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Physical Properties of *Mucuna flagellipes* Nuts

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ABSTRACT

The physical properties of *Mucuna flagellipes* nut were investigated to explore the possibility of developing its bulk handling and processing equipment. In the moisture range of 3.38-10.7% (d.b.), the major, intermediate and minor axial dimensions increased from 2.73–2.8, 2.71–2.74 and 1.87–2.04 cm, respectively. The arithmetic mean, geometric mean and equivalent sphere effective diameter determined at the same moisture level were significantly different from each other ($P < 0.05$), with the arithmetic mean diameter being of the highest value. In the above moisture range, one thousand nut weight, particle density and porosity increased non-linearly with moisture content from 6.24 to 6.77 kg, 1107 to 1147 kg m^{-3} and 41.2 to 49.4%, respectively, while bulk density decreased non-linearly with increase in moisture content from 568 to 488.8 kg m^{-3}. Nut roundness and sphericity and angle of repose increased logarithmically with moisture content from 85.5-96.6%, 85.5-98.8% and 16.4-20.2° respectively. The kinetic coefficient of friction decreased linearly with moisture content on Hessian bag, fibre glass, galvanized steel sheet and plywood with wood grain parallel to the direction of movement, increased linearly with moisture content on plywood with wood grain perpendicular to the direction of movement. Static coefficient of friction increased linearly with moisture content on all the above structural surfaces. The coefficient of restitution of the nut on different structural surfaces under longitudinal fall ranged from 0.026-0.661 and from 0.0045-0.334 under lateral fall. It decreased with increase in moisture content and drop height on galvanized steel sheet.

Keywords: Angle of repose, coefficient of restitution, kinetic coefficient of friction, one thousand nut weight, static coefficient of friction

INTRODUCTION

Mucuna flagellipes, known as 'okpobo' among the Igbos of Nigeria, belongs to the legume family Fabaceae. It is found mainly in the Tropical Rainforest of the country and has been noted to be grown as a minor food crop by other ethnic groups in Asia and other parts of Africa (Dako and Hill 1977; Iyayi and Egbarevba 1998). Vegetable fibres and cloths, leather, wooden objects and pottery are dyed black or blue-black by boiling them up with stems and leaves of *M. flagellipes* (Jansen 2005).

The tree is mainly important for its nut (**Fig. 1**) which contains a kernel with approximately 20% protein and 70% carbohydrate (Jansen 2005), and oil content of 3.77% (Ajayi *et al*. 2006). The composition of the oil compares well with those of rape seed, sesame, sunflower and groundnut seed oils. The kernel therefore serves as a very good source of protein and edible oil. Gum extracted from *M. flagellipes* kernel showed high emulsion properties and pseudoplasticity, which suggest its suitability as a stabilizer and emulsifier in oil-water emulsions like mayonnaise and salad dressings as well as in meat emulsions (Onweluzo *et al.* 1993). Nwokocha and Williams (2009) reported that the seed gum of *M. flagellipes* did not exhibit pronounced shear thinning at low concentrations which could be the reason why the flour of *M. flagellipes* kernel functions as a thickening agent in soups (Anumnu 1990; Ene-Obong and Carnovale 1992; Versteeg *et al.* 1998). The plant leaves and kernel are used as herbal treatments against a range of conditions such as urinary tract, neurological and menstruation disorder, constipation, fever, tuberculosis, ulcer, Parkinson's disease and elephantiasis (Ukachukwu 2000). Ojiako *et al.* (2010) studied the nutritional and antinutritional properties of *M. flagellipes* seed processed using different methods and reported that the method of processing the seed had significant effect on the properties.

The processing of *M. flagellipes* nut involves cracking it using a hard object to extract the kernel. This is then boiled in water, ground and mixed with red palm oil to form a yellow loose powder. The product is then packaged in transparent polyethylene bags for marketing or use in thickening the soup. The present methods of carrying out these operations are not only labour and time consuming but also wasteful. Improved methods of handling and processing the nut using suitable machines and equipment can be developed if the physical properties are known.

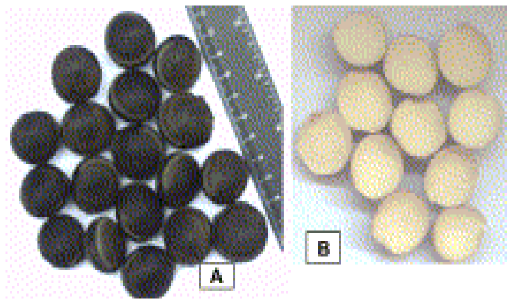

Fig. 1 *M. flagellipes* nuts (**A**) and kernels (**B**).

Several researchers (Aviara *et al.* 1999; Aviara and Haque 2000; Singh and Goswani 1996; Ogunjimi *et al.* 2002; Tabatabaeefar 2003; Aviara *et al.* 2005a, 2005b; Tunde-Akintunde *et al.* 2007; Burubai *et al.* 2007; Simonyan *et al.* 2007; Zewdu and Solomon 2008) determined the physical properties of such agricultural products as guna seed, guna seed kernel, cumin seed, locust bean seed, wheat, *Balanites aegyptiaca* nuts, sheanut, beniseed, wheat grain, sorghum grain, African nutmeg, and grass pea. These investigators determined the size of various seeds and grains by measuring their principal axial dimensions. Singh and Goswani (1996), Ogunjimi *et al.* (2002), Tabatabaeefar

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(2003), Aviara *et al.* (2005a, 2005b) and Simonyan *et al.* (2007), using an electronic balance, determined the 1000-seed or nut weight of various products (cumin seed, locust bean seed, wheat, *Balanites aegyptiaca* nuts, sheanut and sorghum grains). Dutta *et al.* (1988), Oje (1994) and Aviara *et al.* (2000) determined the sphericity and roundness of gram, cowpea and shea nut, respectively using the shadow graphs of the products in their natural position of rest. Singh and Goswani (1996), Aviara *et al.* (1999), Ogunjimi *et al.* (2002), Tabatabaeefar (2003), Milani *et al.* (2007), Simonyan *et al.* (2007) and Burubai *et al.* (2007) determined the particle density of various agricultural products (cumin seed, guna seed, locust bean seed, wheat, cucurbit seed, sorghum and African nutmeg) using the liquid displacement method. This method was reported to be simpler and involved the immersion of the material fully in liquid (water or toluene) and noting the amount of liquid displaced. When water is used, a thin layer of epoxy resin is applied over the material to prevent the absorption of moisture during the experiment. Carman (1996), Singh and Goswani (1996), Ogunjimi *et al.* (2002), Tabatabaeefar (2003), Aviara *et al.* (2005a, 2005b), Burubai *et al.* (2007) and Simonyan *et al.* (2007) determined the bulk density of such products as lentil seed, cumin seed, locust bean seed, wheat, *Balanites Aegyptiaca* nuts, sheanut, African nutmeg and sorghum grains. Most of the investigators used the AOAC (1980) recommended method to determine bulk density. This involves the filling of a standard container with the material from a height of 15 cm, levelling the surface and weighing the content. The relationship existing between porosity, particle density and bulk density stated by Mohsenin (1986) has been frequently employed in determining the porosity of grains and seeds. Different methods have been used in studying the static coefficient of friction of agricultural products on different structural surfaces. These include moving a given surface against the material (Lawton 1980), tilting an inclined plane (Mohsenin 1986; Dutta *et al.* 1988; Aviara *et al.* 1999) and the use of shear box equipment (Osunade and Lasisi 1994). The structural surfaces usually employed are galvanized steel sheet, Hessian bag, fibre glass and plywood. Two methods of determining the kinetic coefficient of friction of agricultural materials have been utilized by investigators. These include the use of an open-ended box connected to a weighted pan with a thread running through the groove of a pulley (Kaleemulah 1992; Aviara *et al.* 2000) and a friction device developed by Tsang *et al.* (1984). Investigators (Dutta *et al.* 1988; Singh and Goswani 1996; Aviara *et al.* 1999), using a specially constructed box with a removable front panel, studied the angle of repose of grains and seeds. The method described by Kumar (1995) has been used to determine the coefficient of restitution of agricultural products (Lo Curto *et al.* 1997; Jayan and Kumar 2004).

