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Moisture – Influenced friction properties of ackee apple (*Blighia sapida*) seeds

Olajide Ayodele Sadiku, David Omogunsoye*

Department of Agronomy, Faculty of Agriculture, University of Ibadan, Ibadan, Oyo State, Nigeria

**Corresponding author: olajidesadiku@yahoo.com, oa.sadiku@mail.ui.edu.ng*

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Abstract: The friction properties of ackee apple (*Blighia sapida*) seeds at an 11.9, 17, 22, 27, and 32% (w.b.) seed moisture were determined, which are vital for designing their processing techniques and equipment to replace the present manual methods. The ackee apple grows in many West African countries, especially Nigeria. The ackee seeds were harvested at Lanlate, Oyo State, Nigeria, where ackee trees are predominant. Standard experimental methods were adopted to determine the properties. The data were analysed using an ANOVA and the least significant difference (LSD) at $P \leq 0.05$. As the moisture increased, the static coefficient of friction on glass (27.6–36.4^0), aluminium (27.0–30.2), polyvinyl chloride (PVC; 27.9–32.8) surfaces and normal stress at 200 g (8.73–8.93 g·cm^{-2}), 300 g (11.65–11.79 g·cm^{-2}) and 400 g (14.37–14.65) loads increased significantly and linearly. The shear stress linearly decreased at a 200 g load (1.62–1.25 g·cm^{-2}), but was non-significant at the 300 and 400 g loads. The coefficient of internal friction linearly decreased (0.744–0.588) implying that the wet seeds flow more easily than the dry ones, which should be considered in designing conveyors. The relationships between the ackee seeds' moisture and friction properties were expressed with regression models. Data for designing the handling techniques and machines for the ackee seeds were obtained.

Key words: machine; technique; data; processing; shear stress

Blighia sapida, commonly called the ackee apple is an evergreen, multipurpose fruit tree hailing from the *Sapindaceae* family. It is native to Jamaica and tropical West African countries, especially Nigeria, and grows in the wild in the humid areas of Nigeria's groecological zone. In Nigeria, it is underutilised, but has an economic potential. The ackee is propagated by seeds, cuttings or grafting in some countries like Jamaica, the Republic of Benin and Guinea. It can bear fruit all year round, but produces the most between December and May. The study by (Omosuli 2014) affirmed that 7.5 to 10 cm long fruits (with lipids) are produced by the tree throughout the year with peak periods in January–March and June–August. According to Olorode (1984), the fruit looks like a fleshy capsule having three valves. At full maturity and ripeness, the fruit splits open to show three black seeds attached to cream-coloured arils. The mature arils are eaten fresh or cooked as a meat substitute. It has been reported that nausea, vomiting and stomach aches have been found to be treatable with ackee seeds (Figure 1) in traditional medicine. Also, the seeds' extract can be used to dispel parasites while both the fruit capsule and seeds are useful in soap making and fishing (Ekue et al. 2009). In addition, the seeds' extract has been discovered to possess an adsorption ability, thus it is useful in removing the "Congo red dye" from aqueous solutions (Bello et al. 2012). In their findings, Onuekwusi et al. (2014) stated that the oil extracted from ackee seeds may find use in the production of therapeutic agents and industrial oils. Furthermore, the seeds are presently under consideration as a potential biofuel source. If the economic benefits and potential of ackee seeds will be tapped and commercialised, the seeds' handling and processing must be mechanised, but hitherto, this has only been performed manually in a cumbersome way at all levels, especially

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Figure 1. Dried ackee apple seeds after removal of the aril

in Nigeria. This calls for and justifies the determination of the friction properties of ackee seeds which would help to generate the data required to develop handling techniques and process line machinery. The behaviour of ackee seeds can also be determined, especially during the handling and processing using such knowledge.

