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SELECTED MECHANICAL PROPERTIES OF BAMBARA GROUNDNUT SEEDS UNDER COMPRESSIVE LOADING

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ABSTRACT

Knowledge of mechanical properties of agricultural materials is useful in the development of equipment for processing and handling them.Selected mechanical propertiesnamely rupture force, maximum deformation at rupture point, hardness and toughness of cream and light brown varieties of Bambara groundnut (BGN) seeds were determined at four moisture levels (5, 15, 25 and 35% dry basis) under compressive loading alongaxial and longitudinal orientations.Rupture force, deformation, hardness and toughness of BGN seedswere within the ranges 45.58-438.55 N, 0.31-5.71 mm,14.61-448.55 Nmm^{-1} and0.01-1.02J, respectively. Rupture force, deformation and toughnessof the seeds had interplay of increasing and deceasing trends while hardness decreased consistently as moisture content increased from 5% to 35%.The cream variety withstood higher rupture force and deformed more without failure than the light brown variety within moisture content range of 5-25% along both loading orientations.Bothvarieties demonstrated greater hardness when loaded along the longitudinal orientations than the axially loaded samples. All the investigatedproperties were dependent on moisture content andorientationof loading. Predictive mathematical models forestimating the investigated properties at different moisture contents with reasonable accuracy were also established in this study.

***Keywords*: Bambara groundnut, Mechanical properties, Moisture content, Loading orientation, Handling.**

INTRODUCTION

Bambara groundnut(BGN) is a leguminous crop which is believed to have originated from the African continent. It is majorly produced in Nigeria and Ghana where it is considered a good source of protein. However, it has low status in comparison to other legumes such as groundnut and cowpea, as it is not considered as a lucrative cash crop but as a snack or food supplement (Fery, 2002; Lacroix*et al.*, 2003)

Bambara groundnut seed is highly nutritious,consisting of considerable amount of carbohydrate, protein, ash, fat, and fibre contents. It also consists of varying quantities of minerals such as potassium, sodium, calcium etc(Adu-dapaah andSangwan, 2004).Its seed has thepotential of replacing animal protein in various diets(Yao *et al*., 2015). It is consumed in different forms by man and animals. Various heat treatments on the seeds give unique diets depending cultural differences and individual choices. It can also be eaten as snack or used in the preparation of various food products such as*akar*, *moin-moin* and *okpa* in Nigeria. The seeds are also useful for livestock feeds and medicinal purposes (Heller, 1997; Atiku, 2002).

Bambara groundnut seeds undergo various unit operations in their conversion to various end products. These processing operations include cleaning (threshing, winnowing, de-stoning and washing), pre-treatment (soaking), milling (dry or wet milling), heat treatments (drying, frying, roasting and cooking), packaging etc. These processes are still being carried out mainly by using traditional technology in many developing countries. This necessitates appropriatemechanization of these processes so as to reduce the drudgery involved and ensure timeliness of operations.

Development of equipment for handling and processing BGN seed requires the understanding of its mechanical properties which describe the behaviour of the seed under various applied forces. Knowledge of mechanical properties of the seeds under compressive loading becomes imperative for proper design of systems for efficient mechanization of the processing operations as well as the optimization of the processes and product parameters (Gupta and Das, 2000). Force at the pointof rupture or seed failure, compressive strength, hardness and amount of energy required for seed breakage(toughness), among other mechanicalproperties, therefore, play a very essential role in the development of machines for harvesting, handling, cleaning and sorting BGN seeds (Baryeh, 2001).

