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Seed Moisture Influence on Some Physical and Mechanical Properties of African Mesquite (*Prosopis africana*)

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Authors' contributions

Author SO designed the study, strictly supervised all the experiments, performed some of the experiments, supplied the literatures, performed the results analyses and wrote the first draft of the manuscript. Author FO supplied some of the literature, co-supervised some of the experiments and offered professional assistance in the collation of data. Author MD performed some of the experiments and assisted in the results analysis.

Original Research Article

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ABSTRACT

The physical and some mechanical properties of *Prosopis africana* seeds (African mesquite) as affected by seed moisture content in the range 10–22% wet basis (w.b.) were investigated. Mohsenin, Stepanoff and ASABE standard methods were used in determining the properties. Results showed that there was increase in seed length (11.40–12.90 mm), width (8.10– 9.60 mm) and thickness (4.8–5.9 mm) while arithmetic and geometric mean diameters increased in the range; 8.1–9.4 mm and 7.5–8.9 mm respectively. Increases in bulk density (508 – 856 kgm^{-3}), surface area (176 – 249 mm^2) and sphericity (0.66–0.70) were recorded while a decrease was observed in true density (1205.9–1090 kgm^{-3}) with increasing seed moisture content. Increase was also observed in static angle of repose (30.8 - 36.2^o). Static coefficient of friction increased on plywood (26.7 - 32.2), glass (25.7 - 33.8), mild-steel (26.2 - 31.0), galvanized iron (27.5 - 32.7), rubber (27.5 - 31.5), aluminium (26.0 - 28.5) and stainless steel (24.0 - 31.8). Shear stress was highest at 22% moisture wet basis (w.b.) under 500 g load (6.3 gcm^{-2}) and lowest at 10% moisture w.b., under 200g load (2.0 gcm^{-2}). Effect of seed moisture content

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on all the properties was statistically significant (*P*=.05) except static coefficient of friction on aluminium and mild steel surfaces. All the properties are pre-requisite for the engineering design and development of equipment for the handling and processing of African mesquite; the purpose for which baseline data was developed in this work.

Keywords: Bulk density; seed volume; shear stress, porosity; sphericity; angle of repose; internal friction.

1. INTRODUCTION

Prosopis spp. is an important tree genus in many tropical and sub-tropical regions of the world as a woody perennial. It is native to North, Central and South America, Asia, Africa and also commonly known all over the world as ‘mesquite’. *Prosopis africana* (Guill., Perrott. & Rich.) Taub, is the most common specie in Africa, belonging to the family *Fabaceae Minosoidae* and popularly known as African mesquite. Other species, native to Africa include *Prosopis cineraria* and *Prosopis pallid* [1].

Trees of *prosopis africana* are common in the middle belt and Northern parts of Nigeria. The tree height ranges between 4 and 20m with an open canopy and drooping foliage. It has a deep, fast growing tap root and a very dark, scaly bark with streaks (that are orange to red-brown with white color). The leaves are alternate, bipinnate leaflets arranged in 9-16 pairs. The pods are dark red, cylindrical, hard and shiny, up to 15x3 cm and compartmentalized with wood cells within. The seeds mature in February-March and an average of 10 loose rattling seeds are contained in a pod. All the major tree parts have important uses. The wood is hard, durable and easy to carve, turn and glue thus, it is sought for art and craft. It is also highly valued as fuel and for charcoal making. Pounded dry pods are used as a fish poison. All the parts are used for medicinal purposes. Among the useful parts of the plant, the seeds are the most commonly used. A poultice of the boiled seeds is usually applied externally to relieve sore throat. It was reported that the powdered form of the seeds could be adjudged as a potential botanical substitute to synthetic insecticide for protecting Cowpea against Cowpea bruchid in Benue State of Nigeria [2]. The pulp covering the seeds of *Prosopis africana* contains 9.6% protein; 3% fat; 53% carbohydrate; energy value of 1168 J; 160 mg of calcium and 70 mg of iron per 100 g of fresh seed weight [3]. Primarily and largely in Nigeria, the seeds are fermented to prepare a food condiment which is consumed by over 15 million people. The regular consumption of the condiment is medicinal and nutritious to the human body.