Most investigations show that the physical properties of agricultural products are moisture dependent. Aviara *et al.* (1999) noted that the moisture-dependent characteristics of the physical properties of agricultural products have effect in the adjustment and performance of processing machines. A range of moisture content usually exists within which optimum performance is achieved. Therefore, the effect of moisture content on the physical properties of *M. flagellipes* nut is of important consideration in the design of the handling and processing equipment. However, no work appears to have been carried out on the physical properties of the nut and their relationship with moisture content.

The objective of this work was to determine the physical properties of *M. flagellipes* nut and investigate their relationship with moisture content. The properties include nut size, 1000-nut weight, particle density, bulk density, porosity, roundness and sphericity, static coefficient of friction, kinetic coefficient of friction, coefficient of restitution and angle of repose. The methods employed were selected on the basis of simplicity, accuracy of results, and wide acceptability.

MATERIALS AND METHODS

For this work, a bulk quantity of *M. flagellipes* nut was obtained from Monday market in Maiduguri, Borno State, Nigeria. The nuts were cleaned and sorted so that foreign matter, broken and immature nuts were removed.

The moisture content of *M. flagellipes* nut was determined using the oven method as described by Aviara *et al.* (2005a). Samples were oven dried at 105°C for 7 hrs, with weight loss monitored on an hourly basis to give an idea of the time at which the weight began to remain constant. Weight of samples was found to remain constant after oven drying for a period of about 6 hours. Four moisture levels were used to investigate the effect of moisture content on the physical properties. Nut samples of desired moisture levels were prepared by conditioning the samples using the method of Ezeike (1986). This involved soaking different bulk samples in clean water for a period of 16, 32 and 48 hrs, followed by spreading out in a thin layer to dry in natural air for about 8 hrs. Trial conditioning had indicated that it is the above durations of soaking that would yield different moisture levels. After this, the samples were sealed in polyethylene bags and stored at the ambient temperature condition for a further 24 hrs. This enabled stable and uniform moisture content of the samples to be achieved.

To determine the nut size, 100 nuts were randomly selected at each moisture level, following a method similar to that employed by Dutta *et al.* (1988). For each nut, the three principal axial dimensions, namely the major, intermediate and minor axes, were measured using a vernier calliper reading to 0.05 mm. Since the size of nut was considered to be an important parameter in processing (Teotia and Ramakrishna 1989; Joshi *et al.* 1993; Suthar and Das 1996), the bulk samples of nut were classified into three categories, namely large ($a > 2.47$ cm), medium ($2.27 \text{ cm} \leq a \leq 2.47$ cm) and small ($a < 2.27$ cm) based on the major axis. The weight of one thousand nuts was obtained using an electronic balance weighing to 0.001 g. Particle density was determined by the water displacement method. Thirty nuts, each coated with very thin layer of epoxy resin to prevent the absorption of water during the experiment, were used. Increase in nut weight due to the adhesive was negligible (< 2%).

Bulk density was determined using the AOAC (1980) method. This involved the filling of a 1500 ml cylinder with nuts from a height of 15 cm and weighing the content.

Porosity was calculated from the particle and bulk densities using the relationship given by Mohsenin (1986).

$$P = [(1-\rho_b)/\rho_t] \times 100 \quad (1)$$

where P is porosity (%), ρ_b is bulk density (kg m^{-3}), and ρ_t is particle density (kg m^{-3})

Roundness and sphericity were determined by tracing the shadowgraphs of the nut on a graph sheet. The shadowgraph was produced by drawing the shape of the nut at its natural position of rest. This was followed by drawing of inscribing and circumscribing circles on the shadowgraph. The projected area and that of the smallest circumscribing circle were determined by the method of counting the squares and the diameters of the inscribing and circumscribing circles were measured. Twenty shadowgraphs were used. Nut roundness was evaluated using the following expression:

$$R = (A_p/A_c) \times 100 \quad (2)$$

where R is roundness (%), A_p is projected area (m^2) and A_c is area of smallest circumscribing circle (m^2).

Sphericity was calculated from the relation:

$$S = (D_i / D_c) \times 100 \quad (3)$$

where S is sphericity, D_i is diameter of inscribing circle (m) and D_c is diameter of the circumscribing circle (m).

The static coefficient of friction of the nut was evaluated on five structural surfaces, namely; galvanised steel sheet, Hessian bag, fibre glass, plywood with wood grains parallel to the direction of movement, and plywood with wood grains perpendicular to the direction of movement. The inclined plane method as described by

Table 1 Axial dimensions of *Mucuna flagellipes* nut at different moisture contents.

Moisture content. % (d.b)	Major diameter a (cm)	Intermediate diameter b (cm)	Minor diameter c (cm)	Arithmetic mean diameter ((a+b+c)/3) (cm)	Geometric mean diameter $(abc)^{1/3}$ (cm)	Equivalent sphere effective diameter $(6W_{1000}/1000\rho_t\pi)^{1/3}$ (cm)
3.38	2.73 ± 0.18	2.70 ± 0.18	1.87 ± 0.17	2.43	2.40	2.34
5.75	2.74 ± 0.24	2.71 ± 0.22	1.88 ± 0.17	2.44	2.41	2.21
8.28	2.77 ± 0.21	2.72 ± 0.19	2.00 ± 0.22	2.50	2.47	2.20
10.7	2.80 ± 0.26	2.74 ± 0.20	2.04 ± 0.28	2.53	2.50	2.24

Table 2 Size distributions of *Mucuna flagellipes* nuts at moisture content of 3.38 % (d.b).

