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EFFECT OF MOISTURE CONTENTS AND COMPRESSION AXES ON SOME PHYSICAL AND MECHANICAL PROPERTIES OF *DIOCLEA REFLEXA* SEED

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ABSTRACT. Interest in unconventional seeds such as *Dioclea reflexa* is growing in the tropical regions, with the potential for utilisation as food or industrial materials. Researchers confirmed that *Dioclea reflexa* seed has the potential for clinical use, use as a food source, and as industrial raw material. This research studies the effect of moisture content on the physical properties of *Dioclea reflexa* seed and the effect of moisture content and compression axes its mechanical properties. Standards methods were used to determine the physical properties, while the mechanical properties were derived from force-deformation curves for the moisture content range 4.8 to 12.1% (wet basis). The mean values of the seed's length increased by 3.55% (from 31.01 mm), the width increased by 4.13% (from 26.64 mm), and the thickness decreased by 2.48% (from 21.75 mm). The geometric mean diameter increased by 1.68%, surface area increased by 3.68%, sphericity decreased by 1.54% and individual seed mass increased by 10.46%. The physical properties exhibit linear relationships with moisture content. Rupture force increased by 75% (from 0.80 kN) for loading along the major axis; by 84% (from 0.72 kN) for the intermediate axis; and by 41% (from 0.78 kN) for the minor axis. Rupture energy increased from 0.18 J to 1.25 J for compression along the major axis, from 0.087 J to 0.43 J for the intermediate axis, and from 0.080 J to 0.18 J for the minor axis. The mechanical properties were found to be moisture content and loading orientation-dependent. Reducing moisture content reduced both the force and the energy required to rupture the seeds. The data generated will be useful in the design of processing machinery and storage facilities for the seeds.

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Keywords: Moisture content; linear dimension; loading orientation; rupture force; rupture energy.

INTRODUCTION

Interest in non-conventional edible and non-edible seeds is getting more attention in the tropical regions, because of their potential for utilisation as food or industrial raw materials (Ogunsina *et al.*, 2016). One such seed is *Dioclea reflexa* seed. The species *Dioclea reflexa* hook F. belongs to leguminous plants, which include the legume, pea and bean families. The range of its habitat is the tropical region of Africa and South America. It is an annual crop and a climber that can be cultivated more than once a year (Iliemene and Atawodi, 2014). Researchers established the potential usefulness of *Dioclea reflexa* seeds in clinical applications because of their medicinal properties, including antioxidant and inflammation activities, which have been exploited to treat a number of diseases with extremely impressive outcomes (Oladimeji *et al.*, 2018; Arthur *et al.*, 2019; Ajayi, 2014). Its potential as a food source, for both humans and livestock, and as industrial raw material has been scientifically demonstrated (Ajatta *et al.*, 2019; Ajayi, 2014; Faleye, 2012; Yusuf and Lasisi, 2006).

The physical properties of seeds are important, with regards to their processing for food and industrial products. It has been established that the moisture contents of agricultural materials have a profound effect on both the physical and mechanical properties of such materials (Dobrzański and Stępniewski, 2013; Aviara *et al.*, 2013). According to Ahangarnezhad *et al.* (2019), the physical and mechanical properties of agricultural products are the most relevant parameters in the design of processing machines for their transportation, sorting, separation, processing and storing. The moisture-dependent physical properties of biological materials include size, shape, mass, bulk density, true density, and the coefficient of static friction of the material against various surfaces (Mohsenin, 1986).

The literature reveals that physical and mechanical properties have been studied for various conventional and non-conventional seeds, such as Cowpea (*Vigna unguiculata*) (Adanu *et al.*, 2022), Cashew nut (*Anacardium occidentale* L.) (Sudaryanto *et al.*, 2022*)*, Soybean (*Glycine max* L.*)* (Ahmad *et al.*, 2021), Tiger nut (*Cyperus esculentus*) (Emurigho *et al.*, 2020; Ince *et al.*, 2017), Quinoa seeds (*Chenopodium quinoa*) (Jan *et al.*, 2019), Pea seeds (*Pisum sativum* L.) (Mahawar *et al.*, 2018), and Mung beans (*Vignaradiata L.*) (Inekwe *et al.*, 2019).