The food condiment from *Prosopis africana* is exported by Nigerian food marketers to various countries outside Nigeria, serving as a means of foreign exchange. Its processing provides source of income and livelihood for majority of the rural dwellers in the areas where it is commonly practiced. However, the handling and processing of the seeds (from harvest to end product) especially into the food condiment in Nigeria had been manual hitherto and laborious; hence, large scale production has been impractical. It is therefore necessary to mechanize the production process and optimize the processing conditions. These primarily require the determination of the engineering properties of the seed needed for the development of necessary equipment for the production process. Production of the condiment involves boiling the seeds in water for about 12 hours (h); removing the cotyledons from the seed coats (dehulling); washing the cotyledons in water; parboiling them for about 2 h and wrapping them up in leaves after allowing them to cool. Part of the processing also includes drying the seeds after harvest. However, a number of important changes in the structure of raw materials especially seeds and pulses take place in the course of hydration and they are mainly associated with increased moisture content [4]. Adigun and Alonge [5]; Akaiimo and Raji [1] worked on the engineering properties of African mesquite but not subject to the seed moisture content. Since the processing of the seeds involves hydration, it is vital to take seed moisture content into consideration in determining the engineering properties. Other researchers among many, who worked on related topics are Nalbandi et al. [6] on *Turgenia latifolia*; Akbarpour et al. [7] on Pomegranate seeds; Karimi et al. [8] on wheat. There remains a dearth of information on the relationship between seed moisture content and the engineering properties of *Prosopis africana*.

Therefore this study not only determined the engineering properties of *Prosopis africana* but also investigated the influence of the seed moisture content on the engineering properties as well as established models for predicting the value of these properties at any seed moisture content value. Relationship between the seed moisture content and the engineering properties were also depicted by the models.

2. METHODOLOGY

2.1 Sample Preparation

Prosopis Africana seeds were got from Benue state in Nigeria. The sample lot was manually cleaned to remove all foreign matter and damaged seeds. Part of the seed bulk (3/4) was sundried until they favorably compared with those made ready for processing into condiment by the processors in the area. The moisture contents of the samples (at harvest and after sun-drying) were determined by oven drying at (103±1)℃ for 72h according to ASAE [9] standard. The samples of the desired moisture contents were prepared by adding a required and calculated amount of distilled water according to the method described and adopted by Nalbandi [6].

The samples were transferred to four separate polyethylene bags, sealed tightly and kept at 5ºC in a refrigerator for a week to enable the moisture to be distributed uniformly throughout each sample. Before starting the test, the required quantities of the samples were taken out of the refrigerator and allowed to equilibrate with the room temperature for about 2 hours. Four seed moisture levels were used.

2.2 Seed Axial Dimensions

From each sample lot, 30 seeds were randomly selected and their true axial dimensions namely length, width and thickness were measured using a vernier caliper with a 0.02 mm accuracy [10,6].

2.3 Principal Dimensions, Surface Area and Sphericity

Arithmetic and Geometrical dimensions are the principal dimensions which were calculated according to Akbarpour et al. [7]. Surface area was calculated using the method adopted by Sacilik et al. [11]. Sphericity was also determined using method adopted by Estefania et al. [12].

2.4 Individual Seed Mass and Thousand Grain Mass

The mass of individual seed was determined by weighing 50 g of seeds and counting the number of seeds in the 50 g mass. The 50 g mass was divided by the number of seeds in the 50 g mass to determine the mass of individual seed. The Thousand grain mass was evaluated by randomly selecting hundred seeds and weighed on a battery weighing balance. The result was then multiplied by 10 to obtain the mass of 1000 seeds.

2.5 Seed Volume

Seed volume was determined by using the liquid displacement method [13].

2.6 True Density, Bulk Density and Porosity

The liquid displacement method was also used as described and adopted by Shafiee et al. [14] for true density while bulk density for all the samples were determined by using the ‘beaker method’ described by Nalbandi et al. [6]. Porosity was calculated using the values of bulk and true densities [15].

2.7 Dynamic and Static Angles of Repose

These were determined by using methods described by Nalbandi et al. [6].