Particulars	Major diameter a (cm)	Percentage of sample		Average major diameter (cm)	Average intermediate diameter (cm)	Average minor diameter (cm)	Average major/ intermediate ratio.	Average major/minor ratio.	Average mass (g)	Average major diameter /mass ratio
		by number	by mass							
Nut ungraded	2.22 – 3.21	100	100	2.73 ± 0.32	2.71 ± 0.20	1.87 ± 0.17	1.05 ± 0.06	1.48 ± 0.12	6.53 ± 0.67	0.42 ± 0.053
Large	a >2.27	54	53	2.85 ± 0.14	2.79 ± 0.18	1.89 ± 0.12	1.09 ± 0.09	1.49 ± 0.12	7.46 ± 0.74	0.38 ± 0.044
Medium	2.27≤a≤2.47	40	30	2.54 ± 0.21	2.62 ± 0.11	2.55 ± 0.014	1.01 ± 0.04	1.47 ± 0.09	5.88 ± 0.44	0.43 ± 0.054
Small	a<2.27	6	17	2.37 ± 0.09	2.38 ± 0.09	1.81 ± 0.16	0.98 ± 0.06	1.46 ± 0.13	4.72 ± 0.49	0.502 ± 0.046

Dutta *et al.* (1988) and Mohsenin (1986) was used. This involved placing an open-ended box on an adjustable tilting structural surface. The box was filled with nuts and the structural surface with the box and its content on top was gradually raised with a screw device until the box just started to slide down. The angle of tilt was read from a graduated scale and the tangent of this angle was taken as the static coefficient of friction of the nut at a specified moisture level.

For the kinetic coefficient of friction, the open-ended box used in determining the static coefficient of friction was placed on a horizontal surface. Five structural surfaces (same surfaces used for static coefficient of friction determination) were used at each moisture level. The box was filled with nuts. It was connected by means of a string, parallel to the surface and passed over a pulley to a pan hanging from it. Weights were placed in the pan until the box and its content moved uniformly when given a gentle push. The kinetic coefficient of friction of the nut on a given structural surface was determined using the expression

$$\mu = \frac{\text{weight of pan + weight placed in pan to move the box}}{\text{weight of box + weight of sample}} \quad (4)$$

where μ is the kinetic coefficient of friction on a structural surface.

The coefficient of restitution of the nut was determined using the method described by Kumar (1995). In this method, the nut was dropped from a height of 30, 70, 100, 150 and 200 cm, on four structural surfaces, namely wood, galvanized steel sheet, Hessian bag, and fibre glass. A graduated scale was kept at the background and the maximum height of nut rebounded was recorded using a video camera. This was replicated three times at each moisture level for nut fall on both axial and longitudinal orientation. The coefficient of restitution was calculated using the following equation:

$$CR = \sqrt{\frac{h}{H}} \quad (5)$$

where CR is the coefficient of restitution, h is height of rebound (cm) and H is height of drop (cm).

In determining the angle of repose, a specially constructed open-ended box made of plywood and 150 × 150 × 150 mm in size, with a removable front panel, was used. The box was placed on a table and filled with nuts. The front panel was quickly removed to allow the material to slide and assume its natural slope in bulk. The angle of repose was calculated from the depth of the free surface of the product, measured at two known horizontal distances from one end of the box.

Experimental design, sampling and statistical analyses

The nuts used in carrying out investigations were randomly selected using a multi-slot riffle box divider following a completely randomized design procedure. All the experiments were repeated five times and the average values were reported. Frequency distributions of the nut axial dimensions were determined and plotted. At each moisture level employed, the one way ANOVA and least square difference (LSD) was used to compare and separate the arithmetic mean, geometric mean and equivalent sphere effective diameter of the nut. The relationships existing between the physical properties and nut moisture content were expressed using regression equations obtained using curve fitting procedures. In the case of one thousand nut weight, the relationship existing between the property and moisture content was mathematically modelled using a mechanistic approach. The developed model was tested and evaluated using the non linear regression procedure in SPSS 16.0 for Windows. The coefficient of restitution of the nut was carried out using a factorial design of 5 fall heights by 4 structural surfaces by 4 moisture levels at each of two orientations at fall. Each test was replicated five times.

RESULTS AND DISCUSSION

Nut moisture content

The initial moisture content of the nut was found to be 3.38 ± 0.71% (d.b.). The three other moisture levels obtained after conditioning the nuts were 5.75 ± 0.62, 8.28 ± 0.38 and 10.70 ± 0.62% (d.b.), respectively. The investigations were carried out at the above moisture levels to determine the effect of moisture content on the physical properties of *M. flagellipes* nut.

Nut size and size distribution

The results of *M. flagellipes* nut size measured at different moisture contents are presented in **Table 1**. The table shows that the three axial dimensions increased with moisture content in the moisture range of 3.38-10.70% (d.b.). The major, intermediate and minor axial dimensions of the nut increased from 2.73-2.80, 2.71-2.74 and 1.87-2.04 cm, respectively, in the above moisture range. The size distribution of *M. flagellipes* nut at the initial moisture content of 3.38% (d.b) is presented in **Table 2** while the frequency distribution curves of the major, intermediate and minor axial dimensions of the nut at the above moisture level are presented in **Fig. 2**. This shows that the nut size has a normal distribution. The average major, intermediate and minor axis was 2.73, 2.72 and 1.85 cm, respectively. About 54% by number and 53% by mass of the nuts were large (a > 2.47 cm), 40% by number and 30% by mass were medium (2.27 cm ≤ a ≤ 2.47 cm) and 6% by number and 17% by mass (a < 2.27cm) were small sized. The arithmetic mean of the three principal axes, the geometric mean and the equivalent sphere effective diameters of the nut at different moisture contents, also presented in **Table 1**, increased with increase in moisture content. The arithmetic mean diameter had higher values than the geometric and equivalent sphere effective diameters of the nut.

M. flagellipes nut was found larger in size than neem

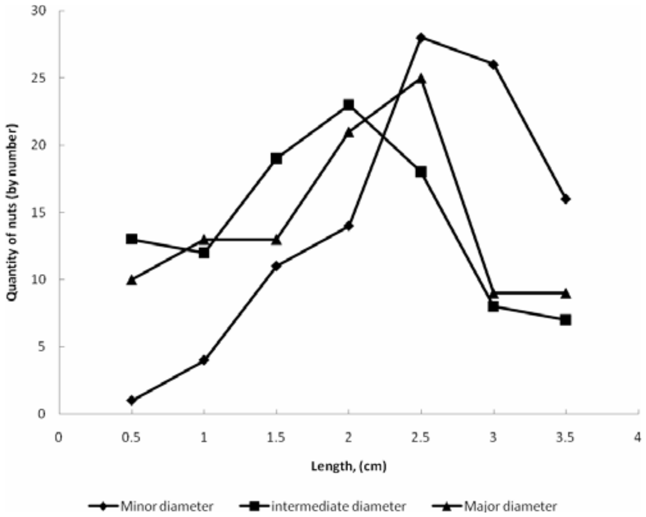


Fig. 2 Frequency distribution curves of *Mucuna flagellipes* nut axial dimensions at 3.38% (d.b) moisture content. n = 500

nut (Visvanathan *et al.* 1996), hazel nut (Aydin 2002), almond nut (Aydin 2003) and pine nut (Ozguven and Vursavus 2005).