Despite the established evidence from the literature as to the usefulness of *Dioclea reflexa* seeds as food, as well as in the medicinal and biochemical fields, there is little or no information about its physical or engineering properties. In designing machines for the harvest, storage, transportation, processing and packaging of agricultural materials, knowledge of their physical and mechanical properties are important machine design parameters (Jahanbakhshi *et al.*, 2019; Stopa *et al.*, 2018). Moisture content, loading direction and variety are the main factors influencing the physical and mechanical properties of agricultural materials (Su *et al.*, 2019). Evaluating the effects of the moisture content of *Dioclea reflexa* seeds on their physical properties, and the combined effect of seed orientation and moisture content on their mechanical properties, is of great importance when designing and building the machinery and equipment needed for processing them at an industrial scale. Therefore, the aims of this study were: (i) to determine the effect of moisture content on the physical properties of *Dioclea reflexa* seeds and (ii) to determine the effect of both the moisture content and seed orientation in compression testing on the mechanical properties of *Dioclea reflexa* seeds.

MATERIALS AND METHODS

The seeds used in this research were obtained from a farm in Ile-Oluji (7.170° N, 4.726° E), a rural community in Ondo state, Nigeria, during the rainy season in the year 2022. The rainy season spans the months of March to September. The soil in this environment is characteristic of clay loam (Nkwunonwo *et al.*, 2020). The moisture content of the *Dioclea reflexa* seeds used in this study was determined by the oven drying method, as specified by the Association of Officiating Agricultural Chemists-AOAC (2016). Because the seeds were collected at the peak of the rainy season (July 2022; average precipitation: 259.91 mm) and the seeds were likely to be at their maximum natural moisture content level, it was decided to vary the moisture content by drying the seeds. The seeds were dried in an oven (MINO/75, Genlab classic oven, Widnes, UK) set at temperature 80±0.75°C until the desired moisture content was reached, based on *Eq. (1)* (Aremu and Ogunlade, 2016).

$$B = \frac{A(100 - a)}{(100 - b)} \tag{1}$$

where *B* is the final mass of the sample after drying, in kg; *A* is the initial mass of the sample, in kg; *a* is the initial moisture content of the sample, in % (wet basis, w.b.); and *b* is the desired moisture content of the sample, in % (w.b.). Four moisture content levels (4.8, 7.2, 9.5, and 12.1% w.b.) were established for the seeds using this method. These values are within the normal values for the seed in post-harvest storage.

Determination of physical properties

In order to determine the physical properties of *Dioclea reflexa* seed, three linear dimensions were defined for the seed, as shown in *Figure 1a*. These are the length L (mm), width W (mm) and thickness T (mm). Twenty seeds were randomly selected at each of the pre-determined moisture contents and the individual seeds' linear dimensions were measured using a digital Vernier caliper (Syntek Digital caliper, Model B016), with an accuracy of 0.01 mm (*Figure 1b*). From these measurements, the geometric mean diameter (D_g) was determined for each individual seed using *Eq. (2)* (Altuntas and Mahawar, 2022; Mohsenin, 1986).

$$D_g = (LWT)^{1/3} \; [mm]) \tag{2}$$

Sphericity is the measure of the degree of roundness of the seed. The shape with the maximum value of sphericity is the sphere with a sphericity value of 1. Sphericity (ϕ) was determined using *Eq. (3)* (Jahanbakhshi *et al.*, 2019; Mohsenin, 1986).

$$\phi = \frac{D_g}{L} X \, 100 \;\; [\%] \tag{3}$$

The surface area (S) of *Dioclea reflexa* seed was found by approximating with a sphere of the same geometric mean diameter, using *Eq. (4)* (Jahanbakhshi *et al.*, 2019; Mohsenin, 1986).

$$S = \pi(\mathrm{D_g})^2 \;\; [mm^2] \; \pi \tag{4}$$

π was assumed to be 3.142. The individual seed mass, for each sample containing twenty randomly selected seeds, was measured at each moisture level using an electronic balance (Ohaus Corp, Pine Brook, NJ, USA) with a readability of 0.0001 g.

