Moisture dependent physical properties of Detarium microcarpum seed

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Abstract: Physical properties of Detarium microcarpum seed were investigated as a function of moisture content with a view to exploring the possibility of developing its bulk handling and processing equipment. In the moisture range of 8.2%–28.5% (d.b.), the major, intermediate and the minor axes increased from 2.95–3.21 cm, 1.85–2.61 cm, and 0.40–1.21 cm respectively. The arithmetic mean, geometric mean and equivalent sphere effective diameters determined at the same moisture level were significantly different from each other with the arithmetic mean diameter being of the highest value. The seed can be described as an irregularly shaped spherical disc. In the above moisture range, the surface area, one thousand seed weight, particle density and porosity increased linearly with moisture content from 354.62-433.19 cm^2, 3.184-3.737kg, 1060-1316 kg/m^3 and 30% to 53.1% respectively, while bulk density decreased with increase in moisture content from 647.6-617.2 kg/m^3. Angle of repose increased linearly with moisture content from 13.9^o-28.4^o. Static and kinetic coefficients of friction increased linearly with moisture content and varied with structural surface. Highest value of static coefficient of friction at each moisture level in the above range was on galvanized steel sheet, while the lowest value was on fiber glass. For the kinetic coefficient of friction, the highest values were on Hessian bag material, while the lowest values were on fiber glass.

Keywords: detarium microcarpum, angle of repose, particle and bulk densities, static and kinetic coefficients of friction

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1 Introduction

Detarium microcarpum also known as sweet detar is an African food crop tree belonging to the fabaceaefamily. The fruit is fleshy and quite edible (Keayet al., 1964). In South Eastern Nigeria, Detarium microcapum is called “ofor” and there, its seed flour is popularly used as thickening agent in soup. The very high carbohydrate content and its ability to form viscous gum at low concentration in sauce shows that it belongs to the class of food ingredients known as hydrocolloids (Ihekoronye and Ngoddy, 1985). The fruit is rich in vitamin C (3.2mg), with 4.8g protein, and 64.5gof sugar per 100g and can be eaten raw or cooked. It was found to have the highest total phenolic, flavonoid and antioxidant value among fourteen wild edible fruit in Burkina Faso (Abdalbasit et al., 2009). The seed (Figure 1) yield 7.5% oil with the predominant fatty acid being linoleic acid. The hulled seed flour contains per 100g, 3.5 to 6.5g water, 3g crude fibre, 13 to 15g crude fat, 13.5 to 27g of crude protein, 39g carbohydrate.

Figure 1 Detarium microcarpum seeds

Detarium microcarpum is usually harvested during the dry season. A long pole is normally used to knock down the fruits from the tree and the fruits can also fall

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to the ground on their own and are picked manually. In order to obtain the seed, a stone or cutlass is used to break the fruit and a sharp object is used to remove the seed. Usually, one seed is contained in a fruit. The coat or hull of Detarium microcarpum seed is brown in colour and hard. The edible kernel inside the seed is milky white, and both the seed and kernel is disc shaped. The seed is normally processed further to release the kernel.

The present methods of processing the seed involve such unit operations as boiling, roasting or frying of sorted seeds for a period of time. After these operations, the seeds are dehulled using rubbing action which involves moving a cylindrically shaped stone over a thin layer of the seeds with slight pressure. The kernels obtained are washed 3 to 4 times and soaked in water overnight. The water is then drained off and the kernels are sundried and milled. The seed kernel flour is a traditional emulsifying and thickening agent used to prepare cakes, bread, couscous, baby food and local beer.

The above processes as carried out not only lead to quantitative and qualitative losses of the finished product but are also tasky and time consuming. There is the need to develop more efficient methods and systems for processing and storing Detarium microcarpum seeds and their products. The development of such methods and equipment requires knowledge of the physical properties of the seed. Mieszkalski (1997) and Aviara et al. (1999) reported that the moisture content of agricultural materials influence the adjustment, performance efficiency and energy consumption of processing machines. Therefore, information on physical properties determined at different moisture contents is important in the design and development of machines and facilities for processing and storing seeds and grains.

Several researchers (Duttaet al., 1988, Singh and Goswani 1996, Aviara et al., 1999, Ogunjimi et al., 2002, Tabatabaeefar 2003, Aviara et al., 2005a, 2005b, Burubai et al., 2007, Simonyan et al., 2007, Tunde-Akintunde et al., 2007, Zewdu and Solomon 2008, Bamgboye and Adejumo 2009, Shafiee et al., 2009, Simonyan et al., 2009, Aviara et al., 2010, Shafiee et al., 2010, Gholami et al., 2012, Gebreselassie 2012, Satimehin and Philip 2012, Aviara et al., 2013, Aviara et al., 2014a, 2014b) studied the physical properties of different agricultural products for the above purpose. The physical properties investigated at different moisture contents include axial dimensions and size distribution, seed surface area, one thousand seed weight, roundness and sphericity, aspect ratio, particle and bulk densities, angle of repose, static and kinetic coefficients of friction on different structural surfaces and coefficient of restitution. No study however appears to have been carried out on the physical properties of Detarium microcarpum seed and the dependence of their values on seed moisture content. This study was therefore aimed at determining the physical properties of Detarium microcarpum seed and investigating their variation with seed moisture content.

2 Materials and methods

The bulk quantity of Detarium microcarpum seeds used for this study was obtained from eke-awgbu market in Awgbu town of Orumba North Local Government Area, Anambra State, Nigeria. The seeds were carefully cleaned of dirt, and foreign materials, broken and immature seeds were removed. The seeds were preserved by storing them in air tight polyethylene bags.

The moisture content of Detarium microcarpum seeds was determined using the method of Aviara et al. (2010). Samples of seed were dried in an oven at 105^{o}C to constant weight with weight loss monitored on hourly basis to give an idea of the time at which the weight began to remain constant. The samples were found to maintain constant weight after oven drying at the above temperature for 6 h. To investigate the effect of moisture content on the physical properties of the seed, five moisture levels were used. Seed samples of desired moisture levels higher than the initial moisture content, were prepared by conditioning the samples using the method of Ezeike (1986) as employed by Aviara et al. (2010) and Aviara et al. (2013). This involved the soaking of different bulk samples in clean water for a period of 30 min to 2 h followed by spreading out in thin layer to dry under natural air for 8 h. For the moisture level below the initial moisture content, triplicate samples of the seed were sun-dried at ambient temperature for 3 h. The samples were then sealed in marked polyethylene bags and stored in that condition for a further 24 h. This enabled stable and uniform moisture content of the samples to be achieved.