1000-nut weight

The variation of one thousand nut weight with moisture content is presented in **Fig. 3**. This shows that the 1000-nut weight increased from 6.24 to 6.77 kg as the moisture content increased from 3.38-10.70% (d.b). This trend of nut weight with moisture content could be attributed to increase in weight gain due to moisture uptake at higher moisture levels.

Let increase in nut weight with moisture content be considered analogous to growth just as coefficient of volumetric shrinkage was defined in analogy to coefficient of thermal expansion (Tang and Sokhansanj 1993). Assuming that the quantity of increase in weight is proportional to the weight and moisture content, with the increase in weight being irreversible (France and Thornley 1984), then, a coefficient of gravimetric expansion can be defined as:

$$\beta_w = \frac{\partial w / w}{\partial M} \quad (6)$$

where β_w is coefficient of gravimetric expansion, W is nut weight in kg and M is moisture content in % (db). Assuming coefficient β_w as constant in specified boundary conditions throughout the rehydration process, Equation (6) can be stated as

$$\beta_w \int_{M_o}^{M} \partial M = \int_{W_o}^{W} \frac{\partial w}{w} \quad (7)$$

where M_o is the initial moisture content in % (db) and W_o is the corresponding nut weight in kg. Integrating Equation (7) and rearranging the resulting relationship yields:

$$\beta_w (M - M_O) = \text{In}\left(\frac{W}{W_O}\right) \quad (8)$$

Taking M_o = 0 and rearranging terms, Equation (8) becomes

$$LnW = LnW_o + \beta_w M \quad (9)$$

A plot of LnW against M yielded a straight line with slope as β_w having a value of 0.006 and intercept on the y-axis as LnW_o from which W_o was obtained as 6.111 kg.

Equation (9) yields

$$W = W_o e^{\beta w M} \quad (10)$$

And the relationship existing between the one thousand nut weight of *M. flagellipes* with moisture content can be expressed as follows:

$$W = 6.111e^{0.006M} \ (R^2 = 0.86) \quad (11)$$

where W is 1000 nut weight in kg, and M is moisture content in % (d.b).

Particle density

The effect of moisture on particle density is presented in **Fig. 4**. This shows that the particle density *M. flagellipes* nut increased from 1107 to 1147 kg m^{-3} as the moisture content increases from 3.38-10.70% (d.b). The relationship existing between particle density and moisture content was found to be parabolic and can be represented by the following equation:

$$\rho_t = -7.461M^2 + 133.30M + 568.10 \ (R^2 = 0.98) \quad (12)$$

where ρ_t is particle density in kg m^{-3} and M is moisture content in % (d.b). Results of similar studies showed that particle density increased from 922.48 to 992.74 kg m^{-3} in the moisture range of 4.72 – 26.35% (d.b) and 964 to 1052.01 kg m^{-3} in the moisture range of 4.71 – 24.18% (d.b) for the oblong and spheroidal nuts of *Balanites aegyptiaca* (Aviara *et al.* 2005a). For sheanut (Aviara *et al.* 2005b), guna fruits (Aviara *et al.* 2007), cumin seed (Singh and Goswani 1996), beniseed (Tunde-Akintunde and Akintunde 2007) and cucurbit seed (Milani *et al.* 2007) particle density increased from 643 to 789 kg m^{-3}, 637 to 803 kg m^{-3}, 1047 to 1134 kg m^{-3}, 966 to 1220 kg m^{-3} and 825 to 890 kg m^{-3} in the moisture ranges of 6 – 27.90% (d.b), 85.07 – 92.45% (w.b), 7 – 22% (d.b), 3.50 – 25% (d.b) and 5.18 – 42.76% (w.b) respectively. Investigations by Dutta *et al.* (1988), Aviara *et al.* (1999), Tabatabaeefar (2003) and Simonyan *et al.* (2007) however, showed that the particle density of gram, guna seed, wheat and sorghum grain decreased with increase moisture content from 1311 to 1257 kg m^{-3}, 870 to 680 kg m^{-3}, 1240 to 847.20 kg m^{-3} and 1630 to 290 kg m^{-3} in the moisture ranges of 9.64 – 31% (d.b), 4.70 – 39.30% (d.b), 0 – 22% (d.b) and 8.89 – 16.50% (w.b), respectively.

Bulk density

The effect of moisture on the bulk density of *M. flagellipes* nut is shown in **Fig. 5**. The bulk density of the nut was found to decrease from 568 to 488.80 kg m^{-3} as the moisture content increased from 3.38-10.70% (d.b). This result could be attributed to increase in size with moisture content which gives rise to decrease in the quantity and therefore weight of nuts occupying the same bulk volume (Aviara *et al.* 1999). The relationship exiting between moisture content and bulk density was a parabola and could be represented by the equation:

$$\rho_b = 2.627M^2 - 47.39M + 697.00 \ (R^2 = 0.98) \quad (13)$$

where ρ_b is bulk density in kgm^{-3} and M is moisture content in % (d.b).

A similar trend of bulk density decreasing with increase in moisture content was reported for lentil seed (1190 to 935 kg m^{-3} in the 6.50 – 32.60% d.b moisture range) (Carman 1996), *Balanites aegyptiaca* nuts (546.90 to 521.60 kg m^{-3}, 4.71 – 26.35% d.b) (Aviara *et al.* 2005a), wheat (740 to 538.80 kg m^{-3}, 0 – 22% d.b) (Tabatabaeefar 2003), beniseed (659 to 557 kg m^{-3}, 3.50 – 25% d.b) (Tunde-Akintunde and Akintunde 2007), grass pea seed (882.58 to 774.00 kg m^{-3}, 8.50 – 30.66% w.b) (Zewdu and Solomon 2008) and cucurbit seed (550.30 to 308.30 kg m^{-3}, 5.18 – 42.76% w.b) (Milani *et al.* 2007). However, for buckwheat cultivars (Parde *et al.* 2003) and sheanut (Aviara *et al.* 2005b), the bulk density increased from 603.90 to 612.90