Determination of mechanical properties

Determination of the mechanical properties of seeds and grains was usually obtained by analysing the force-deformation curve obtained from compression testing (Dobrzański and Stępniewski, 2013). Using the American Society of Agricultural and Biological Engineers -ASAE S368.4 (ASAE, 2008) publication as a guide, uniaxial quasi-static compression tests were carried out on the seeds using the Hydraulic Universal Tensile Testing Machine (Model HD-620, Haida International, Donguan City, China). To investigate the effect of moisture content and loading direction on mechanical properties, a full 4 by 3 factorial design (4 moisture content levels x 3 loading axes) was replicated 10 times. Specifically, seeds were conditioned to four levels of moisture content, with 10 seeds at each moisture content level loaded in the X-direction (major axis), 10 in the Y-direction (intermediate axis), and 10 in the Z-direction (minor axis) (see *Figure 1a* and *Figure 2a(ii-iv)*).

The individual seeds were placed on the base platen of the Universal Testing Machine and pressed by the downward movement of the top platen, as shown in *Figure 2a(i)*, until cracking occurred, as denoted by a rupture point in the force-deformation curve.

For loading along the x and y axes, seeds were propped up in the desired orientation on the lower platen, until the upper platen held it in a grip to prevent it from rolling over into its natural pose on a flat surface. This was achieved by wedging the seed into a cut made at one end of a thick strip of polyethylene foam, which extended safely out of the compression zone of the machine. Once a firm grip of the platens had been observed on the seed, the strip was slowly pulled away, freeing the seed as the compression process continued.

The experiments were carried out at a loading rate of 0.1 kN/sec for all levels of moisture content. Rupture (cracking) force (N) and deformation at the rupture point (mm) were measured for each orientation of the seed on the testing machine. The energy absorbed by the sample at the rupture point was determined by calculating the area under the force–deformation curve up to the rupture point. A typical force-deformation curve for the seed was plotted by the Universal Testing Machine and is depicted in *Figure 2b*.

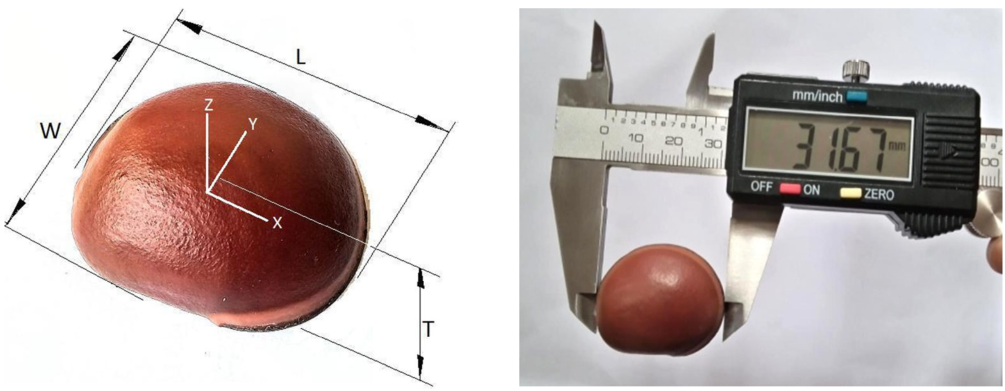


Figure 1 - (a) Representation of the three perpendicular dimensions of *Dioclea reflexa* seed. (b) Dimensional seed measurement with Vernier caliper