2.8 The Static Coefficient of Friction

This was determined on seven different material surfaces viz: plywood, rubber, galvanized sheet, stainless steel, mild steel, aluminum and glass. The method described by Nalbandi et al. [6] was adopted for this experiment.

2.9 Coefficient and Angle of Internal Friction

Internal friction refers to the friction of grain against grain. Its coefficient and angle were measured using the ‘rectangular guide frame’ method [16].

2.10 Normal and Shear Stresses

The experimental set up or apparatus for measurement of shear stress (τ) for different values of normal stress (σ) is similar to that of coefficient and angle of internal friction except for a normal load on top of the rectangular cell [16]. The measurements were carried out for 200, 300, 400 and 500g loads for both normal and shear stresses.

3. RESULTS AND DISCUSSION

All the engineering properties in consideration were determined at 10, 14, 18 and 22% w.b (wet basis) seed moisture content. Table 1 shows the effect of seed moisture on the engineering properties of *Prosopis africana*.

3.1 Seed Axial Dimensions

Effect of moisture content on seed length, width and thickness was statistically significant (*P*=.05) at 22% moisture content (Table 1). All the three axial dimensions increased linearly (Fig. 1) as seed moisture increased from 10 to 22% w.b.

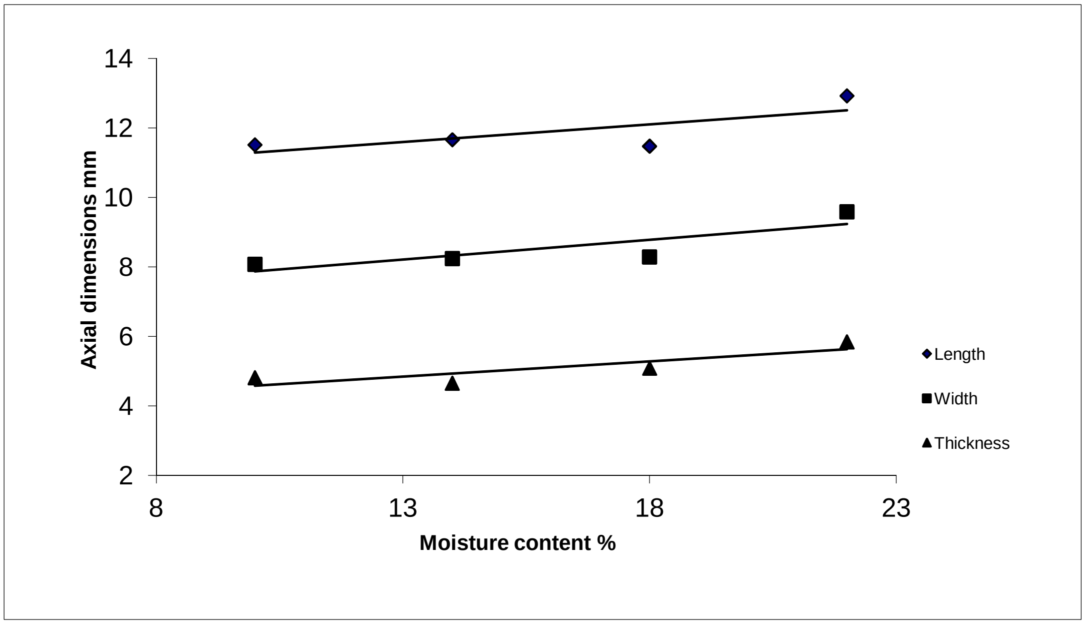

Fig. 1. Effect of seed moisture content on axial dimensions

The sharp and significant increase in the axial dimensions at 22% moisture content shows that the African mesquite seed slowly absorbs moisture because of its hard seed coat. The swelling of the seed along its three axes is due to the filling of the capillaries and voids in the seed and also due to the cell arrangement in the seed. Cell arrangement determines the direction of the increase in seed size when moisture is absorbed. This phenomenon causes the seed to tend towards high sphericity. A linear increase in all the three axial dimensions for locust bean (*Parkia filicoidea*) was reported by Sobukola and Onwuka [17] within a moisture range of 7.37-28.09% dry basis (d.b). Increase in the three axial dimensions of cotton seed and *Turgenia latifolia* were also reported [18,6]. The equations representing the relationship between moisture content and the axial dimensions of *Prosopis africana* seeds are shown in Table 2 (Eq. 13, 14 & 15).