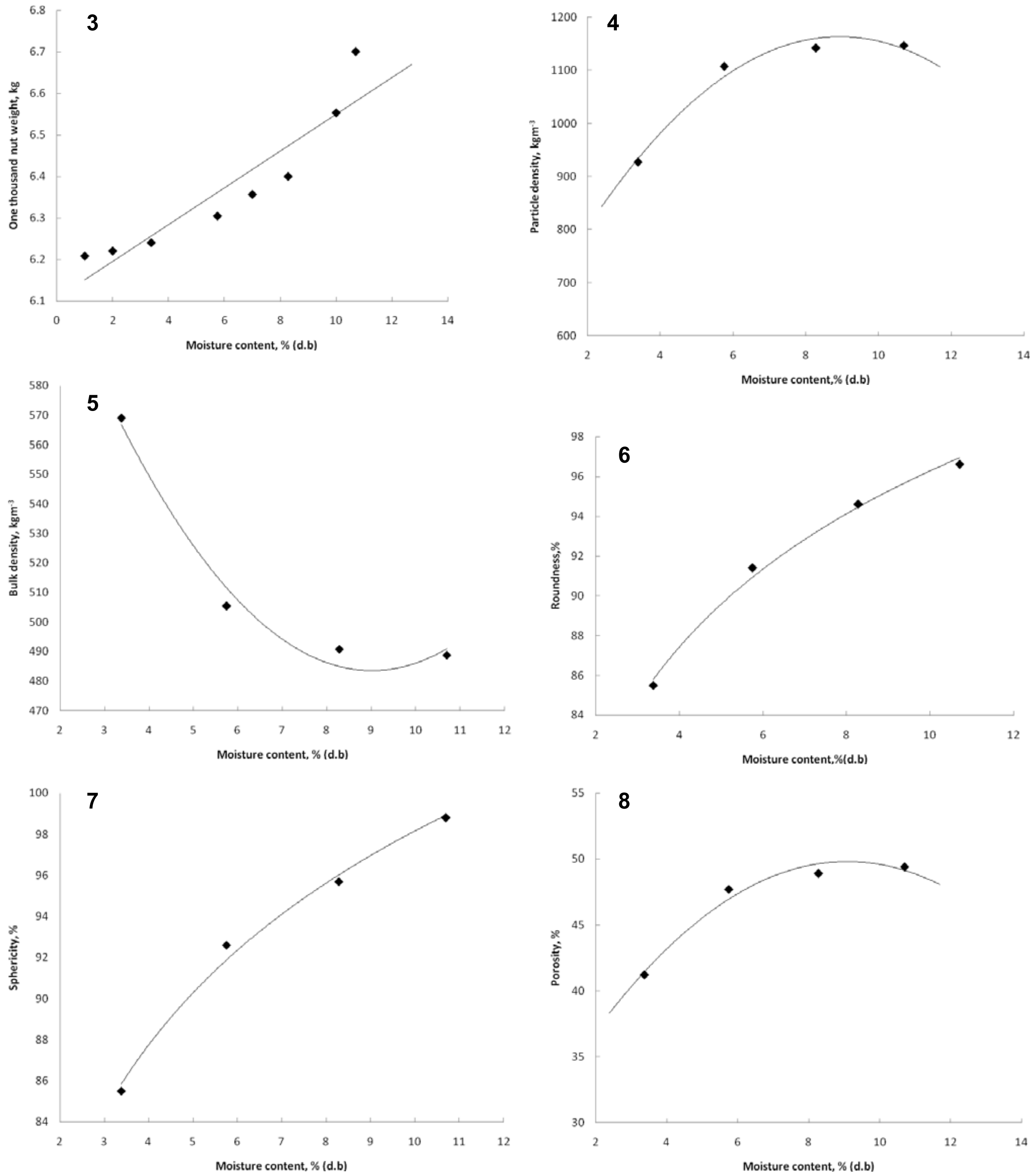


Fig. 3 Effect of moisture content on 1000-nut weight of *Mucuna flagellipes.* n = 20000. **Fig. 4** Effect of moisture content on the particle density of *M. flagellipes* nut. n = 2400. **Fig. 5** Effect of moisture content on the bulk density of *M. flagellipes* nut. n = 2400. **Fig. 6** Effect of moisture content on the roundness of *M. flagellipes* nut. n = 600. **Fig. 7** Effect of moisture content on the sphericity of *M. flagellipes* nut. n = 600. **Fig. 8** Effect of moisture content on the porosity of *M. flagellipes* nut. n = 2400.

kg m^{-3} and 291.30 to 356.20 kg m^{-3} as the moisture content increased from 14.80 to 15.80% and 6.00 to 27.90% (d.b), respectively.

Roundness and sphericity

The effect of moisture on roundness and sphericity on the nut of *M. flagellipes* is presented in **Figs. 6** and **7**, respectively. The value for roundness and sphericity increased linearly from 85.5 to 96.6% and from 85.5 to 98.8% with increase in the moisture content of the nut. The high values obtained for roundness and sphericity of *M. flagellipes* nut coupled with its axial dimensions indicate that the nut could be described as an oval disc in shape. The relationships existing between roundness and sphericity and moisture content were found to be logarithmic and to be represented by following the equations:

$$R = 9.671 \text{Ln}M + 74.01 \quad (R^2 = 0.99) \qquad (14)$$

$$S = 11.34 \text{Ln}M + 72.01 \quad (R^2 = 0.99) \qquad (15)$$

where R is roundness in %, S is sphericity in % and M is moisture content in % (d.b).

The roundness and sphericity of the nut were higher than those of cocoa pod that respectively ranged between

50.30 – 53.10% and 49.3 – 52.4% (Maduako and Faborode 1990). The sphericity of the nut was higher than that of nutmeg (74%) (Burubai et al. 2007) and beniseed (56 – 59% in the moisture range of 3.50 – 25% d.b) (Tunde-Akintunde *et al.* 2007) and within the same range as that of Iranian apricot fruit (87.50 – 97.30%) (Jannatizadeh *et al.* 2008), conophor nut (91%) (Asoegwu 1995), and bergamot (89%) (Rafiee *et al.* 2007).

Porosity

The value of porosity calculated from experimental data on particle density and bulk density was found to increase from 41.2 to 49.4% as the moisture content increased from 3.38 to 10.70% (d.b). The effect of moisture content on the nut porosity is presented in **Fig. 8**. The relationship existing between porosity and moisture was found to be parabolic and can be represented by the equation:

$$P = - 0.255M^2 + 4.653M + 28.65 \quad (R^2 = 0.97) \qquad (16)$$

where P is porosity in % and M is moisture content in % (d.b).