To determine the seed size, 100 seeds were randomly selected at each moisture level following a method similar to that employed by Dutta et al. (1988). For each seed, the three principal axial dimensions, namely the major, intermediate and minor axes were measured using a vernier caliper reading to 0.05mm. The arithmetic mean, geometric mean and equivalent sphere effective diameters were then calculated. Since size of seed was considered to be an important parameter in processing (Teotia and Ramakrishna 1989, Joshi et al., 1993, Suthar and Das 1996), the bulk sample of seed at the market storage (initial) moisture content was classified into three categories, namely large (a > 3.07 cm), medium (2.53 cm⩽ a⩽ 3.07 cm) and small (a < 2.53 cm) based on the major axis. Seed surface area was determined using the coating method described by Mohsenin (1986) with modifications. Thirty Detarium microcarpum seeds at specified moisture content were randomly selected. Each seed was carefully wrapped round with foil paper to cover its outline. Excess foil paper was cut off and the covering on the seed was carefully unwrapped and spread out on a sheet of graph paper. The outline of the foil paper on the graph sheet was traced out and the surface area was determined by counting the squares. One thousand seed weight at each moisture level was obtained using an electronic balance weighing to 0.001g. The particle density of Detarium microcarpum seed was determined using the water displacement method. Thirty seeds, each coated with very thin layer of epoxy resin to prevent the absorption of water during the experiment, were used.

Bulk density was determined using the AOAC (1980) method. This involved the filling of a 500ml cylinder with seeds from a height of 15cm and weighing the content. Porosity was calculated from particle and bulk densities using the Equation (1) given Mohsenin (1986).

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

whereλ = porosity (%), ρ_b = bulk density (kg/m^3),ρ_t = particle density (kg/m^3).

Roundness and sphericity were determined by tracing shadowgraphs of the seed at its natural position of rest on a graph sheet. This was followed by the drawing of inscribing and circumscribing circles on the shadowgraph. The projected area was determined using the method of counting the squares, the diameter and area of the smallest circumscribing circle as well as the diameter of the largest inscribing circle were measured. Thirty shadowgraphs were used at each moisture level. Seed roundness and sphericitywere calculated using the following Equation (2) and Equation (3):

$$R = \frac{A_p}{A_c} \times 100 \qquad (2)$$

where$R$ = Roundness (%), A_p = Projected area (cm^2), A_c = Area of smallest circumscribing circle (cm^2)

$$\phi = \frac{D_i}{D_c} \times 100 \qquad (3)$$

whereφ =Sphericity (%), D_i = diameter of the largest inscribing circle (cm), D_c = diameter of the smallest circumscribing circle (cm).

In determining the angle of repose, the cylindrical pipe method was used. This involved the filling of a topless and bottomless cylinder with seeds. The cylinder was slowly raised up from the seeds on a flat surface until it left the seeds forming a cone and the base diameter and height of the cone was used to calculate the angle of repose.

The static coefficient of friction was evaluated on five structural surfaces namely: hessian bag material, fiber glass, galvanized steel sheet, plywood with wood grain parallel to direction of movement and plywood with wood grain perpendicular to direction of movement. The inclined plane method as described by Dutta et al. (1988) and Suthar and Das (1996) was used. This involved the placing of an open-ended box (150 × 150 × 150mm) on an adjustable tilting surface which was formed with a structural surface. The box was filled with seeds and the structural surface with the box and its content on top was gradually raised using a screw device until the box 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 seeds at specified moisture content.

For the kinetic coefficient of friction, the open-ended box used in determining the static coefficient of friction was placed on a horizontal surface. Four different surfaces were used at each moisture level of the seed namely: hessian bag material, fiber glass material, plywood with wood grain parallel to the direction of movement and plywood with wood grain perpendicular to the direction of movement. The box was filled with seeds and connected by means of a string, parallel to the surface and passing 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 seed on a given structural surface was determined using the following Equation (4):

$$\mu = \frac{W_p + W_m}{W_b + W_s} \qquad (4)$$

where W_p = mass of pan (g), W_m = total weight placed in pan to move the box and content (g), W_b = mass of box (g), and W_s = mass of sample (g).

All the experiments were repeated five times and the frequency distributions of axial dimensions were determined and plotted. Data obtained on surface area, one thousand seed weight, particle and bulk densities and angle of repose were subjected to one way Analysis of Variance (ANOVA) and Least Square Differentials (LSD) in completely randomized block design to investigate the level of significance of the variation of these properties with moisture content The variation of seed size with moisture content and average diameter, and variation of static and kinetic coefficients of friction with moisture content and structural surface respectively, was analyzed using two-way ANOVA and LSD in split plot design. The relationships existing between the physical properties of Detarium microcarpum seed and moisture content were expressed using regression equations. The statistical package used was SPSS version 20 for Windows.

3 Results and discussion

3.1 Seed moisture content

The initial moisture of Detarium microcarpum seed was found to be 14.1% (d.b.). The four other moisture levels obtained after conditioning the seed were 8.2%, 21.9%, 25.8% and 28.5% (d.b.) respectively. Investigations were carried out at the above moisture levels to determine the effect of moisture content on the physical and frictional properties of the seed.