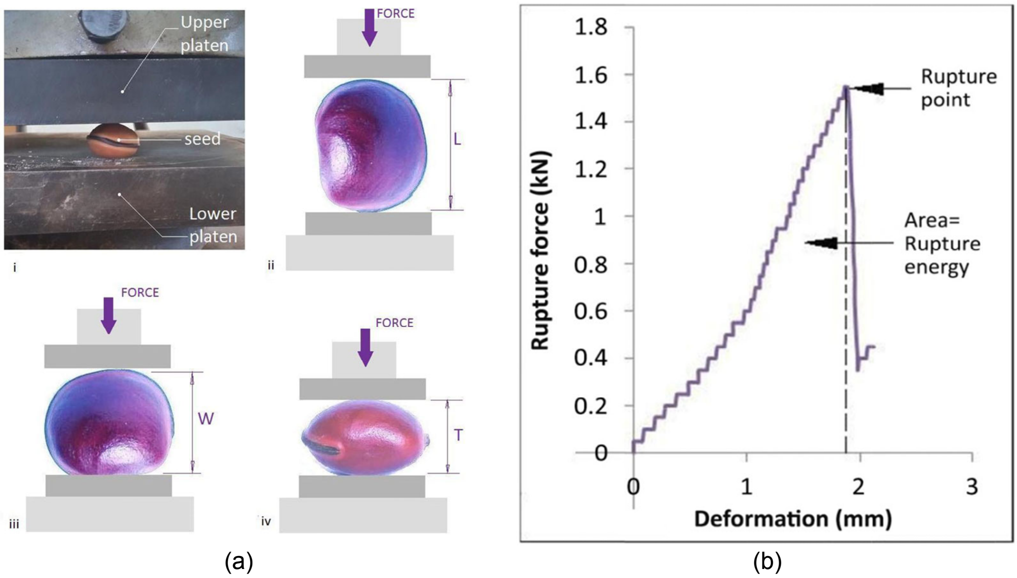


Figure 2 - (a) (i) Compression of *Dioclea reflexa* seeds on Universal Testing Machine. (ii) Orientation of seed for compression along the Major axis (iii), along the Intermediate axis (iv) and along the Minor axis. (b) A sample of an experimental force-deformation curve of *Dioclea reflexa* seed (compression along major axis)

Statistical analysis

Graphs describing the relationship between each property and moisture content were plotted and regression equations generated. Data were presented as mean ± SD (Standard Deviation). All the data obtained were subjected to analysis of variance and the means were separated using Duncan multiple range tests at 5% probability level, using SPSS software version 21. The Duncan test is commonly used in agriculturally related research.

RESULTS AND DISCUSSION

Physical properties

The mean and standard deviation of seed length, width, thickness, geometric mean diameter, surface area, sphericity, and individual seed mass, are presented in *Table 1*. The initial moisture content of the seeds was 12.1% (w.b.). The four levels of moisture content were 4.8, 7.2, 9.5 and 12.1% (w.b.). The relationship between moisture content and each of the measured physical properties are presented in *Table 2*. It was observed that all of the physical properties studied exhibited a linear relationship within the moisture content range 4.5 to 12.1%. The mean length values increased by 3.55% (from 31.01 mm), width increased by 4.13% (from 26.64 mm), and thickness decreased by 2.48% (from 21.75 mm). Also, geometric mean diameter increased by 1.68% (from 26.18 mm), mean surface area increased by 3.68% (from 2155.51 mm^2), mean sphericity decreased by 1.54% (from 84.41%), and mean individual seed mass increased by 10.46% (from 7.75 g), for the moisture range 4.5 to 12.1%. The approximate proportion of the thickness (T), width (W), and length (L) of *Dioclea reflexa* seed is 5:6:7.

Table 1- Physical properties of *Dioclea reflexa* seeds †

Physical properties	Moisture content (% w.b.)			
	4.8	7.2	9.5	12.1
Length, mm	31.01 (1.45)[d]*	31.45 (1.34)[b]	31.77 (1.54)[b]	32.11 (2.17)[a]
Width, mm	26.64 (1.24)[d]	26.85 (0.83)[b]	27.68 (1.36)[a]	27.74 (1.93)[a]
Thickness, mm	21.75 (0.89)[c]	21.7 (1.07)[b]	21.395 (1.13)[b]	21.21 (1.30)[a]
Geometric mean diameter, mm	26.18 (0.88)[d]	26.36 (0.80)[b]	26.58 (1.01)[b]	26.62 (1.45)[a]
Sphericity, %	84.41 (2.10)[d]	083.93 (2.69)[b]	84.01 (3.14)[b]	83.11 (2.13)[a]
Surface area, mm^2	2155.51 (143.94)[c]	2184.17 (133.94)[b]	2223.71 (170.15)[d]	2234.90 (260.43)[a]
Mass, g	7.75 (0.72)[d]	7.95 (0.76)[c]	8.25 (0.85)[b]	8.55 (0.89)[a]

† Measurement was made with 20 replicates. *Numbers in parenthesis are standard deviations. Means with the same superscripts within the same row are significantly different (p< 0.05).