The porosity of *M. flagellipes* was higher than that of grass pea seeds (34.24 – 37.10% in the moisture range of 8.50 – 30.66 % w.b) (Zewdu and Solomon 2008) and jack bean seed (32.6%) (Eke *et al.* 2007), and within the same range as that of *Balanites Aegyptiaca* nuts (41.86 – 49.37%, 4.71 – 26.35% d.b) (Aviara *et al.* 2005a), almond nut (35.32 – 53.21%, 2.77 – 24.97% d.b) (Aydin 2003), date palm (46.56%) (Keramat Jahromi *et al.* 2007), nutmeg 41.10% at the moisture content of 4.93% d.b) (Burubai *et al.* 2007) and water melon varieties (39.14 – 51.68%) (Razavi *et al.* 2006), but lower than that of cucurbit seed (52.50 – 64.10% at moisture contents above 30% w.b) (Milani *et al.* 2007) and sheanut (54.70 – 56.90%, 6.00 – 22.70% w.b) (Aviara *et al.* 2005b). The above studies all show that porosity increased with increase in moisture. However, in beniseed (46 – 22.30%, 3.50 – 25% d.b) (Tunde-Akintunde *et al.* 2007), porosity decreased with increase in moisture content.

Static coefficient of friction

The static coefficient of friction of *M.flagellipes* nut increased linearly with moisture content and varied with structural surface in the moisture range of 3.38-10.7% (d.b.) (**Fig. 9**). This may be due to the development of higher shear stress at the nut structural surface contact as the moisture content increased, which must have made it increasingly difficult for the nut to slide on the surface, so that the static coefficient of friction increased. Its value was highest on fibre glass (0.234-0.439), followed by plywood with wood grains perpendicular to the direction of movement (0.164-0.418), galvanized steel sheet (0.272-0.408), Hessian bag (0.266-0.401) and least on plywood with wood grains parallel to the direction of movement (0.178-0.318). The relationship existing between the static coefficient of friction of *M. flagellipes* nut and moisture content can be expressed for different structural surfaces using the following equations:

$$f_{pp} = 0.0192M + 0.1282 \quad (R^2 = 0.93) \qquad (17)$$

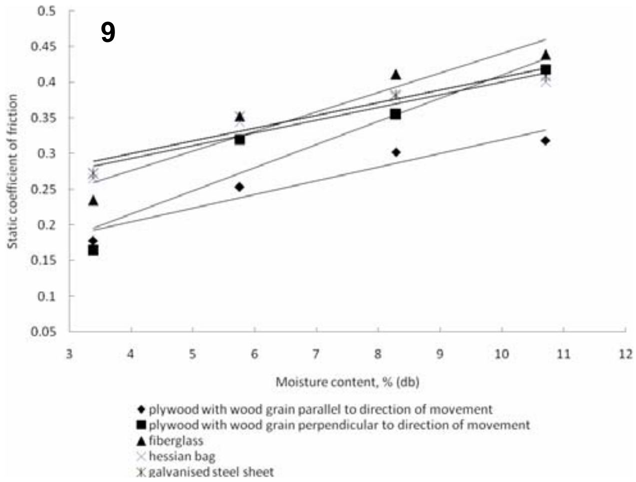
$$f_{pi} = 0.0324M + 0.0863 \quad (R^2 = 0.90) \qquad (18)$$

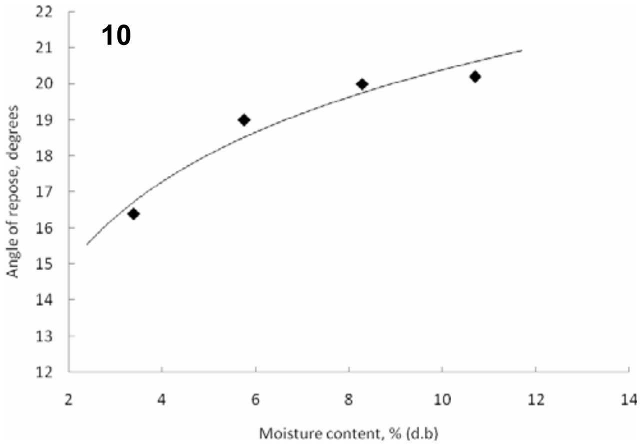
$$f_{fg} = 0.0274M + 0.1668 \quad (R^2 = 0.91) \qquad (19)$$

$$f_{hb} = 0.0179M + 0.2214 \quad (R^2 = 0.91) \qquad (20)$$

$$f_{gs} = 0.0179M + 0.2282 \quad (R^2 = 0.91) \qquad (21)$$

where f_{pp}, f_{pi}, f_{fg}, f_{hb} and f_{gs} are the static coefficients of friction of *M. flagellipes* nut on plywood with wood grains parallel to the direction of movement, plywood with wood grains perpendicular to the direction of movement, fibre glass, Hessian bag material and galvanized steel sheet, respectively.