3.2 Seed size and size distribution

he size of Detarium microcarpum seed measured in terms of axial dimensions and average diameters at different moisture contentsare presented in Table1. Table 1shows that the three axial dimensions, the arithmetic mean and geometric mean diameters increased with moisture content in the moisture range of 8.2%-28.5% (d.b.) while the equivalent sphere effective diameter decreased. The ANOVA of seed size with moisture content and proxies of size characteristic showed that moisture content significantly affected the seed size (df = 4, F-ratio = 22.725 and p-value = 0.000), and that the size characteristics of Detarium microcarpum seed differed significantly, at 1% level of significance (df = 5, F-ratio = 214.491 and p-value = 0.000). The major, intermediate and minor axes of the seed increased significantly from 2.95–3.21cm, 1.85–2.61cm and 0.4–1.21cm respectively, in the above moisture range. The arithmetic mean and the geometric mean diameters of the seed increased as the moisture content increased, while the equivalent sphere effective diameter decreased with increase in moisture content. These proxies of size characteristic were significantly different with the arithmetic diameter being of the highest values. The size distribution of Detarium microcarpum seed at the market storage moisture content of 14.1% (d.b.) is presented in Table 2, while the frequency distribution curves of the major, intermediate and minor axial dimensions of the seed are presented in Figure 2. Table 2 shows that at the above moisture level, average major, intermediate and minor axial dimension was 3.03, 2.17 and 0.71cm respectively. About 48% by number and 51.6% by mass of the seed were large (a>3.07cm), 48% by number and 45% of the seed were medium (2.53cm≤ a≤3.07cm) and 4% by number and 3.4% by mass were small (a< 2.53cm). Figure 2 shows that the intermediate and minor axes of the seed have single normal distribution while the major axis has a bimodal normal distribution. This is in agreement with the finding of Lawal et al. (2014).

Table 1Axial dimension of Detarium microcarpum seed at different moisture contents

Moisture content % (d.b)	Major diameter (cm)	Intermediate diameter (cm)	Minor diameter (cm)	Arithmetic mean diameter (cm)	Geometric mean diameter (cm)	Equiv. sphere effective diameter (cm)
8.2	2.95 (0.14)*	1.85 (0.13)	0.40 (0.11)	1.73	1.30	1.79
14.1	3.03 (0.27)	2.1 (0.203)	0.65 (0.11)	1.97	1.67	1.78
21.9	3.1 (0.21)	2.27 (0.204)	0.90 (0.14)	2.09	1.85	1.77
25.8	3.18 (0.31)	2.47 (0.215)	1.1 (0.145)	2.25	2.05	1.76
28.5	3.21 (0.28)	2.61 (0.193)	1.21 (0.138)	2.34	2.16	1.75

Note: *Numbers in parentheses are standard deviations

Table 2 Size distribution of Detarium microcarpum seed at the market storage moisture content of 14.1% (d.b.)

Particular	Major diameter a, (cm)	Percentage of sample		Average						
		By No.	By mass	a (cm)	b (cm)	c (cm)	a/b	a/c	M (kg)	a/M
Seed ungraded 0.84±0.02	2.0 – 3.6	100	100	3.03±0.27	2.1±0.2	0.65±0.11	1.43±0.12	4.66±0.19	3.62±0.53	
Large 0.82±0.07	a>3.07	48	51.6	3.28±0.15	2.4±0.17	0.72±0.11	1.40±0.09	4.61±0.63	4.01±0.46	
Medium 0.89±0.06	2.53≤a≤3.07	48	45	2.70±0.12	2.13±0.2	0.74±0.19	1.38±0.12	4.06±0.62	3.29±0.23	
Small 0.85±0.09	a<2.53	4	3.4	2.33±0.11	1.86±0.19	0.65±0.10	1.25±0.13	3.68±0.43	2.75±0.17	

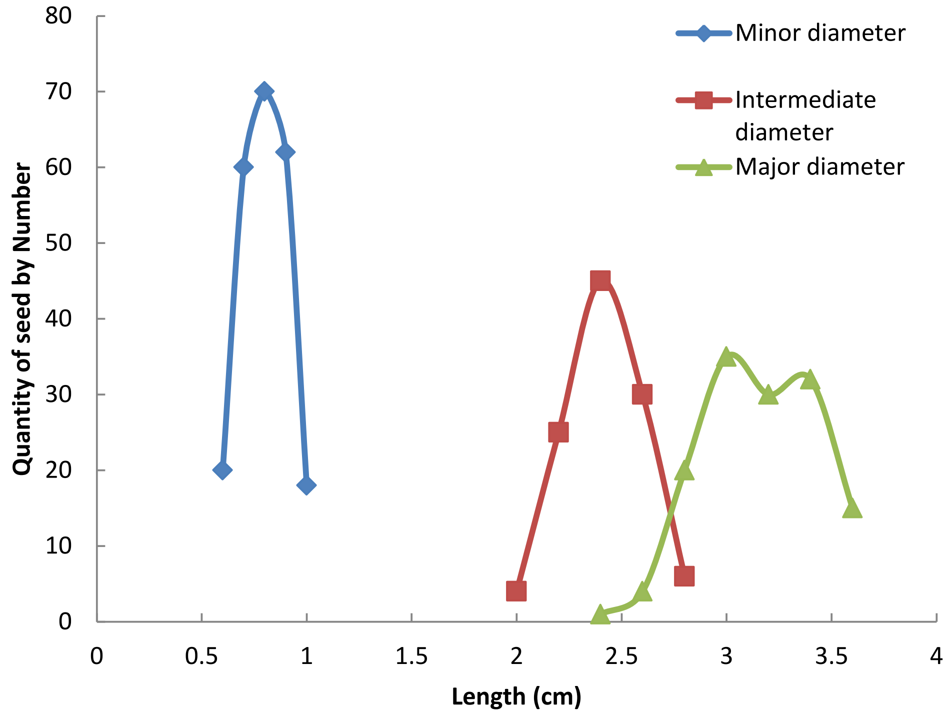

Figure 2 Frequency distribution of Detarium microcarpum seed axial dimensions at 14.1% (d.b.) moisture content

The effect of moisture content on the surface area of Detarium microcarpum seed is presented in Figure 3. This shows that the surface area increased from 354.62 to 413.19cm^{2}in the moisture range of 8.2% to 28.5% (d.b.). The seed surface area was significantly affected by moisture content at 1% level of significance (df = 4, F-ratio = 220.582 and p-value = 0.000). The relationship between the moisture content and surface area of the seed was found to be linear and can be expressed with Equation (5) as follows

$$S_a = 3.646M + 330.8, \qquad R^2 = 0.95 \qquad (5)$$

where S_a is surface area (cm^2) and M is moisture content (%, d.b.).