Mechanical properties of agricultural materials can be significantly influenced by several factors which include the amount of moisture present in the biomaterial, maturity stages, storage period, direction of force application, rate of loading, portion of the material tested etc (Aremu *et al*., 2014; Swain *et al*., 2020).Mechanical properties of several crops have been investigated under various conditions and some of these include sunflower seeds(Gupta and Das, 2000),*Balanitesaegyptiaca* nuts (Mamman*et al*., 2005), *Garciniakola* seeds

(Igbozulike andAremu, 2009), chickpea seeds (Aymanet *al*., 2010),jatropha seeds (Bamgboye and Adebayo, 2012), *Canavalia* seed and kernel (Niveditha*et al*., 2013), mahogany seed and kernel (Aviara *et al*., 2014), maize grains (Soyoye*et al*., 2018), soybean (Ashaolu and Noibi, 2013; Fumen and Kaankuka, 2018), bush mango nut (Nwigbo*et al*., 2013; Iyilade*et al*., 2018),acha seeds (Bako and Bardey, 2020), sorghum (Swain *et al*., 2020), apricot seed and kernel (Fayed *et al*., 2020), melon seed (Oyerinde*et al*., 2020), arugula seed (Mirzabe*et al*., 2021)and hemp seeds (Kaliniewicz*et al*., 2021). This study therefore, investigated some mechanical properties of Bambara groundnut seeds under compressive loading as influenced by moisture content levels and orientation of loading with a view to providing information that will be useful in the development of processing and handling equipment for the seeds.

MATERIALS AND METHODS

The two varieties of Bambara groundnut seeds used in the study were identified as cream variety (common milk type) and light brown variety (with dark brown eye) and purchased from Aiyen market in Kogi State, Nigeria. The seeds were cleaned manually to remove the unwanted materials including empty pods and broken seeds. Determination of the moisture content of the seeds involved keeping the fresh samples of known weight in an oven maintained at a temperature of 130±2 °C for 6hrs (ASAE, 1983; Aviara*et al*., 2014).The weight of dry matter in the sample was considered to have been obtained when the differences between the consecutive weights became negligible. Moisture content of the samples on dry basis(db) was determined according to Equation 1. The initial moisture content (db) of the cream and light brown varieties were 5.99 and 8.18%, respectively.

$$MC_{db} = \frac{M_w}{M_d} \quad (1)$$

where: $MC_{db}$is moisture content (%, dry basis), $M_w$is mass of moisture removed from the sample (g) and $M_d$is mass of the dried sample (g).

Moisture contents of the seeds were varied by using the procedure described byBaryeh (2001) which involved adding calculated amount of distilled water to the seeds according to Equation 2(Ibrahim, 2007; Solomon*et al*., 2010).The seeds were soaked in water, sealed in polythene bags and kept in a refrigerator for 7 days to ensure uniform moisture distribution within the seeds. The seeds were removed from the refrigerator,left to equilibrate at room temperature for 2 hrs after which they were dried to the desired moisture content before starting the experiments (Baryeh, 2001).

$$Q = \frac{W_i(M_f - M_i)}{100- \quad f} \quad (2)$$

where: Qis mass of water added to seed (g),W_i is initial mass of sample (g),M_f isfinal moisture content (%, dry basis) andM_i isinitial moisture content (%, dry basis)

The selected mechanical properties were determined with the aid of a Universal Testing Machine (UTM) with a 50 kN load cell. The seeds were compressed at the loading rate of 2 mm/min. The seeds were individuallyplaced between the two parallel platesof the UTM and compressed quasi-statically until rupture orfailure of the seeds occurred, after which the loading was stopped.

The mechanical properties namely rupture force, deformation at rupture, hardness and toughness of the seeds were determined along axial and longitudinal loading orientations. Longitudinal orientation is the axis along the longest linear dimension of the seed when at rest while the axial orientation was taken as the axis which is mutually perpendicular to the longitudinal direction. For all levels of moisture content, three seeds of each variety were randomly selected and compressed axially and longitudinally. The force at rupture,which is the minimum force required to break or cause failure of the seed under compressive loading, and deformation at rupture (the reduction in the linear dimensions under the compressive load up to the point of rupture along the loading direction) were obtained from the force-deformation curves and properly documented. Toughness of the seed described as the amount of work done or energy required to cause rupture or failure of the seeds under compressive loading was also obtained directly from the UTM readings while seedhardness which describes its resistance to indentation or breakage under compressive loading was calculated according to Equation 3 (Olaniyan and Oje, 2002).

$$H = \frac{F}{d} \quad (3)$$

where: H is hardness of the seeds (Nmm^{-1}), F is force at rupture (N)and d is deformation at rupture point (mm).