Table 2 - Regression equations obtained for the physical properties of *Dioclea reflexa* seeds in the moisture content range 4.8 to 12.1% (w.b.)

Property	Equation	R^2
Length (mm)	L = 0.1488Mc + 30.334	0.993
Width (mm)	W = 0.1694Mc + 25.805	0.880
Thickness (mm)	T = -0.0795Mc + 22.181	0.940
Geometric mean diameter (mm)	Dg = 0.0625Mc + 25.909	0.925
Surface area (mm^2)	S = 11.413Mc + 2103.7	0.952
Sphericity	ф = -0.002Mc + 0.854	0.997
Mass (g)	m = 0.1116Mc + 7.1875	0.993

R^2: Determination coefficient

Analysis revealed that the effects of the moisture content on the physical properties studied were found to be significant ($p < 0.05$).

These observations indicate that, as the moisture content increases, there is an overall increase in the physical size of the seeds for the moisture content range, despite the fact that the seed thickness decreases accordingly. However, the combined effect of the increases in length and width balance the decreasing effect of the width, as moisture content increases with the other physical parameters (i.e. surface area and mean geometric diameter) except sphericity, which also decreases with the increase in moisture content. Drying the seed increases its roundness for the moisture range investigated. As seeds absorb moisture, they tend to swell; when they lose moisture, they tend to shrink in size and weight. This may be an underlying factor in the observed trends. Similar trends for length, width, mean geometric diameter, surface area, and individual seed mass were also observed for Soybean (*Glycine max* L.*)* (Ahmad *et al.*, 2021), Tiger nut (*Cyperus esculentus*) (Wang *et al.*, 2021; Ince *et al.*, 2017), Mung Bean (*Vignaradiata L.*) (Inekwe *et al.*, 2019), and *Jatropha curcas* (Bamgboye and Adebayo, 2012). However, Ide *et al.* (2019) reported that the aspect ratio, sphericity and harmonic mean diameter of *Mucuna sloanei* seeds decreased as the moisture content increased, while Ahmad *et al.* (2021) reported a decrease in sphericity with an increase in moisture content of Soybean. The data obtained for the physical properties will be useful in the designing of machines for sorting, conveying and processing *Dioclea reflexa* seeds, as well as in the design of its storage facilities.

Mechanical properties

Figures 3a and *3b* describe the relationship between rupture force/energy and moisture content during compression testing of the *Dioclea reflexa* seeds for the three seed orientations and moisture content ranges.

The general trend is an increase in both the rupture force and rupture energy as moisture content increases. Relatively higher rupture force and energy was consistently observed during compression along the major axis, when compared with the other two axes. More specifically, mean rupture force increased by 75% (from 0.80 kN) for loading along the major axis; by 84% (from 0.72 kN) for loading along the intermediate axis; and by 41% (from 0.78 kN) for loading along the minor axis, when moisture content increased from 4.8 to 12.1% (w.b.). Similarly, there is an increase in mean rupture energy, from 0.18 J to 1.25 J for compression along the major axis; from 0.087 J to 0.43 J for compression along the intermediate axis; and from 0.080 J to 0.18 J for compression along the minor axis, when moisture content increased from 4.8 to 12.1% (w.b.).