For example, frictional properties like the angle of repose and static coefficient of friction are important in designing storage structures whose use is affected by the compression ability and flow characteristics of the seeds, designing seed conveyors, and the choice of materials for the various designs. Mechanical properties, like normal and shear stresses, are important in determining the lateral pressure a seed bulk can exert on the walls of the storage equipment which, in turn, dictates the strength of the material to be chosen for the storage device. The study by Andrejko and Kaminska (2005) reported that vital changes occur in the structure of agricultural materials during dehydration or hydration. These changes are peculiar to seeds with a high moisture level. Researchers have examined the effect of seed moisture on friction properties of seeds or grains and recorded diverse results. One such study is by Onwe et al. (2020), where they worked on two varieties of African star apple seeds (Udara and Nwannu) within a 3–18.03% moisture range and recorded that the moisture had a significant effect on all the studied frictional properties of both varieties of the seeds at $P \leq 0.05$. They further stated in their work that the coefficient of static friction was higher on all the surfaces for the Nwannu seeds than for Udara seeds. Togo et al. (2018) investigated alfalfa seeds under seven moisture levels (7.98–22.12% d.b.). They reported a significant seed moisture effect on the investigated friction properties: the plywood surface had the highest coefficient of static friction value, followed by polished steel, rubber and then glass. The coefficient of internal friction decreased and the angle of repose resulted in a non-linear increase as the moisture content increased. As part of their work, Grewal and Singh (2016) evaluated the moisture effect on the angle of repose of two varieties of mustard seeds in the range of a 6–18% moisture content. They recorded a significant increase in the angle of repose for both varieties of mustard seeds. For chard seeds, Ozbakir et al. (2013) reported a significant increase in the angle of repose and static coefficient of friction (on steel, plywood, glass, wood and galvanised sheet metal) as the moisture increased from a 14.1 to 22.2% d.b. Seifi and Alimardani (2010) also reported that the moisture had a significant influence on the friction properties of sunflower seeds in the range of a 4–22% wet basis. According to the authors, the angle of repose increased and the coefficient of static friction increased linearly against the plastic, plywood and galvanised iron with an increasing moisture content.

The processing of ackee seeds causes seed moisture changes either by drying or by washing which definitely results in the seeds' internal structural changes that may affect the properties of the seeds. This phenomenon would surely influence the behavioural trends of the seeds. Furthermore, until now, there is insufficient knowledge of the behavioural response of ackee seeds to moisture changes especially in their friction properties. Though the study of engineering properties of seeds is large in general, this work is focused on investigating the influence of the seed moisture content on the friction properties of ackee seeds as an effort to bridge the earlier stated knowledge gap.

METHODS

Preparation of the sample. The sample collection was undertaken at Lanlate, Oyo State, (7°36'0" N, 3°27'0" E) Nigeria, where ackee trees are predominant. The clean and whole seeds were picked from the lot collected and thereafter dried under some shade with ambient air. The bulk dried seeds were divided into five equal weights. Afterwards the seed moisture content was determined using the oven-drying method, at 103 ± 1 °C for 72 h as recommended by the American Society of Agricultural Engineers (ASAE 2001). To prepare the samples at the

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desired seed moisture levels, calculated amounts of distilled water, as shown in Equation (1), were mixed with the seed samples.

$$M_w = \frac{M_s\left(Mc_f - Mc_i\right)}{100 - Mc_f} \quad (1)$$

where: M_w – quantity of the water added (g); M_s – initial sample mass (g); Mc_f – final seed moisture (w.b.); Mc_i – initial seed moisture in (w.b.).

One of the sample lots was left without any addition of water to retain the moisture content level after drying. Each sample lot was packed in bags made of polythene for the preservation of the seed moisture content. The five bulk samples were refrigerated at 5 °C for 120 h according to Davies and Mohammed (2014) and Nalbandi et al. (2010) to obtain an effective moisture distribution within each bulk sample. For all the experiments, the required seed quantity was taken from each refrigerated bulk sample and left to attain equilibrium at room temperature.