The results obtained from the experiments carried out on bothBGN varieties were subjected to regression analysis,analysis of varianceand Duncan multiple range test.

RESULTS AND DISCUSSION

Rupture Force of the Seeds

Variations of rupture force with moisture content for cream and light brown varieties are presented in Figure1. The rupture force for the seeds decreased with increasing moisture content from 5 to 35% (db). The rupture force at 15% was the highest (438.55 N) when loaded longitudinally while the least rupture force (45.58N)was obtained at 35% moisture level when loaded axially for cream variety. For light brown variety, the rupture force at 25% moisture content was the highest (167.92 N) when loaded longitudinally while the least rupture force was 87.83 N at 5% and 15% when loaded axially. Bambara groundnut seeds at lower moisture content withstood greater force before breaking or rupturing under compressive loading. This indicates that the seeds are structurally stronger at lower moisture content. The lower rupture force at higher moisture content may be attributed to the soft texture of the seeds at higher moisture content which resulted in less force requirement before rupture. This showed that the power requirement for size reduction at lower moisture levels would be higher than at higher moisture levels. It is therefore, recommended that Bambara groundnut seed should be soaked as a form of pre-treatment before milling to as to reduce the energy requirement and thereby, reduce the overall cost of processing.

The results also showed that the seeds could withstand greater force before rupture along the longitudinal direction than axial loading for all moisture levels. Statistical evaluation showed that theeffect of moisture content on rupture force measured along both orientations was significant ($p \leq 0.01$). Similar results have been reported for shea nut (Olaniyan and Oje, 2002), apricot pit (Vursavus and Özgüven, 2004), faba beans (Altuntas and Yildiz, 2007),fennel seeds (Hojat*et al*., 2009), corn varieties (Seifi and Alimardani, 2010), chickpea seed (Ayman*et al*., 2010)and jatropha seeds (Bamgboye and Adebayo, 2012).

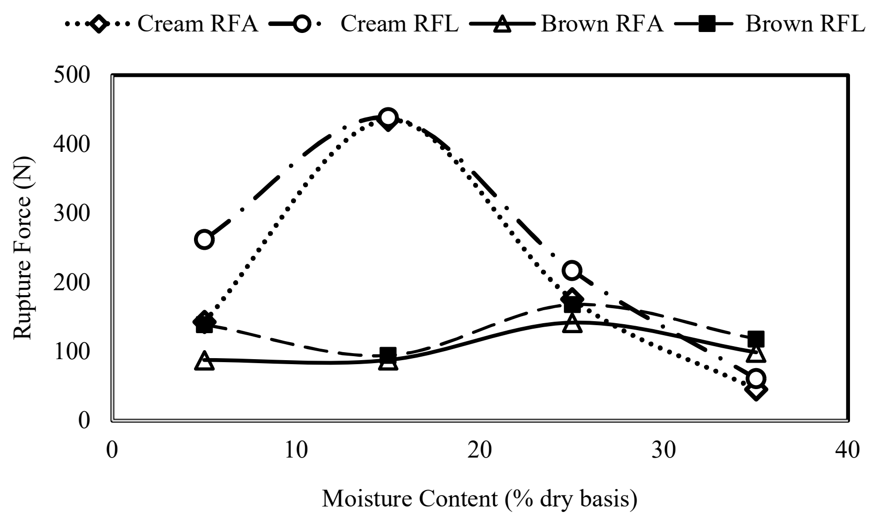

Figure 1: Rupture Force of Bambara Groundnut Seeds

Note: Cream RFA= rupture force in axial loading direction for cream variety; Cream RFL= rupture force in longitudinal loading direction for cream variety; Brown RFA= rupture force in axial loading direction for light brown variety; Brown RFL= rupture force in longitudinal loading direction for light brown variety.