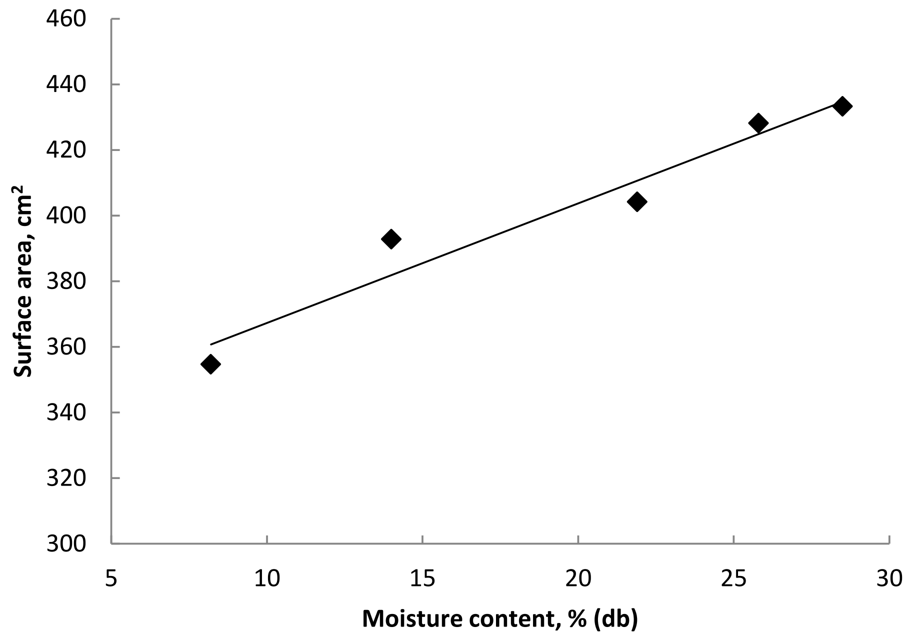

Figure 3 Effect of moisture content on surface area of Detarium microcarpum *seed*

3.4 One thousand seed weight

The variation of one thousand seed weight with moisture content of Detarium microcarpum seed is presented in Figure 4. One thousand seed weight increased from 3.184 to 3.737kg as the moisture content increased from 8.2% to 28.5% (d.b.). The variation of one thousand seed weight with moisture content was significant at 5% level of significance (df = 4, F-ratio = 4.858 and p-value = 0.019). The trend of one thousand seed weight with moisture content could be attributed to increase in weight gain due to moisture up-take at higher moisture level. The relationship between moisture content and mass of the one thousand seeds of Detarium microcarpum was found to be linear and can be represented with the following Equation (6):

$$W_{1000}=0.026M + 2.96, \qquad R^2 = 0.97 \qquad (6)$$

where W_{1000} is the one thousand seed weight (kg) and M is the moisture content (%, d.b.).

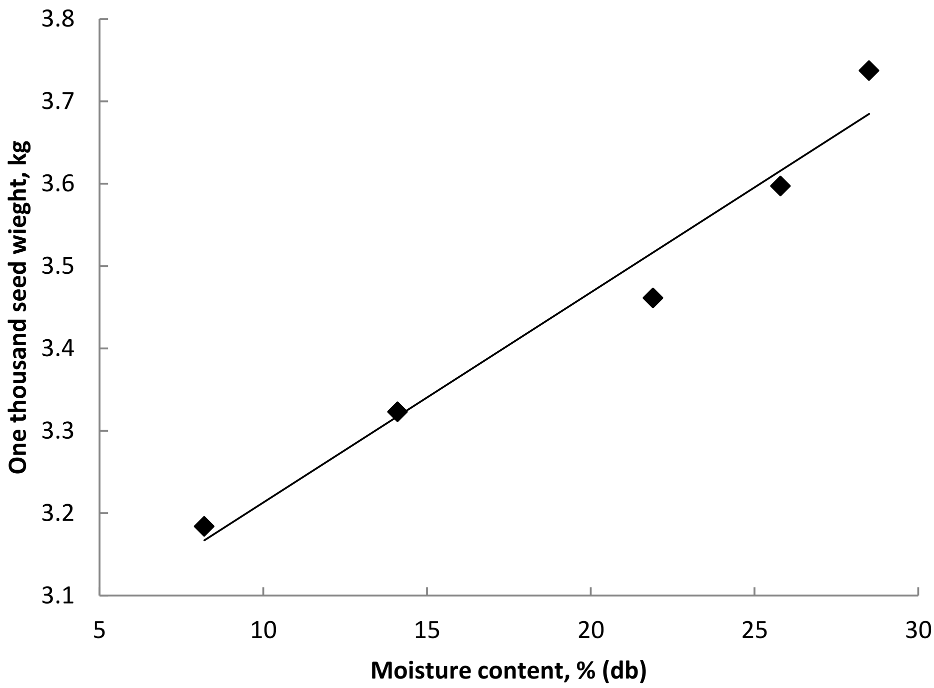

Figure 4 Effect of moisture content on one thousand seed weight of Detarium microcarpum seed

3.5 Particle Density

The effect of moisture and particle density is presented in Figure 5. This shows that particle density increased from 1060 to 1316kg/m^3 as the moisture content of the seed increased from 8.2% to 28.5% (d.b.). The particle density of the seed was significantly affected by moisture content at 1% level of significance (df = 4, F-ratio = 2.288E3 and p-value = 0.000). The relationship existing between particle density and moisture content was found to be linear and can be represented by the following regression Equation (7).

$$\rho_t = 11.97M + 951.72, \qquad R^2 = 0.96 \quad (7)$$

where ρ_t is particle density(kg/m^3) and M is moisture content (%, d.b.).

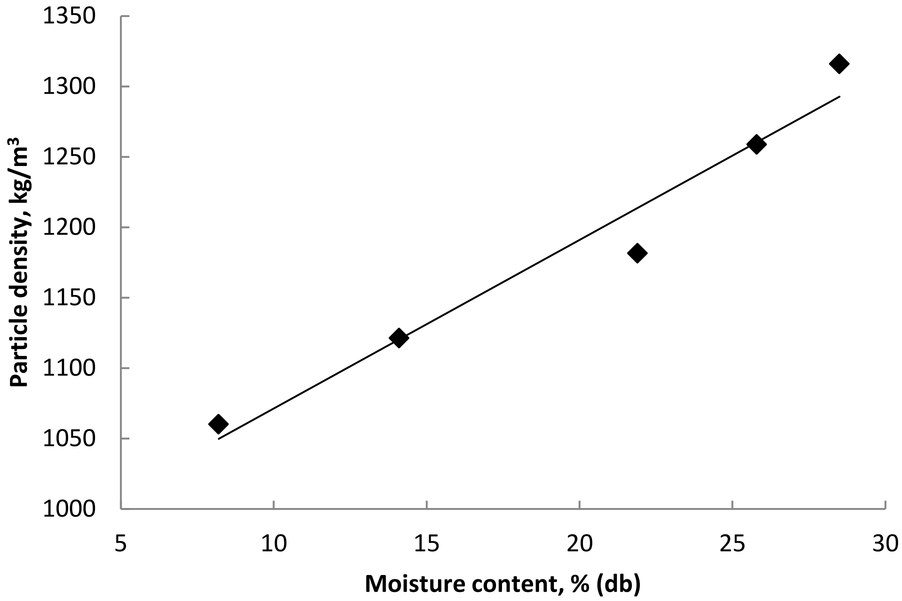

Figure 5 Effect of moisture content on particle density of Detarium microcarpum seed