Table 1. Seed moisture effect on the engineering properties of African mesquite

Properties	**Moisture content (%) w.b.**			
	10	**14**	**18**	**22**
Geometrical properties				
Seed length mm	11.52a±0.88	11.67a±0.82	11.48a±1.38	12.93b±1.20
Seed width mm	8.08a±0.74	8.25a±0.91	8.29a±0.83	9.59b±1.14
Seed thickness mm	4.82a±0.78	4.66a±0.78	5.09a±1.44	5.85b±1.54
Arithmetic mean diameter mm	8.10a±0.55	8.20a±0.61	8.24a±0.71	9.36b±1.01
Geometric mean diameter mm	7.58a±0.55	7.56a±0.56	7.72a±0.74	8.86b±0.99
Surface area mm^2	196.4a±94.81	182.7a±27.10	186.1a±35.51	249.4b±56.99
Sphericity	0.66ab±0.05	0.65a±0.04	0.68ab±0.07	0.70b±0.09
Gravimetric properties				
Thousand grain mass g	304.2a±4.66	318.8a±4.66	325.2a±14.20	384.0b±25.56
Seed volume cm^3	0.26a±0.04	0.29ab±0.02	0.29ab±0.03	0.33b±0.05
Seed mass g	0.32a±0.05	0.32a±0.05	0.30a±0	0.4b±0
Bulk density kg m^{-3}	508a±10.96	616b±16.73	808c±17.89	856d±21.91
True density kg m^{-3}	1209.5b±84.89	1156.3ab±18.40	1191.6ab±40.80	1118.8a±45.86
Porosity %	57.8d±3.31	46.7c±1.48	32.1b±2.98	23.4a±1.98
Frictional properties				
Static coefficient of friction on:				
Plywood	30.00a±2.55	31.40a±1.14	35.00b ±1.87	34.00b±1.58
Rubber	31.00a±1.58	32.60ab±1.14	34.20b±2.17	33.00ab±1.58
Mild steel	29.40a±3.21	33.20a±3.56	33.60a±3.65	32.40a ±1.82
Glass	28.80a±0.84	32.20b±1.48	33.60b±2.07	36.20c±1.92
Aluminium	29.20a±2.95	31.00a±1.73	30.60a±1.52	29.40a±0.89
Stainless steel	26.80a±0.84	34.00b±1.87	32.60b±1.14	33.80b±1.92
Galvanized	31.00a±1.58	34.00b±1.41	35.60b±1.82	34.60b ±2.30
Coefficient of internal friction	0.77c±0.04	0.68b±0.05	0.56a±0.05	0.54a±0.10
Angle of internal friction°	37.4b±1.39	34.2b±1.77	29.2a±2.02	28.4a±4.29
Dynamic angle of repose°	26.4a±0.38	28.1b±1.38	30.3c±0.81	31.0c±0.74
Static angle of repose°	39.4b±2.30	34.2a±1.10	39.8b±1.64	35.2a±2.28
Normal stress (gcm^{-2}) on loads:				
200	3.112	2.222	0.8	0.035
300	4.078	3.19	1.766	1.001

Table 1 Continued……….

400	5.044	4.154	2.733	1.967
500	6.01	5.12	3.699	2.933
Shear stress (gcm^{-2}) on loads:				
200 g	2.49a±0.447	3.06b±0.19	3.06b±0.10	3.55b±0.22
300 g	2.33a±0.20	3.51b±0.17	3.63b±0.16	3.80b±0.17
400 g	3.69a±0.33	4.27b±0.25	4.34b±0.14	4.64b±0.39
500 g	4.71a±0.09	4.67a±0.02	4.70a±0.11	5.62b±0.69

Values along the same row followed by different letters (a-d) are statistically significant at $P< .05$

Table 2. Physical and mechanical properties of *Prosopis africana* and models representing the relationship between the properties and seed moisture content