Coefficient of static friction. For the ackee seeds, this property was determined on aluminium, galvanised sheet, glass, PVC and plywood surfaces materials. Each surface material was set on a flat and plain surface that could tilt (be inclined). It was designed and constructed with polished wood for the purpose of the experiment. A hollow and open-ended 50 × 50 mm (diameter and height) plastic cylinder was placed on the surface material to be tested. Filling it with seed sample, the cylinder was gently raised to a height of 5 mm above the surface material so that it did not touch the test surface. The inclined polished wood surface was raised gradually with a screw device to the point where the movement of the seeds caused the cylinder to start sliding. The ackee seeds, tightly filling the cylinder, held the cylinder in place till sliding occurred. At the sliding point, the angle of the inclined surface was recorded and its tangent is the coefficient of static friction (Nalbandi et al. 2010).

Dynamic angle of repose. The dynamic angle of repose is the angle a pile of seeds or grains would make relative to the horizontal when the seeds poured.

This experiment was performed with a hollow and open-ended 15 × 25 cm (diameter and height) cylinder placed on a smooth and wide circular tray. Filled with ackee seeds, it was slowly raised until the seeds formed a conical pile on the tray. The base and height of the cone were measured to calculate the angle of repose per Equation (2) (Onwe et al. 2020). The experiment was in five replications.

$$\Theta_r = \tan^{-1}\left(\frac{2Y}{X}\right) \quad (2)$$

where: Y –the height of the seed cone (cm); X – diameter of the seed cone (cm); Θ_r – the repose angle.

Coefficient of internal friction. This is the seed-to-seed friction within the seed bulk as described by (Irtwange 2000). A 7 × 5 × 5 cm cardboard cell was placed on a 11 × 9 × 5 cm cardboard guide frame and was filled with ackee seeds. A cord was tied to the cell, which was passed over a frictionless pulley and finally tied to an empty pan. A weight (w_2) was placed in the pan (taken as the force) to just slide the filled cell. Afterwards, the cell was emptied and a weight (w_1) was placed in the pan (taken as the force) to slide the empty cell over the guide frame. Hence, the coefficient of internal friction was determined using Equation (3):

$$C_{if} = \frac{\left(W_2 - W_1\right)}{W} \quad (3)$$

where: C_{if} – coefficient of internal friction; W_2 – the weight (force) needed to slide the filled cell over the filled frame; W_1 – the weight (force) needed to slide the empty cell over the filled frame; W – weight of the ackee seeds in the cell [volume of the cell (cm^3) × bulk density of the ackee seed ($g{\cdot}cm^3$)].

Angle of internal friction. This was determined using Equation (4).

$$\theta_{if} = \tan^{-1} C_{if} \quad (4)$$

where: θ_{if} – angle of internal friction (°); C_{if} – coefficient of internal friction.

The experiment was replicated five times for each ackee seed bulk sample.

Normal and shear stresses. The experimental set up to determine the shear (τ) and normal (σ) stresses is similar to that described above for the Coefficient of internal friction except for the normal load placed on the cell. The measurements taken individually for the 200, 300 and 400 g loads per each sample were recorded. The experiment was replicated three times for each seed bulk sample, Equation (5) was used to calculate normal stress ($g{\cdot}cm^2$).

$$\sigma = \frac{\left(W_3 + W_4\right)}{A - \rho h} \quad (5)$$

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where: W_3 – weight or force to pull the filled cell (g); W_4 – weight or force to pull the filled cell plus the normal load on the cell (g); A – area of the cell (cm^2); h – height of the sample materials in the cell (cm); ρ – density of the sample materials (g·cm^{-3}); (Irtwange 2000).

The shear stress (τ) is calculated using Equation (6).

$$\tau = \frac{\left[W_5\left(1-W\right)\right]}{A} \tag{6}$$

where: W_5 – (weight or force needed to slide the filled cell with load – weight or force needed to slide the empty cell) (g); W – friction coefficient of the pulley (Irtwange 2000).