The mathematical expressions for the relationship between rupture force/energy and moisture content (for the moisture range 4.8 to 12.1% w.b.) are given in *Eqs. (5-10)*, where $F_{RL,}$ $F_{Rw,}$ and $F_{Rt,}$ are rupture forces along the major, intermediate and minor axes, respectively. $E_{RL,}$ $E_{Rw,}$ and E_{RT} are the rupture energies for the major, intermediate and minor axes, respectively. Compared to the physical properties, the rupture force and energy variation with moisture content was not linear but polynomial in nature. Statistical analysis indicated that the rupture force and energy along the three axes and the moisture levels differed significantly ($p < 0.05$); therefore, both seed orientation and moisture content has an effect on rupture force and energy.

Similar trends in rupture force, as moisture content increases, were reported for Cashew nuts (*Anacardium occidentale*) (Ogunsina and Bamgboye, 2013), Dika nuts (*Irvingia sp.*) (Ogunsina *et al.,* 2008) and *Mucuna sloanei* seeds, under vertical loading (Ide *et al.*, 2019). The reason for this may be due to the fact that, as the moisture content increases, the seed cotyledon tends to be more rubbery and expands against the seed coat, thus delaying the fracture of the seed coat. However, when dried, the cotyledon shrank and became more brittle and easier to fracture. In contrast, rupture force decreases as moisture content increases for raphia palm kernels (*Raphia farinifera*) (Dauda *et al.*, 2019), mucuna beans (*Mucuna crens*) (Etim et al., 2021) and *Mucuna sloanei* seeds in horizontal loading (Ide *et al.*, 2019).

$F_{RL} = 0.0049\ M_C{}^2 + 0.0058\ M_C + 0.6366$ $R^2 = 0.956$ (5)

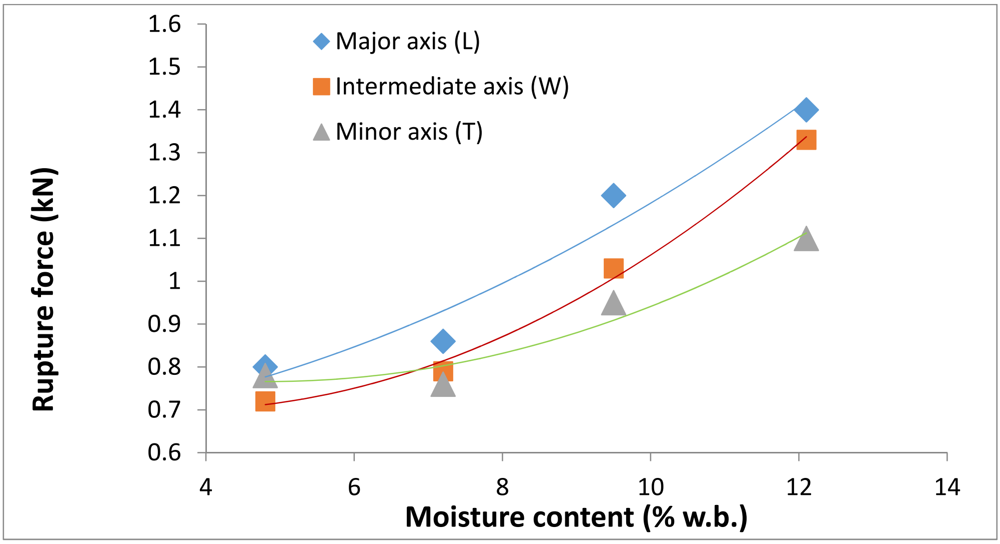
$F_{RW} = 0.0088\ M_C{}^2 - 0.0632\ M_C + 0.8124$ $R^2 = 0.995$ (6)

$F_{RT} = 0.0066\ M_C{}^2 - 0.0634\ M_C + 0.9191$ $R^2 = 0.949$ (7)