Increase of particle density with seed moisture content has also been reported by Gupta and Das (1998) for sunflower seeds, Aviara et al. (1999) for guna seeds, Chandrasekar and Visvanathan (1999) for coffee, Singh and Goswani (1996) for cumin seed, Tunde–Akintunde and Akintunde (2007) for beniseed, Aviara et al. (2010) for Mucuna flagellipes nut, Aviara et al. (2013) for Moringa oleifera seed and kernel and Aviara et al. (2014a) for Brachystegia eurycoma seed.

3.6 Bulk Density

The effect of moisture on bulk density of Detarium microcarpum seeds is shown in Figure 6. The bulk density of the seed decreased from 652.5 to 617.2kg/m^3 as the moisture content increased from 8.2% to 28.5% (d.b.). The bulk density of the seed varied significantly with moisture content at 1% level of significance (df = 4, F-ratio = 47.767 and p-value = 0.000). This could be attributed to increase in size with moisture content which gave rise to decrease in quantity of the seeds occupying the same bulk volume. Also, the resistance of the seeds to consolidation may have increased with moisture content as a result of increase in internal pressure. The relationship existing between moisture content and bulk density was linear and can be represented by the Equation (8):

$$\rho_b = -1.949M + 670.25, \qquad R^2 = 0.95 \qquad (8)$$

where ρ_b is the bulk density (kg/m^3)and M is moisture content (%, d.b.).

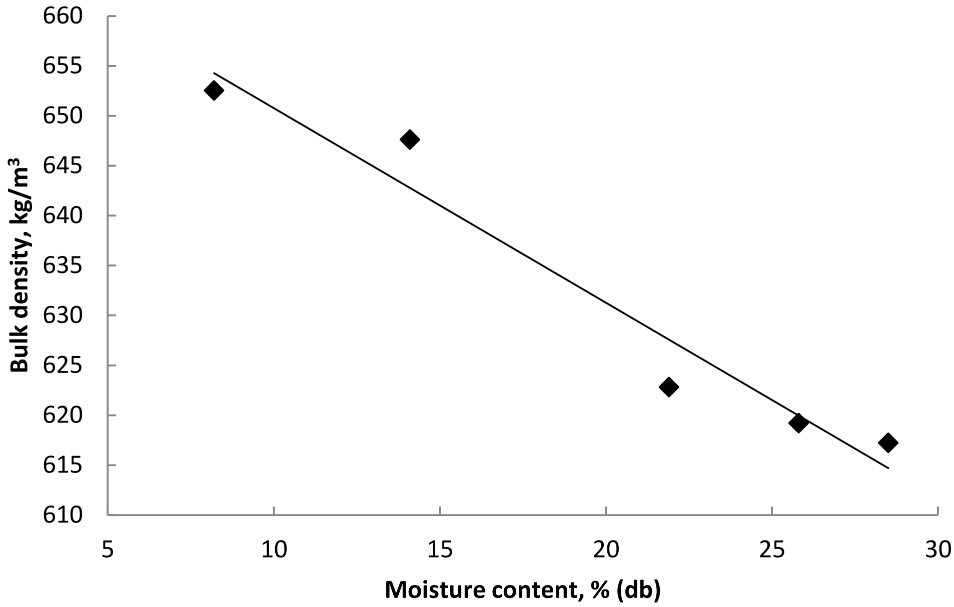

Figure 6 Effect of moisture content on bulk density of *Detarium microcarpum* seed

Carman (1996), Gupta and Das (1997), Aviara et al. (2010), Kibar et al. (2010), Visvanathan et al. (1996) and Aviara et al. (2014a) found the bulk density of lentil seeds, sunflower seeds, Mucuna flagellipes nuts, rice seeds, neem nuts and Brachystegia eurycoma seed respectively decreased as the seed moisture content increased.

3.7 Porosity

The variation of the seed porosity of Detarium microcarpum with moisture content is presented in Figure 7. The porosity of the seed increased from 35% to 53.1% as the moisture content increased from 8.2% to 28.5% (d.b.). The variation of the seed porosity with moisture content was significant at 1% level of significance (df = 4, F-ratio = 108.886 and p-value = 0.000). The relationship existing between porosity and moisture content was found to be linear and it can be represented with the following Equation (9):

$$\lambda = 0.857M + 28.82, \qquad R^2 = 0.99 \qquad (9)$$

where λ is porosity (%) and M is moisture content (%, d.b.). Increase of porosity with moisture content has been reported for green gram (Nimkar and Chattopadhyay, 2001), chickpea seed (Konak et al., 2002), Balanites aegyptiaca (Aviara et al., 2005a), water melon varieties (Razaviand Milani, 2006), Mucuna flagellipes nut (Aviara et al., 2010), Moringa oleifera seed and kernel (Aviara et al., 2013), dry bean grain (Kibar et al., 2014), and Brachystegia eurycoma seed (Aviara et al., 2014a).