Property	Model (Equation)	R^2	Eq.
Length mm	$y_L = 0.101M + 10.284$	0.5689	13
Width mm	$y_W = 0.1143M + 6.7245$	0.7152	14
Thickness mm	$y_T = 0.088M + 3.697$	0.7424	15
Geometric mean diameter mm	$y_{GMD} = 0.0181M^2 - 0.48M + 10.608$	0.9726	16
Arithmetic mean diameter mm	$y_{AMD} = 0.0159M^2 - 0.4145M + 10.708$	0.9384	17
Surface area mm^2	$y_{SA} = 1.2031M^2 - 34.44M + 422.63$	0.9683	18
Sphericity	$y_{SPH} = 0.0005M^2 - 0.0113M + 0.7231$	0.9153	19
Thousand grain mass g	$y_{TGM} = 24.58M + 271.6$	0.818	20
Seed mass g	$y_{SM} = 0.025M^2 - 0.103M + 0.405$	0.8339	21
Seed volume cm^3	$y = 0.0055M + 0.2043$	0.9073	22
True density kg m^{-3}	$y_{TD} = -5.92M + 1263.8$	0.5802	23
Bulk density kg m^{-3}	$y_{BD} = 30.9M + 202.6$	0.9562	24
Porosity %	$y_P = -2.945M + 87.12$	0.9916	25
Static coefficient of friction:			
Plywood	$y_{PLY} = -0.0375M^2 + 1.59M + 17.51$	0.8548	26
Rubber	$y_{RUB} = -0.0438M^2 + 1.59M + 19.335$	0.9252	27
Glass	$y_{GL} = 0.59M + 23.26$	0.9764	28
Mild steel	$y_{MST} = -0.0781M^2 + 2.735M + 9.9525$	0.985	29
Aluminium	$y_{AL} = -0.0469M^2 + 1.505M + 18.908$	0.958	30
Stainless steel	$y_{SS} = -0.0937M^2 + 3.49M + 1.835$	0.818	31
Galvanized iron	$y_{GI} = -0.0625M^2 + 2.31M + 14.09$	0.993	32

Table 2 Continued……….

Coefficient of internal friction	$y_{CIF} = -0.0203M + 0.9615$	0.940	33
Angle of internal friction (Deg.)	$y_{AIF} = -0.8M + 45.1$	0.941	34
Static angle of repose (Deg.)	$y_{SAR} = -0.0547M^3 + 2.6344M^2 - 40.681M + 237.46$	1	35
Dynamic angle of repose (Deg.)	$y_{DAR} = 0.4M + 22.55$	0.966	36
Normal stress under load:			
200 g	$y_{NS} = -0.2663M + 5.8035$	0.987	37
300 g	$y_{NS} = -0.2664M + 6.7708$	0.987	38
400 g	$y_{NS} = -0.2663M + 7.7353$	0.987	39
500 g	$y_{NS} = -0.2663M + 8.7013$	0.987	40
Shear stress under load:			
200 g	$y_{SS} = 0.0795M + 1.768$	0.897	41
300 g	$y_{SS} = 0.1133M + 1.5055$	0.764	42
400 g	$y_{SS} = 0.073M + 3.067$	0.901	43
500 g	$y_{SS} = 0.069M + 3.821$	0.591	44

M = Moisture content; R^2 = Coefficient of recommendation; Eq. = Equation.R^2 = 0.97 and R^2 = 0.94 indicate a good representation of the relationship. Increase in both mean diameters was reported for barley grains [19].

3.2 Geometric and Arithmetic Mean Diameters

The values of these average diameters actually depend on the values of the three axial dimensions. The arithmetic and geometric mean diameters increased in a polynomial trend (Table 2) from 8.10±0.55 to 9.36±1.01 mm and 7.58±0.55 to 8.86±0.99 mm respectively. The increments were also sharp and statistically significant at 22% moisture content. The average diameters are vital to aperture size in the engineering design of screens in separating machines. It therefore holds that the screen mesh used for separating African mesquite seeds during shelling would be different from that used during dehulling as regards aperture size. This is due to the significant increase in the values of the arithmetic mean and geometric mean diameters with increasing seed moisture content (Table 1). The equation representing the relationship between seed moisture content and the average diameters is given in Table 2 (Eq. 16 and 17). The high correlation coefficient $R^2 = 0.97$ and $R^2 = 0.94$ indicate a good representation of the relationship. Increase in both mean diameters was reported for barley grains [19].