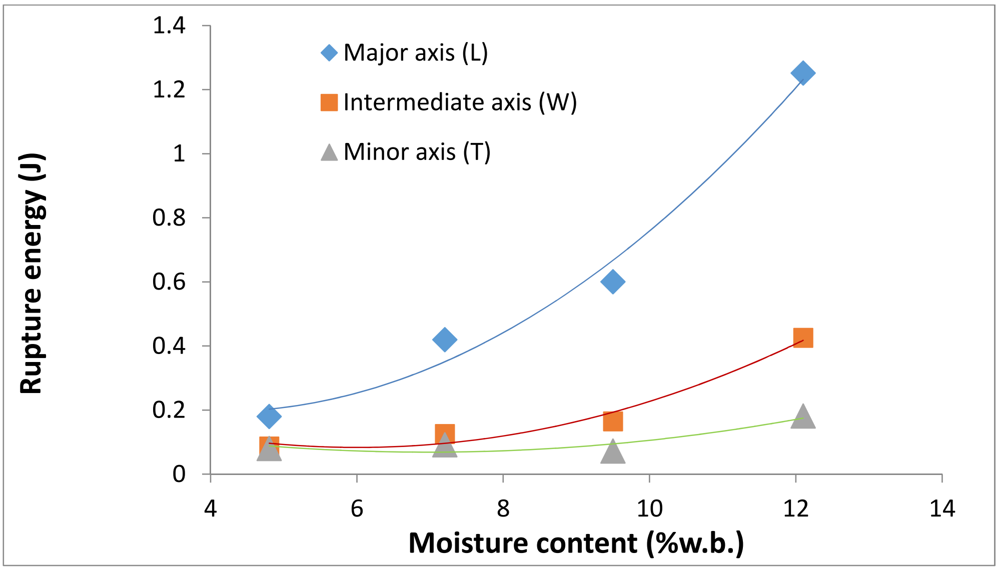
$E_{RL} = 0.0162\ M_C{}^2 - 0.1329\ M_C + 0.4672$ $R^2 = 0.984$ (8)

$E_{RW} = 0.009\ M_C{}^2 - 0.1081\ M_C + 0.4082$ $R^2 = 0.974$ (9)

$E_{RT} = 0.004\ M_C{}^2 - 0.0565\ M_C + 0.2657$ $R^2 = 0.856$ (10)



(a)



(b)

Figure 3 - (a) Relationship between rupture force and moisture content.
(b) Relationship between rupture energy and moisture content

CONCLUSIONS

This study is limited to investigating the effect of moisture content on the physical properties and its combined effect with compression axes on the mechanical properties of *dioclea reflexa* seeds. The moisture range was 4.8 to 12.1% (w.b.). The findings derived from the study will be useful in designing processing machinery for the seed. The following conclusions were reached by this study:

(i) Moisture content has an effect on the physical dimensions of *Dioclea reflexa* seeds. For an increase in moisture content, from 4.8 to 12.1% (w.b.), the mean values of the linear dimensions of the seed increased by 3.55% (length) and 4.13% (thickness) and decreased by 2.48% (width). This corroborates the trends observed and the results obtained for various agricultural materials under similar studies in the literature review. This information will be useful in designing sorting, grading and conveyance equipment.

(ii) Geometric mean diameter increased by 1.68%, surface area increased by 3.68, and sphericity decreased by 1.54. Unlike length and width, which increased linearly with an increase in the seeds' moisture content, the thickness decreased linearly as moisture content decreased. This has an influence on sphericity, as sphericity also increased with a decrease in moisture content.

(iii) Individual seed mass increased by 10.46%, as moisture content increased from 4.8 to 12.1% (w.b.). This has implications for conveyor capacity and the produce storage requirements.

Rupture force increased by 75% (from 0.80 kN) for loading along the major axis; by 84% (from 0.72 kN) for the intermediate axis; and by 41% (from 0.78 kN) for the minor axis. Rupture energy increased from 0.18 J to 1.25 J under compression along the major axis, from 0.087 J to 0.43 J along the intermediate axis, and from 0.080 J to 0.18 J along the minor axis. Thus, reducing the moisture content also leads to a reduction in the force and energy required to rupture the seeds. This data is useful in determining the power rating for machines designed for processing the seeds.

Author Contributions: conceptualisation (OO), methodology (OO), analysis (OO, EIA), investigation (OO, SO), resources (OO), data curation (EIA, SO), writing (OO, EIA), review (OO, EIA), supervision (OO).
All authors declare that they have read and approved the publication of the manuscript in its present form.

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