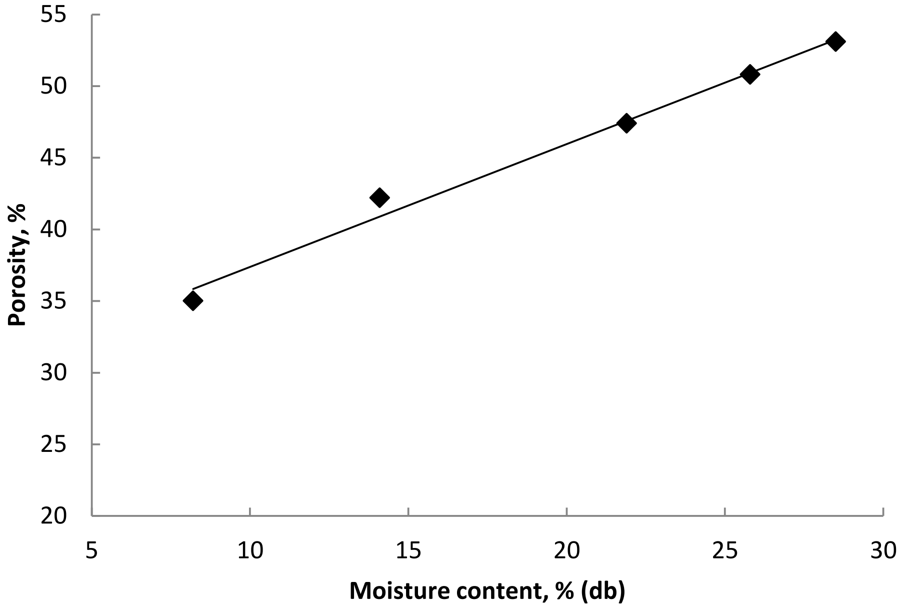

Figure 7 Effect of moisture content on the porosity of Detarium microcarpum seed

3.8 Roundness and sphericity

The effect of moisture content on roundness and sphericity of Detarium microcarpum seed is shown in Figure8. The figure shows that roundness and sphericity increased linearly from 62.5% to 72.1% and 58.4% to 66.6% respectively as the moisture content of the seed increased from 8.2% to 28.5% (d.b.).The roundness and sphericity of the seed was significantly affected by moisture content at 1% level of significance (df = 4, F-ratios = 19.324 and 20.665, and p-values = 0.000 and 0.000). The high values of roundness and sphericity of the seed coupled with its low minor axial dimension indicate that it could be described as an oval disc in shape. The relationship between the moisture content and roundness and sphericity was found linear and it can be expressed by the following (1)0 and Equation (11):

$R= 0.415M+59.6, \quad R^2 = 0.95 \quad (10)$

$\varphi= 0.377M +55.2, \quad R^2 = 0.97 \quad (11)$

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

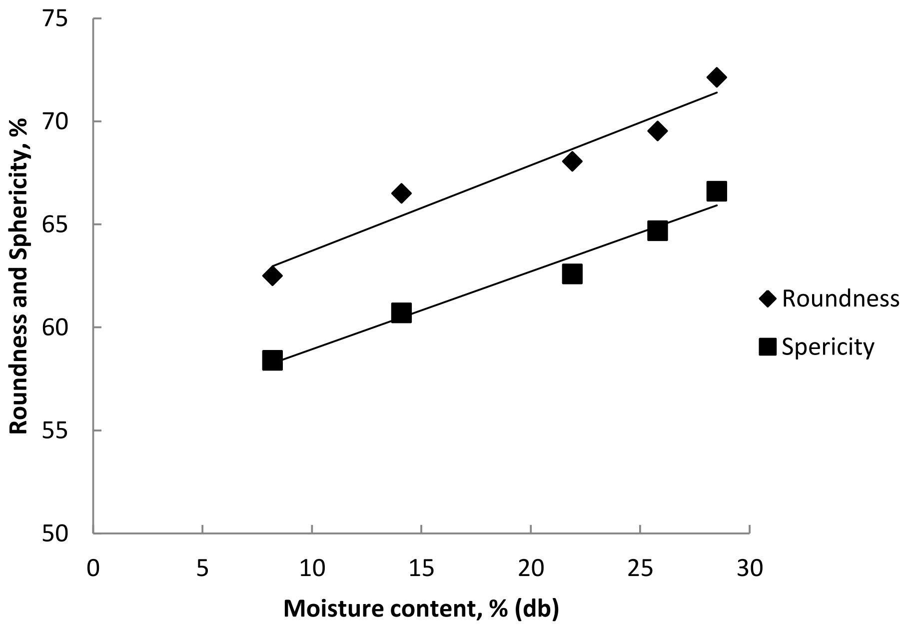

Figure 8 Effect of moisture content on roundness and sphericity of *Detarium microcarpum* seed

Increase in roundness and sphericity with moisture content has been reported for pigeon pea (Baryeh and Mangope, 2002), Turkish Mahaleb (Aydin et al., 2002), hemp seed (Sacilik et al., 2003), red lentil grains (Isik, 2007), sunflower (Isik and Izli, 2007), Mucuna flagellipes nut (Aviara et al., 2010) and Brachystegia eurycoma seed (Aviara et al., 2014a).

3.9 Angle of Repose

The variation of the angle of repose of Detarium microcarpum seed with moisture content is shown in Figure 9. From this, it can be observed that the angle of repose increased from 9 to 28.4^o as the moisture content increased from 8.2% to 28.5% (d.b.). The angle of repose of the seed was significantly affected by moisture content at 1% level of significance (df = 4, F-ratio = 164.399 and p-value 0.000). At higher moisture contents within the experimental range, the seeds might have tended to stick together resulting in better stability and less flowability, which caused increase in the value of angle of repose with moisture content. The angle of repose increased linearly with moisture content in a relationship that can be expressed using the Equation (12):

$$\Theta = 0.962M + 0.65, \quad R^2 = 0.99 \qquad (12)$$

where Θ is angle of repose in degree and M is moisture content (%, db).