3.3 Surface Area and Sphericity

The surface area was calculated as a function of the geometric mean diameter hence it also increased in a polynomial trend. There was an initial, gradual decrease up to 18% moisture level which was followed by a significant (P=.05), rapid and sharp increase between 18 and 22% moisture content levels as shown in Table 1. African mesquite seeds will therefore occupy more space when wet than when dry. The relationship between seed moisture content and surface area of African mesquite seed is perfectly represented by a second degree polynomial equation (Eq. 18 in Table 2). Sphericity increased significantly from 0.66 to 0.7. Igbozulike and Aremu [20] reported that a seed is considered to be spherical when its value of sphericity falls between 0.3 and 1.0. Therefore African mesquite seed is considered spherical and will roll over surfaces more easily as its moisture content increases. Seed moisture effect on sphericity was statistically significant (P= .05) as shown in Table 1 and its relationship with seed moisture content is represented by a second degree polynomial equation (Eq. 19 in table 2). Increase in both surface area and sphericity was reported for curcubit seeds [13].

3.4 Thousand Grain Mass, Seed Mass and Seed Volume

Thousand grain mass is the mass of 1000 seeds. For African mesquite seeds, thousand grain mass increased linearly from 304.2 to 384 g (Table 1) with increasing seed moisture content (10–22% w.b.). It means that as moisture content increases, grain mass increases too. The increase was statistically significant (P= .05) and the equation representing the relationship between grain mass and moisture content is shown in Table 2 (Eq. 20). Seed mass is the mass of an individual seed and it increased from 0.32 to 0.4 g (Table 1) in a second degree polynomial trend (Eq. 21 in Table 2) as moisture content increased from 10 to 22% w.b. The seed volume increased linearly from 0.26 to 0.33 cm^3 (Table 1). This means that with every increase in seed moisture content, there is a unit increase in seed volume of the African mesquite seed. It therefore holds that the number of seeds that will occupy a given volume container at 22% seed moisture content will be less than the number of seeds that will occupy same volume at lower seed moisture content. The relationship between seed moisture content and seed volume is represented by Eq. 22 in Table 2. These properties are vital to the engineering design of storage bins, conveyors and hoppers.

Similar results were reported for thousand grain mass in coriander seeds [21]. Increase in volume per seed was also reported for fenugreek seeds [22].

3.5 Bulk Density, True Density and Porosity

Bulk density increased linearly from 508 to 865k gm^{-3} while true density and porosity decreased from 1209.5 to 118.8 kgm^{-3} and 57.8 to 23.4% respectively (Table 1) with increasing seed moisture content from 10 to 22% w.b (Fig. 2 and 3). Increase in bulk density of African mesquite was due to the rate of increase in mass of seeds being higher than the rate of increase in volume occupied by the seeds. Meanwhile the decrease in true density was due to higher rate of increase in volume occupied by the seeds compared to the rate of increase in mass of the seeds as seed moisture increased. Porosity is a function of both bulk and true densities. Decreasing porosity with increasing seed moisture content in African mesquite means that the available pore spaces within the grain bulk reduces as seeds acquire moisture. This is due to water molecules on the surface of the seeds filling the pore spaces because the seed coat of African mesquite is not readily permeable (slow permeability) therefore retaining moisture on its surface for some time. The swelling of the seeds at high moisture content is another reason for decreasing porosity. Also, the seeds' surfaces become a little sticky at high moisture content and they tend to cling to one another thereby reducing porosity. The latter is made easy by virtue of the smooth seed coat and the high sphericity of the seeds at high moisture content. Equations representing the relationship between seed moisture content and these three properties are given in Table 2 (Eq. 23, 24, 25).