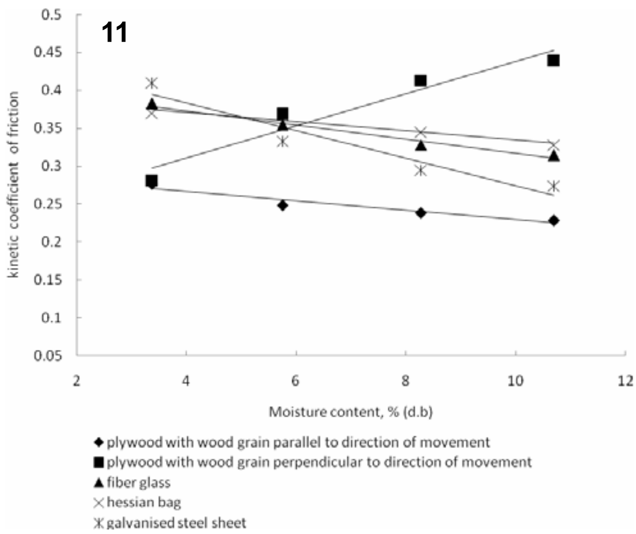
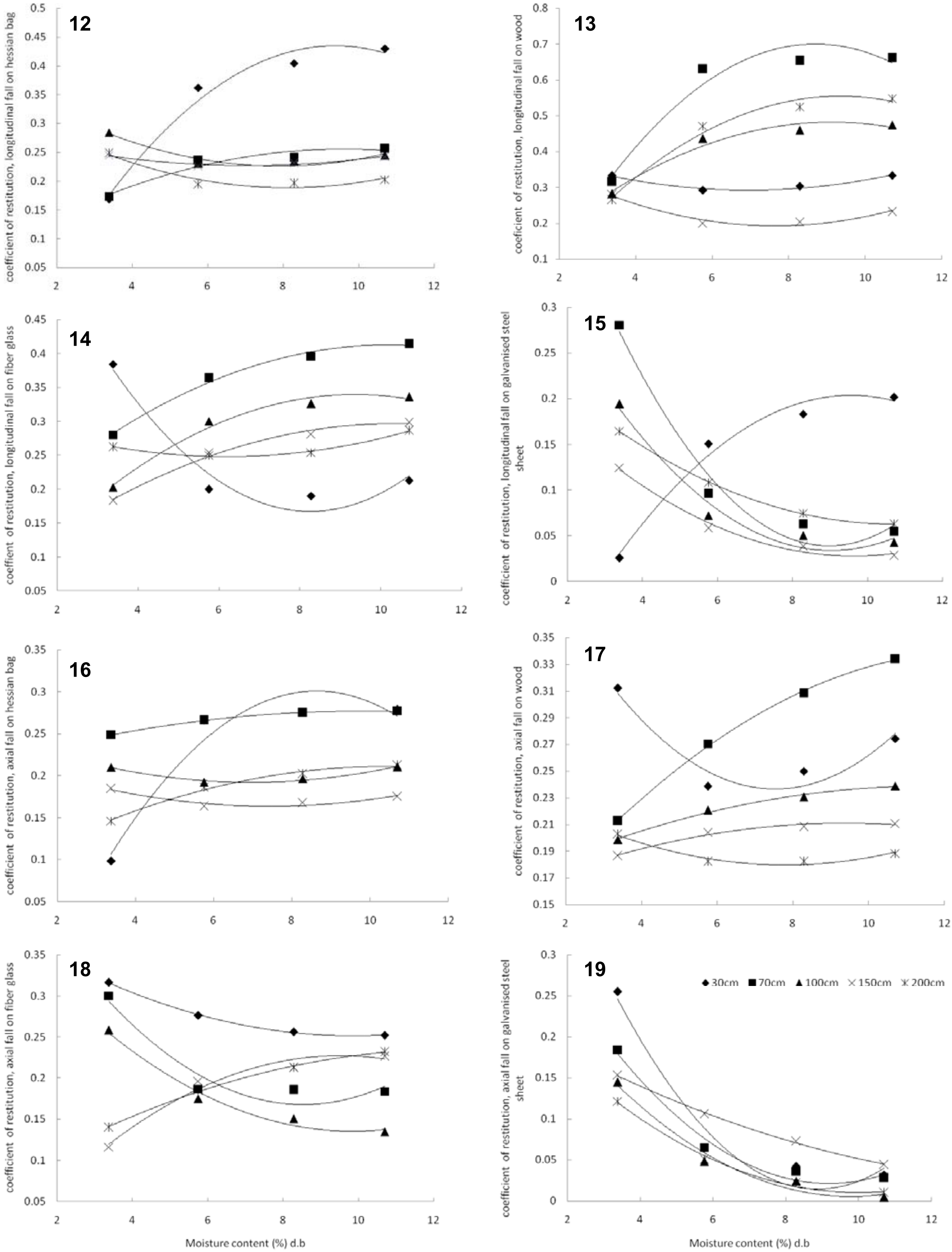


Fig. 9 Variation of static coefficient of friction of *Mucuna flagellipes* nut with moisture content. n = 8000. **Fig. 10** Variation of angle of repose of *M. flagellipes* nut with moisture content. n = 2400. **Fig. 11** Variation of kinetic coefficient of friction of *M. flagellipes* nut with moisture content. n = 8000.

A linear increase in static coefficient of friction with moisture content was also reported by Singh and Goswani (1996); Milani *et al.* (2007) and Kheiralipour *et al.* (2008) for cumin seed (0.37 – 0.70), cucurbit seeds (0.31 – 0.99), and wheat (0.33 – 0.55), respectively. This property is very useful in the design of silos, bins and other storage containers for the nut.



Variation of the coefficient of restitution of *Mucuna flagellipes* nut on longitudinal fall with moisture content at various drop heights on hessian bag (**Fig. 12**), plywood (**Fig. 13**), fiber glass (**Fig. 14**), or galvanized steel sheet (**Fig. 15**). Variation of the coefficient of restitution of *M. flagellipes* nut on axial fall with moisture content at various drop heights on hessian bag (**Fig. 16**), plywood (**Fig. 17**), fiber glass (**Fig. 18**), or galvanized steel sheet (**Fig. 19**). For all treatments, n = 1000.

Angle of repose

The variation of the angle of repose for *M. flagellipes* nut with moisture content is shown in **Fig. 10**. From this figure, it can be seen that the angle of repose increased logarithmically with moisture content from 16.4 to 20.2° in the moisture range of 3.38-10.7% (d.b.). The relationship existing between the angle of repose of the nut and moisture content can be expressed using the following equation:

$$\theta = 3.3853\text{Ln}M + 12.594\ (R^2 = 0.94) \quad (22)$$

where θ is angle of repose in degrees and M is moisture content in % (d.b).

A logarithmic relationship between the angle of repose and moisture content has been reported for Okra seed (27.60 – 39.74°, 8.16 – 87.57% d.b) (Sahoo and Srivastava 2002) and sheanut (24.70 – 25.10°, 6.00 – 27.90% d.b) (Aviara *et al.* 2005b). However, a linear relationship was reported for cumin seed (36.50 – 51.30°, 7.00 – 22.00% d.b) (Singh and Goswani 1996) and coriander seed (24.90 – 30.70°, 7.10 – 18.94% d.b) (Yalcin and Ersan 2007).

Kinetic coefficient of friction

The variation of the kinetic coefficient of friction of *M. flagellipes* nut with moisture content on five surfaces is shown in **Fig. 11**. The kinetic coefficient of friction increased linearly with moisture content on plywood with wood grains perpendicular to the direction of movement and on Hessian bag, fibre glass, galvanized steel sheet and plywood with wood grains parallel to the direction of movement. Its value was highest against plywood with wood grains perpendicular to the direction of movement (0.280 – 0.438) and lowest on plywood with wood grains parallel to the direction of movement (0.229 – 0.276).

The relationship existing between the kinetic coefficient of friction of *M. flagellipes* nut and moisture content can be expressed for different structural surfaces using the following equations:

$$\mu_{pp} = -0.0063M + 0.292\ (R^2 = 0.92) \quad (23)$$

$$\mu_{pi} = 0.0211M + 0.226\ (R^2 = 0.93) \quad (24)$$

$$\mu_{fg} = -0.0094M + 0.411\ (R^2 = 0.98) \quad (25)$$

$$\mu_{hb} = -0.0061M + 0.396\ (R^2 = 0.93) \quad (26)$$

$$\mu_{gs} = -0.0182M + 0.456\ (R^2 = 0.92) \quad (27)$$

where μ_{pp}, μ_{pi}, μ_{fg}, μ_{hb} and μ_{gs} are the kinetic coefficients of friction of *M. flagellipes* nut on plywood with wood grains parallel to the direction of movement, plywood with wood grains perpendicular to the direction of movement, fibre glass, Hessian bag material and galvanized steel sheet, respectively.

