values (≥0.998).

**Table 5:** Proximate composition of BBG (%) and their corresponding computed thermal properties as calculated*

| Moisture content | Ash | Fat | Fiber | Protein | CHO+ | $C_p^a$ (kJ/kgK) | $k^a$ (W/mK) | $\alpha^a$ ($x10^{-7}$ $m^2/s$) |
|---|---|---|---|---|---|---|---|---|
| 11.23(0.049) | 3.59(0.029) | 6.18(0.033) | 3.30(0.008) | 16.90(0.025) | 58.80(0.068) | 1.75 | 0.261 | 0.191 |
| 14.09(0.051) | 3.44(0.027) | 5.91(0.047) | 3.42(0.027) | 16.73(0.220) | 56.41(0.180) | 1.83 | 0.271 | 0.187 |
| 16.93(0.037) | 3.18(0.019) | 5.72(0.036) | 3.35(0.019) | 16.51(0.070) | 54.31(0.094) | 1.91 | 0.281 | 0.191 |
| 22.09(0.026) | 2.91(0.011) | 4.57(0.029) | 3.23(0.039) | 16.31(0.011) | 50.89(0.016) | 2.05 | 0.300 | 0.209 |
| 28.11(0.028) | 2.55(0.023) | 4.31(0.031) | 3.11(0.039) | 16.09(0.160) | 45.83(0.238) | 2.22 | 0.321 | 0.207 |

* Mean of 3 replicates with standard deviation in parentheses. +Calculated by difference. aCalculated according to equations 11 - 13.

$$C_p = 1.424X_c + 1.549X_p + 1.675X_f + 0.837X_a + 4.187X_w \quad 11$$

$$k = 0.25X_c + 0.155X_p + 0.16X_f + 0.135X_a + 0.58X_w \quad 12$$

$$\alpha = 0.082\times10^{-6}X_c + 0.075\times10^{-6}X_p + 0.10\times10^{-6}X_f + 0.135X_a + 0.146\times10^{-6}X_w \quad 13$$

## IV. Conclusion

Some physical thermal properties BBG which may likely help in the design and development of handling and processing equipment were evaluated in this study. The investigation has showed that the physical dimensions and size related characteristics of the BBG seeds vary significantly with moisture contents. This information is useful for optimizing milling operations, designing the storage structures and processing machinery, which will help to gain more relevance for the seeds among farmers and processors.

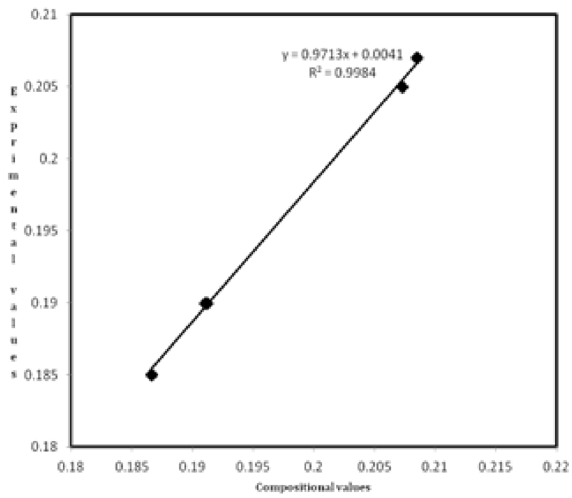


**Fig.5:**Correlation between experimental and compositional values for thermal diffusivity($x10^{-7}$ $m^2/s$)

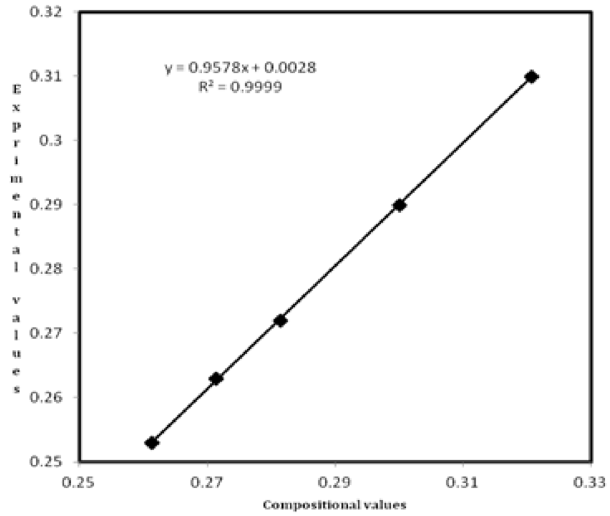


**Fig. 6:** Correlation between experimental and compositional values for thermal conductivity(W/mK)

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