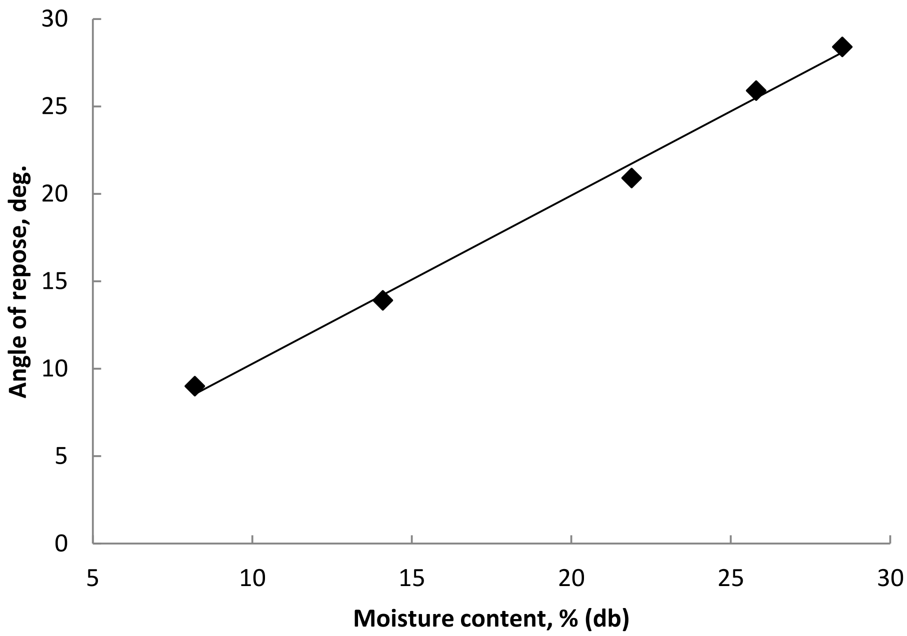

Figure 9 Effect of moisture content on angle of repose of Detarium microcarpum seed

Linear relationship between angle of repose and moisture content was also observed for cumin seed, lentil seed, coriander seed and Brachystegia eurycoma seed (Singh and Goswani, 1996, Amin et al., 2004, Yalcin and Ersan, 2007, and Aviara et al., 2014a).

3.10 Static coefficient of friction

The static coefficient of friction of Detarium microcarpum seed obtained experimentally on five structural surfaces against moisture content in the moisture range of 8.2%–28.5% (d.b.) is presented in Figure 10. This figure shows that the static coefficient of friction of the seed increased linearly with increase in moisture content and varied according to structural surface. Among the five structural surfaces considered, the static coefficient of friction of the seed was highest on galvanized steel sheet (0.362–0.638), followed by plywood with wood grains perpendicular to the direction of movement (0.292–0.541), hessian bag material (0.238–0.539) and plywood with wood grains parallel to the direction of movement (0.256–0.505) and was least on fiber glass (0.166–0.395). The moisture content and structural surface had significant effect on the static coefficient of friction of the seed at 1% level of significance (df = 4, F-ratio = 106.264 and 72.001, and p-values = 0.000 and 0.000). The relationship existing between the static coefficient of friction and moisture content can be expressed for different structural surfaces using the following Equations (13), (14), (15), (16) and (17):

$f_{gs} = 0.012M + 0.258, \quad R^2 = 0.99$ (13)

$f_{pp} = 0.012M + 0.198, \quad R^2 = 0.99$ (14)

$f_{hb} = 0.011M + 0.137, \quad R^2 = 0.99$ (15)

$f_{pl} = 0.012M + 0.156, \quad R^2 = 0.99$ (16)

$f_{fg} = 0.011M + 0.077, \quad R^2 = 0.99$ (17)

where f_{gs}, f_{pp}, f_{hb}, f_{pl} and f_{fg} are static coefficients of friction for Detarium microcarpum seed on galvanized steel sheet, plywood with wood grain perpendicular to the direction of movement, hessian bag material, plywood with wood grain parallel to the direction of movement and fiber glass respectively, and M is moisture content (%, d.b.).

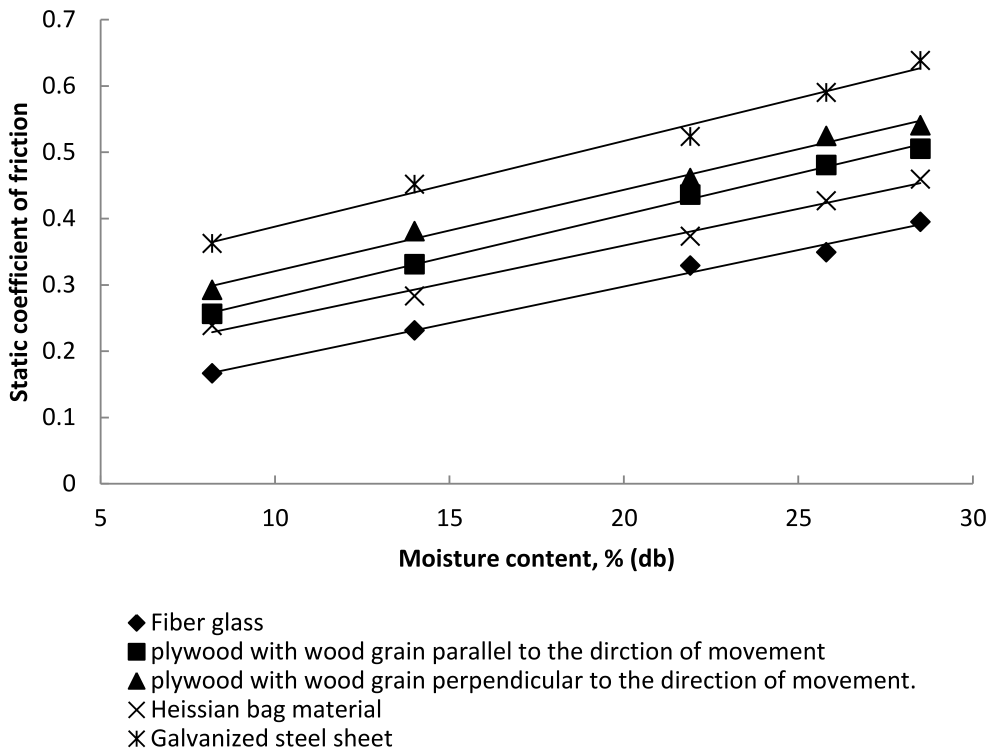

Figure 10 Effect of moisture content on static coefficient of friction of Detarium microcarpum seed

Linear increase in static coefficient of friction with moisture content was also reported by Singh and Goswani (1996); Milani et al. (2007);Kheiralipour et al. (2008); Aviara et al. (2010); Aviara et al. (2013) and Aviara et al. (2014a) for cumin seed, cucurbit seeds, wheat, Mucuna flagellipes nut, Moringa oleifera seed and kernel and Brachystegia eurycoma seed respectively.