Plywood with wood grains perpendicular to the direction of movement also offered the maximum friction of 0.82 for sheanut kernel (Aviara *et al.* 2000). Carman (1996), Altuntas *et al.* (2005) and Sessiz *et al.* (2007) reported a linear increase in kinetic coefficient of friction of 0.28 to 0.48 for lentil seed, 0.343 to 0.475 for fenugreek seeds, and decrease of 0.630 to 0.408 for caper fruit on different structural surfaces as the moisture content increased from7.60 to 21.00% (w.b), 8.90 to 20.10% (d.b) and 71.85 to 80.40% (w.b), respectively.

Coefficient of restitution

The variation of the coefficient of restitution of *M. flagellipes* nut with moisture content on four surfaces namely Hessian bag, plywood, fibre glass and from different drop heights are shown in **Figs. 12-15** for longitudinal fall and in **Figs. 16-19** for lateral fall.

Coefficient of restitution decreased with increase in drop height on both longitudinal and lateral fall. It decreased with increase in moisture content and exhibited a second order polynomial relationship with moisture content on all the surfaces and the two orientations of fall. The relationship between coefficient of restitution and moisture content at the various heights and surfaces on longitudinal and lateral falls can be best expressed using polynomial equations of the form:

$$Y = xM^2 + yM + z \quad (28)$$

where Y is coefficient of restitution, x and y are coefficients of term, z is a constant and M is moisture content in % (d.b). The coefficients of term and constant in Eqn (25) are presented for longitudinal fall on different surfaces in **Table 3** and for axial fall in **Table 4**.

On longitudinal fall, the highest coefficient of restitution was observed on plywood (0.198 – 0.661), followed by fibre glass (0.183 – 0.414), Hessian bag (0.168 – 0.412) and the least was on galvanized steel sheet (0.026 – 0.281). On lateral fall, the highest coefficient of restitution was observed on plywood (0.182 – 0.334), followed by fibre glass (0.116 – 0.316), Hessian bag (0.098 – 0.279) and the least was on galvanized steel sheet (0.0045 – 0.255). The coefficient of restitution of *M. flagellipes* was lower than that of soya bean (0.62 – 0.65) (LoCurto *et al.* 1997), maize (0.374 – 0.707) and red gram (0.424 – 0.817) (Jayan and Kumar 2004), and within the same range as that of cotton seed (0.305 – 0.501) (Jayan and Kumar 2004), chick pea (0.20 – 0.57) and lentil seed (0.33 – 0.48) (Ozturk *et al.* 2010).

Table 3 Values of the constants in Eqn (25) expressing the coefficient of restitution of *Mucuna flagellipes* nut as a function of moisture content at different drop heights under longitudinal fall, on different structural surfaces.

Structural surface	Drop height (cm)	Constants x	y	z	R^2
Hessian bag	30	-0.008	0.143	-0.220	0.98
	70	-0.002	0.039	0.068	0.93
	100	0.003	-0.430	0.400	0.92
	150	0.001	-0.018	0.300	0.95
	200	0.003	-0.042	0.357	0.93
Plywood	30	0.003	-0.042	0.438	0.95
	70	-0.013	0.227	0.287	0.95
	100	-0.006	0.107	0.005	0.96
	150	0.005	-0.070	0.461	0.94
	200	-0.008	0.148	-0.139	0.98
Fibre glass	30	0.006	-0.145	0.770	0.96
	70	-0.003	0.057	0.120	0.99
	100	-0.009	0.070	0.012	0.98
	150	-0.002	0.048	0.050	0.99
	200	0.002	-0.023	0.320	0.99
Galvanized steel sheet	30	-0.005	0.087	-0.212	0.98
	70	0.008	-0.135	0.664	0.97
	100	0.005	-0.088	0.432	0.97
	150	0.002	-0.047	0.253	0.99
	200	0.002	-0.041	0.280	1.00

Table 4 Values of the constants in Eqn (25) expressing the coefficient of restitution of *Mucuna flagellipes* nut as a function of moisture content at different drop heights under lateral fall, on different structural surfaces.

Structural surface	Drop height (cm)	Constants			R^2
		x	y	z	
Hessian bag	30	-0.007	0.121	-0.224	0.95
	70	-0.001	0.014	0.210	1.00
	100	0.001	-0.020	0.260	0.97
	150	0.001	-0.020	0.230	0.90
	200	-0.001	0.027	0.071	0.99
Plywood	30	0.004	-0.063	0.472	0.91
	70	-0.001	0.036	0.110	1.00
	100	-0.001	0.014	0.160	0.99
	150	-0.001	0.013	0.152	0.98
	200	-0.001	-0.018	0.249	0.96
Fibre glass	30	0.002	-0.030	0.401	1.00
	70	0.005	-0.081	0.514	0.93
	100	0.003	-0.057	0.414	0.98
	150	-0.003	0.054	-0.032	0.97
	200	-0.001	0.028	0.058	1.00
Galvanized steel sheet	30	0.001	-0.136	-0.620	0.96
	70	0.005	-0.086	0.420	0.98
	100	0.003	-0.065	0.322	0.98
	150	0.001	-0.026	0.232	1.00
	200	0.003	-0.050	0.260	0.99

CONCLUSIONS

The investigation of various physical properties of *M. flagellipes* nut revealed the following:

(1) The major, intermediate and minor axial dimensions of the nut increased with increase in moisture content. At the moisture content of 3.38% (d.b), the major, intermediate and minor axial dimensions of the nut averaged 2.73, 2.71 and 1.87 cm, respectively. The arithmetic and geometric mean diameters increased, while the equivalent sphere effective diameter decreased with increase in moisture content.

(2) One thousand nut weight of the nut increased from 6.24 to 6.77 kg as moisture content increased from 3.38-10.70% (d.b).

(3) Particle density and porosity of the nut increased parabolically with increase in moisture content from 1107 to 1147 kg m^{-3} and 41.2 to 49.4%, respectively, while the bulk density decreased from 568 to 488.8 kg m^{-3} in the same moisture content range.

(4) Roundness and sphericity increased logarithmically with moisture content from 85.5 to 96.6% and 85.5 to 98.8%, respectively.

(5) Static coefficient of friction increased linearly with increase in moisture content and varied according to structural surface. The highest value was obtained on fibre glass, while the lowest value was on plywood with wood grains parallel. Kinetic coefficient of friction decreased linearly with increase in moisture content on Hessian bag, fibre glass, galvanized steel sheet and plywood with wood grains parallel to the direction of movement, and increased linearly with moisture content on plywood with wood grains perpendicular to the direction of movement.

(6) Angle of repose increased logarithmically from 16.4 to 20.2° as the moisture content of the nut increased from 3.38 to 10.70% (d.b).

(7) Coefficient of restitution decreased with increase in moisture content and drop height on all the structural surfaces employed. It was maximum on plywood and minimum on galvanized steel sheet. On lateral fall, it ranged from 0.0045-0.334 and 0.026-0.661 on longitudinal fall.

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