Deformation at Rupture

Variations in deformation of Bambara groundnut seeds at rupture with moisture content for cream and light brown varieties are presented in Figure2. Deformation at rupture initially increased and later decreased with increasing moisture content for both varieties. Increase in deformation of the seeds before rupture point at higher moisture content could be attributed to the increased visco-elasticity of the seeds. The seeds became softer at higher moisture level and tends to flatten under the compressive load without rupturing, resulting in increased deformation (Olaniyan and Oje, 2002).Similar findings have also beenreported for faba beans (Altuntas and Yildiz, 2007), soybean grain (Tavakoli*et al*., 2009)and barnyard millet grain and kernel (Singh *et al*., 2010).

Deformation at 15% moisture level was the highest (5.71 mm) while the least was obtained at 5% moisture level (0.83 mm) when loaded axially for cream variety. Deformation at 25% level was highest (5.12 mm) when loaded axially while the least (0.31 mm) was obtained at 5% moisture content when loaded longitudinally for light brown variety. The cream variety deformed more than the light brown variety under compressive loading. There was interplay of increasing and decreasing trends for the deformation at rupture along both orientations as moisture content increased. Effect of moisture content on themaximum deformation of the seeds before rupture along both loading orientations was significant ($p \leq 0.01$).

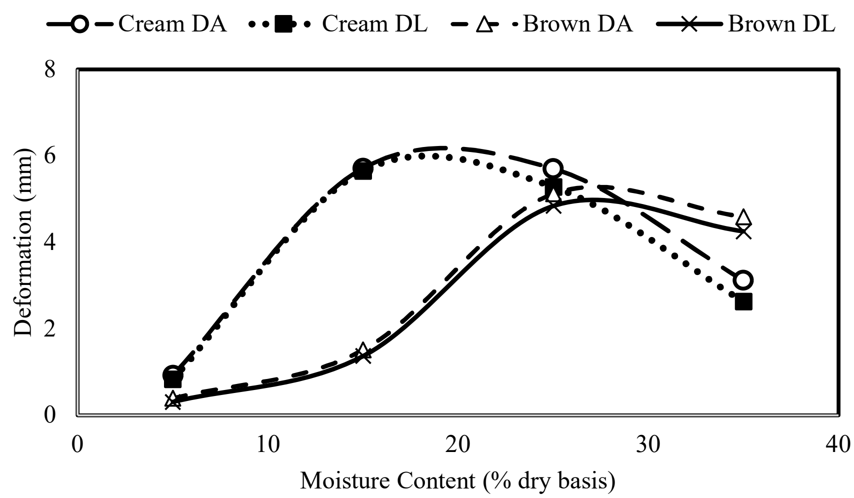

Figure 2: Deformation of Bambara Groundnut Seeds at Rupture

Cream DA=deformation in axial loading direction for cream variety; Cream DL= deformation in longitudinal loading direction for cream variety; Brown DA=deformation in axial loading direction for light brown variety; Brown DL= deformation in longitudinal loading direction for light brown variety.

Hardness of Seeds

Hardness is an important property which indicates the ability of the seeds to resist indentation. Variations in hardness of both varieties of BGN seedsat different moisture levels are as shown in Figure 3. Hardness of the seeds decreased with increase in moisture content from 155.65 to 14.61 Nmm^{-1} and 316.04 to 23.21 Nmm^{-1} for cream variety when loaded axially and longitudinally, respectively. Seed hardness decreased from 225.21 to 21.55 Nmm^{-1} and 448.55 to 27.89 Nmm^{-1} for light brown variety when loaded axially and longitudinally, respectively. Longitudinal loading had higher values for both varieties. Reduction in the ability to resist indentation or breakage under compressive loading at higher moisture content could be attributed to the fact that the seeds became softer and therefore, they were not able to withstand higher compressive load without rupturing. Moisture content of the seeds had a significant effect ($p \leq 0.01$) for both varieties when loaded axially and longitudinally. Similar trends were reported for shea nut (Olaniyan and Oje, 2002) and apricot pit (Vursavus and Özgüven, 2004).