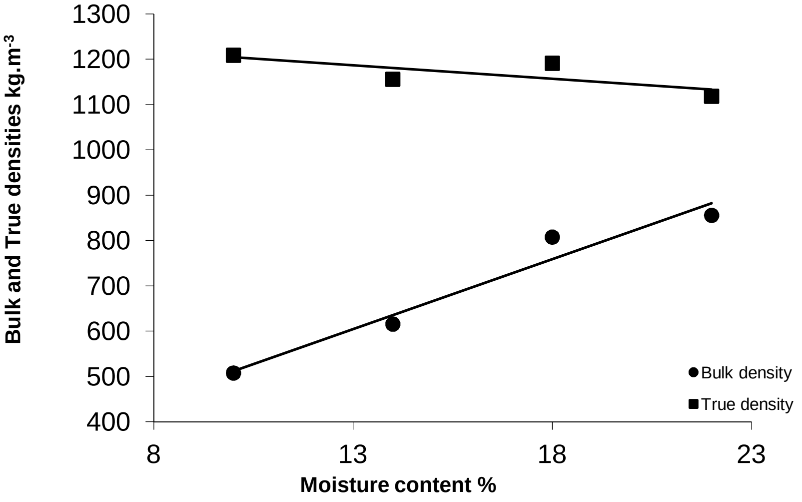

Fig. 2. Influence of seed moisture content on bulk and true densities of African mesquite.

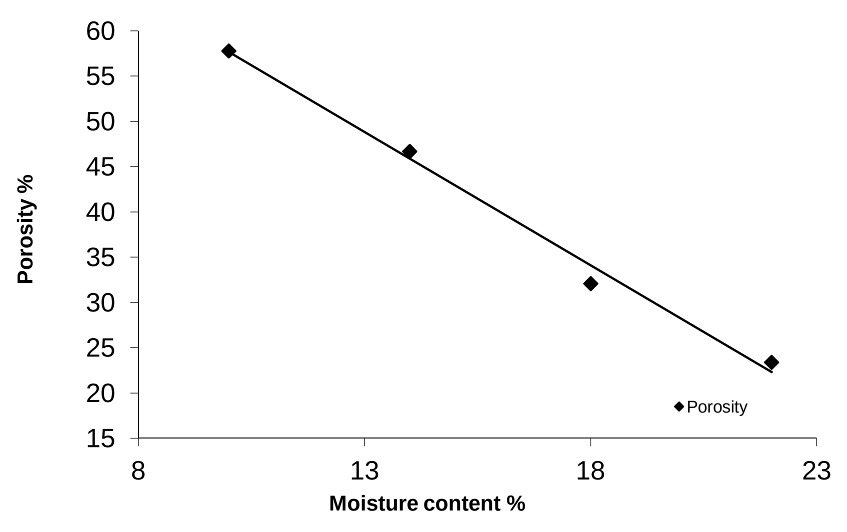

Fig. 3. Influence of seed moisture content on the porosity of African mesquite.

3.6 Static Coefficient of Friction

Static coefficient of friction applies to motionless objects only. It is the ratio of the force that maintains contact between an object and a surface and the frictional force that resists the motion of the object. The static coefficient of friction was statistically significant (*P*=.05) on plywood, rubber, glass, stainless steel and galvanized iron surfaces but not on mild steel and aluminium surfaces; while it was observed that the static coefficient of friction increased with increasing seed moisture content for all tested material surfaces (Table 1). Highest value of coefficient of friction was found on glass (36.20) at 22% moisture content and the lowest on stainless steel (26.8) at 10% moisture content. The reason for the increased friction coefficient at higher moisture content is due to the water present in the seed, which offers a high cohesive force on the material surfaces irrespective of the smoothness of material surfaces like aluminium and stainless steel. Similar results were given for *garcinia kola* seeds [20].

Linear increase in static coefficient of friction for *Prosopis africana* seeds was found on glass surface only, while increases in a second degree polynomial trend was found on other material surfaces. It therefore means that more energy or force will be required to initiate motion in *Prosopis africana* seeds on all the surfaces as seed moisture content increases.