3.11 Kinetic coefficient of friction

The variation of the kinetic coefficient of friction of Detarium microcarpum seed with moisture content on five structural surfaces is shown in Figure 11. The kinetic coefficient of friction of the seed increased linearly with increase in moisture content in the range of 8.2%–28.5% (d.b.). It was observed that the kinetic coefficient friction was highest on hessian bag material (0.351 - 0.617), followed by plywood with wood grain parallel to the direction of movement (0.319 - 0.510), plywood with wood grain perpendicular to the direction of movement (0.255 - 0.50), galvanized steel sheet (0.162 - 0.445) and lowest on fiber glass (0.096 - 0.43). The moisture content, structural surface and the interaction between moisture content and structural surface all had significant effect on the seed kinetic coefficient of friction at 1% level of significance(df = 4, 4 and 16, F-ratios = 339.185, 244.539 and 2.959, and p-values = 0.000, 0.000 and 0.002).

The relationship existing between the kinetic coefficient of friction and moisture content can be expressed for different structural surfaces using Equations (18), (19), (10), (21) and (22) as follows:

μ_{hb}= 0.013M + 0.243, R^2 = 0.99 (18)

μ_{pl}= 0.009M + 0.249, R^2 = 0.99 (19)

μ_{pp} = 0.011M + 0.158, R^2 = 0.99 (20)

μ_{gs}= 0.014M + 0.043, R^2 = 0.99 (21)

μ_{fg} = 0.015M - 0.033, R^2 = 0.99 (22)

where $\mu_{hb}, \mu_{pl}, \mu_{pp}, \mu_{gs}$ and μ_{fg} are the kinetic coefficients of friction of Detarium microcarpum seed on hessian bag material, plywood with wood grain parallel to the direction of movement, galvanized steel sheet and fiber glass respectively.

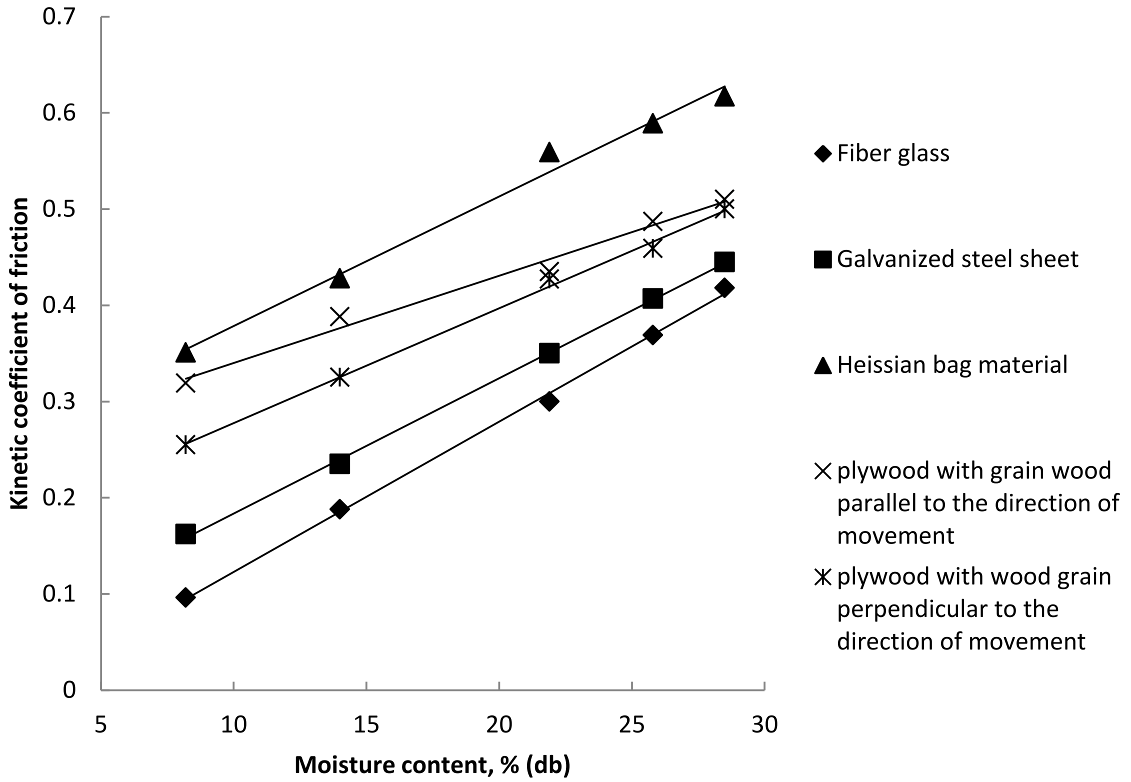

Figure 11 Effect of moisture content on kinetic coefficient of friction of Detarium microcarpum *seed*

Carman (1996), Ebubekir et al. (2004), Sessiz et al. (2007) and Aviara et al. (2010) reported linear increase of kinetic coefficient of friction of lentil seed, fenugreek seed, caper fruit and Mucuna flagellipes nut with moisture content respectively. The value of kinetic coefficient of friction is an essential data in the determination of power required for continuous flow of granular or unconsolidated materials.

4 Conclusions

The investigations of physical properties of Detarium microcarpum seeds revealed the following:

(1) In the moisture range of 8.2%-28.5% (d.b.), the major, intermediate and minor axial dimensions of the seed increased from 3.03 to 3.21cm, 2.17 to 2.61cm and 0.71 to 1.21cm respectively. The arithmetic mean and geometric mean diameters increased from1.97 to 2.34cm and 1.67 to 2.16cm respectively, while the equivalent sphere effective diameter decreased from 1.78 to1.76cm.

(2) The seed surface area increased from 354.6 to 431.1cm2, while one thousand seed weight increased from 3.184 to 3.737kg as the seed moisture content increased from 8.2% to 28.5% (d.b.).

(3) Particle density and porosity increased with increase in seed moisture content from 1060 to 1316 kg/m3and 30% to 53.1% respectively, while bulk density decreased from 652.5 to 617.2kg/m3 in the same moisture range.

(4) Roundness and sphericity both increased from 62.5% to 72.1% and 58.4% to 66.6% respectively as the seed moisture content increased from 8.2% to 28.5 %(d.b.).

(5) Angle of repose increased from 9o to 28.4o and had linear relationship with moisture content.

(6) Static and kinetic coefficients of friction increased linearly with moisture content and varied with structural surface.

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