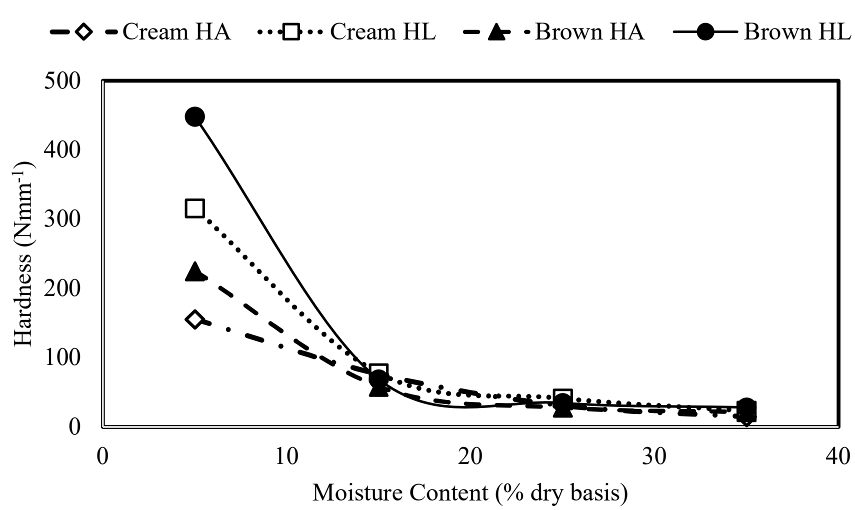

Figure 3: Hardness of Bambara Groundnut Seeds

Note: Cream HA = Hardness of cream variety in axial loading direction; Cream HL = Hardness of cream variety in longitudinal loading direction; Brown HA = Hardness of light brown variety in axial loading direction; Brown HL = Hardness of light brown variety in longitudinal loading direction.

Toughness of Seeds

Variationsin toughness of the seeds with moisture content are as presented in Figure 4 for both varieties. The relationship was sinusoidal in nature as toughness increased between 5 and 15% moisture content from 0.06 to 1.02 J and decreased to 0.08 J at 35% moisture content when loaded axially for the cream variety. When loaded longitudinally, toughnessincreased from 0.01 to 0.30 J as moisture level increased from 5 to 25% and it decreased to 0.02 J at 35% for the cream variety. Interplay of increasing and decreasing trends was also observed for light brown variety loaded along both orientations. This considerably low toughness of Bambara groundnut seeds may be attributed to the tenderness of the seeds at high moisture content levels with an attendant reduction in resistance to rupture or breakage under compressive loading and consequently, lower energy required in size reduction. This necessitates size reduction or milling of the seeds at high moisture content so as to minimise theenergy required. Contrary to the trends observed for toughness of BGN seeds in this study, increasing trend with increase in moisture content was observed for barnyard millet grain and kernel (Singh *et al*., 2010) and soybean grain(Tavakoli*et al*., 2009).The effect of moisture content on the toughness of the seeds when loaded axially was significant (p≤0.01)for both varietieswhile it was not significant (p≤0.01) when loaded longitudinally.

Predictive mathematical models established between the moisture content of Bambara groundnut seeds and the investigated mechanical properties for cream and light brown varieties are presented in Table 1.