The static coefficient of friction is important in the design of conveyors because friction is necessary to hold the seed to the conveying surface without slipping or sliding backward. On the other hand, discharging requires less friction to enhance the discharging process. Static coefficient of friction is also needed in the choice of structural material for the design of machine components involving the flow of bulk granular materials. The relationships between static coefficient of friction (μ) and the moisture content (M) on all tested material surfaces can be represented by eqn: 26, 27, 28, 29, 30, 31 and 32 (Table 2). Similar result was obtained for barley grains [19] where static coefficient of friction increased on all the surfaces tested.

3.7 Coefficient and Angle of Internal Friction

The coefficient of internal friction is simply the friction of grain against grain in the grain bulk. As the seed moisture content increased in the range of 10 – 22% w.b., there was a statistically significant (*P*=.05) decrease in both coefficient of internal friction (0.77 – 0.54) and angle of internal friction (37.4 – 28.4^o) as shown in Table 1, while the decrease in both parameters was linear (Table 2). Highest value was recorded at 10% moisture level for both coefficient and angle of internal friction. The angle of internal friction was higher than the coefficient of internal friction at all moisture levels. The angle and coefficient of internal friction are important in the design of hoppers and flow channels in processing machines and equipment for African mesquite seeds.

3.8 Dynamic and Static Angles of Repose

The dynamic angle of repose increased linearly with increasing seed moisture content in the range of 10 - 22% w.b. but the static angle of repose decreased with increasing seed moisture in the same range in a third degree polynomial trend. Table 1 shows a significant effect (*P*=.05) of seed moisture content on both dynamic and static angles of repose. The static angle of repose was higher at each moisture content level than the dynamic angle of repose. A reason for high angles of repose is the sticky nature of the seeds at high moisture content. At high moisture levels, the seeds of *Prosopis africana* tend to stick to one another because of the presence of water films on their seed coats which holds the seeds together by surface tension. This hinders their free flow therefore angle of repose will increase. The dryer the seeds, the less they stick together and the more easily they roll over one another, hence a low angle of repose. Both angles of repose are important in designing the equipment for mass flow and structures for storage. Equations showing the relationship between moisture content and both angles of repose are in Table 2 (Eq. 35, 36).

These results are similar to those reported for faba bean grains [21]. For *Prosopis Africana*, static angle of repose had a third-order polynomial relationship with seed moisture while dynamic had a linear relationship with seed moisture. It therefore means that, with every increase in seed moisture content of *Prosopis africana*, there must be a corresponding increase in dynamic angle of repose on a regular basis.

3.9 Normal Stress and Shear Stress

Normal stress was constant for all replicates of each sample tested; therefore the values of normal stress could not be analyzed for significance of moisture effect. But from Table 1 and 2, it is shown that normal stress decreased linearly with load (200 – 500 g) with increasing seed moisture content in the range 10 - 22% w.b. Normal stress decreased by 3.112 – 0.035 gcm^{-2}, 4.078 – 1.001 gcm^{-2}, 5.044 – 1.967 gcm^{-2}, 6.01 - 2.933 gcm^{-2} for 200, 300, 400 and 500 g respectively. Effect of moisture content on shear stress under different loads (200 – 500 g) as seen in Table 1 was significant (*P*=.05) considering the extreme moisture points of 10 and 22% w.b. From Table 1, highest value of shear stress for each load was at 22% seed moisture content. Peak value of shear stress was observed for 500 g load at 22% moisture content while the lowest shear stress value was observed at 10%

moisture content under 300 g load. Equations showing the effect of moisture content on both shear and normal stress under the specified loads are given in Table 2.

4. CONCLUSIONS

1. Seed moisture effect was statistically significant on all the physical properties examined except sphericity; static coefficient of friction on mild steel, rubber and aluminium surfaces.

2. Results showed that some physical properties increased with increasing seed moisture content such as seed length, width and thickness; arithmetic mean and geometric mean diameters; surface area and sphericity. Likewise, some decreased with increasing seed moisture content such as true density; porosity; coefficient and angle of internal friction; static angle of repose; and normal stress.

3. Regression equations that can be used to predict the behavior of *Prosopis Africana* seeds (during handling and processing) and the relationship between its varying moisture content and physical properties have been generated.

4. Baseline data necessary for the engineering design of handling and processing equipment for *Prosopis Africana* seeds was also developed.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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