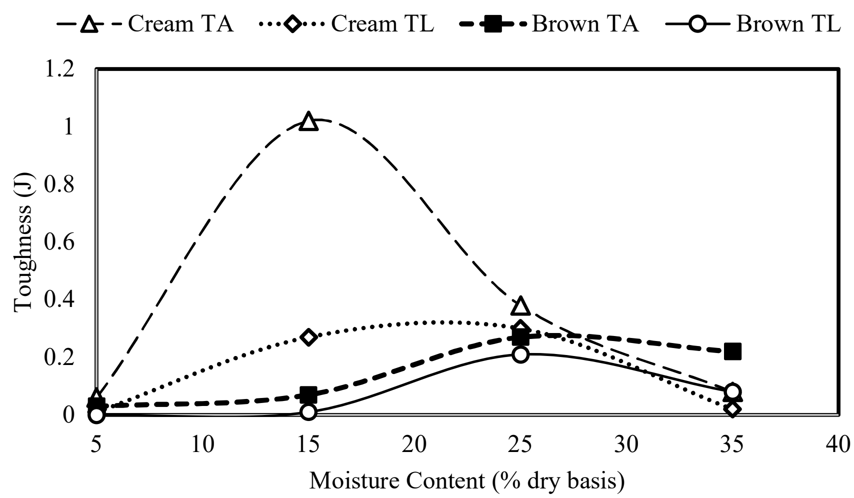

Figure 4: Toughness of Bambara Groundnut Seeds

Note: Cream TA = Toughness of cream variety in axial loading direction; Cream TL = Toughness of cream variety in longitudinal loading direction; Brown TA = Toughness of light brown variety in axial loading direction; Brown TL = Toughness of light brown variety in longitudinal loading direction.

Table 1: Relationships between mechanical properties and moisture content of the seeds

Variety	Mathematical models	R^2
Cream	$RF_a=-0.831M^2+25.02M+181.0$	0.852
	$RF_l=-1.056M^2+36.72M+19.97$	0.721
Light Brown	$RF_a=-0.025M^3+1.405M^2-19.910M+155.400$	1.000
	$RF_l=-0.040M^3+2.397M^2-39.351M+280.900$	1.000
Cream	$D_a=-0.018M^2+0.803M-2.522$	0.985
	$D_l=-0.019M^2+0.797M-2.544$	0.973
Light Brown	$D_a=0.152M-0.365$	0.808
	$D_l=-0.162M-0.339$	0.820
Cream	$H_a=-4.684M+163.0$	0.916
	$H_l=-9.149M+297.5$	0.751
Light Brown	$H_a=-6.414M+211.4$	0.743
	$H_l=-12.96M+404.2$	0.678
Cream	$T_a=-0.003M^2+0.120M-0.365$	0.687
	$T_l=-0.001M^2+0.054M-0.233$	0.995
Light Brown	$T_a=-0.000M^2+0.016M-0.068$	0.790
	$T_l=-0.000M^2+0.018M-0.109$	0.518

Note: RF_a = Rupture force along axial orientation; RF_l= Rupture force along longitudinal orientation; D_a = Deformation along axial orientation; D_l= Deformation along longitudinal orientation; H_a = Hardness along axial orientation; H_l= Hardness along longitudinal orientation; T_a = Toughness along axial orientation; T_l= Toughness along longitudinal orientation.

CONCLUSIONS

Selected mechanical properties of Bambara groundnut seeds namely rupture force, deformation at rupture, hardness and toughness under compressive loading were investigated in this study at four moisture levels and along longitudinal and axial orientations. Rupture force, deformation, hardness and toughness of the seeds rangedbetween 45.58 and 438.55 N, 0.31 and 5.71 mm,14.61 and 448.55 Nmm^{-1}, 0.01 and 1.02J, respectively. Rupture force, deformation and toughness of the seeds had interplay of increasing and deceasing trends while hardness decreased consistently as moisture content increased for samples loaded along both orientations.Level of moisture content and loading orientation had significant effects on the mechanical properties investigated for both varieties. Predictive mathematical models forestimating the investigated properties at different moisture contents with reasonable accuracy were also established in this study.The findings of this study will be useful in the development of processing and handling equipment for Bambara groundnutseeds.

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