RESULTS AND DISCUSSION

Coefficient of static friction. The force parallel to two opposing surfaces that is stationary is referred to as static friction. To initiate movement in a stationary object, enough force must be applied to overcome the static friction which is holding it still. The ANOVA results in Table 1 reveal that the influence of the increased ackee seed moisture on its coefficient of static friction was statistically significant at a 5% probability level on the glass, PVC and aluminium, but not on the plywood and galvanised iron. An increase in the static coefficient of friction, therefore, means that different and higher amounts of force would be required to initiate the flow of the ackee seeds on the glass, PVC and aluminium surfaces at the different seed moisture levels (i.e., as the seeds become moister). The linear rise in the coefficient of static friction of the ackee seeds on the glass, aluminium and PVC implies that a commensurate rise in the coefficient of static friction will occur with an increase in the moisture level to the seeds. It also means that the more moisture the seeds have, the higher the required force to move the seeds on both surfaces at each moisture level.

The non-significant effect of the ackee seeds' coefficient of static friction on the galvanised iron and plywood implies that a relative similar amount of force would be required to initiate the seed movement at all moisture levels. The reason for the increase in the coefficient of static friction as the moisture increases is the presence of a water film on the seed's coat. This causes cohesion between the seed coat surface and the test surface in addition to the weight due to the moisture-laden seed bulk. A similar result was reported by Onal et al. (2013) for the coefficient of static friction for bitter Gourd seeds, but the rubber surface was highest in their case. Obi and Offorha (2015) reported a similar result for melon seeds and kernels where the highest coefficient of static friction was recorded for plywood. The coefficient of static friction is needed in designing and constructing conveyors since it is static friction that holds the seeds to the conveyor surface and does not cause the seeds to slide backwards. In this regard, the highest coefficient of static friction for the ackee seeds was recorded on the galvanised iron (43.4), though not significantly. In contrast, the seed discharge does not need much static friction to affect the discharge process, for example, in designing hoppers and discharge spouts. Aluminium will suit this purpose, as the lowest static friction coefficient was recorded on aluminium for the ackee seeds. Therefore, the coefficient of static friction is also needed in selecting structural materials to design the machine components that have to do with the flow of the bulk granular materials. The relationship between the seed moisture (x) and coefficient of static friction of the ackee seeds (Y) on the material surfaces tested are shown in Equations (7–9).

Table 1. Static coefficient of friction of the ackee seeds at different moisture contents on five structural surfaces

Moisture content (%)	Static coefficient of friction in degrees (°)				
	aluminium	galvanised iron	glass	plywood	PVC
11.9	27.0	42.0	27.6	28.0	27.9
17.0	27.8	41.8	28.8	28.0	29.4
22.0	30.2	43.4	28.8	28.0	30.6
27.0	28.4	42.4	33.4	27.8	33.8
32.0	30.2	42.4	36.4	29.4	32.8
LSD	2.315*	NS	1.894*	NS	2.069*

*Significant at P = 0.05; PVC – polyvinyl chloride; NS – not significant; LSD – the least significant difference

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$$Y_{\text{aluminium}} = 0.1396x + 25.652 \quad R^2 = 0.5923 \tag{7}$$

$$Y_{\text{Glass}} = 0.4418x + 21.289 \quad R^2 = 0.8759 \tag{8}$$

$$Y_{\text{PVC}} = 0.2829x + 24.681 \quad R^2 = 0.8636 \tag{9}$$

where: Y – static coefficient of friction on the different specified surfaces; x – seed moisture content; R^2 – the coefficient of determination.

The relationship trend between the seed moisture and the coefficient of static friction of the ackee seeds on the tested surfaces are also shown in Figure 2.

Coefficient of internal friction. The coefficient of internal friction is simply the friction between two grains. The results for the coefficient of internal friction of the ackee seeds (Table 2) show that an increase in the seed moisture resulted in a significant and linear decrease in the coefficient of internal friction (0.744 to 0.588). The highest value was recorded at an 11.9% moisture content. At higher moisture levels, the ackee apple seeds tend to be more slippery because of the smoothness and the wetness of the seed coat surface; hence, the ability to easily slide over one another which accounts for the decreasing coefficient of internal friction. Therefore, ackee seeds would flow more easily as their moisture content increases. In view of this, structural materials that have a high static coefficient of friction would be recommended for constructing the conveyors or transporting equipment in order to avoid or reduce the seed loss during transportation. In the design of hoppers and flow channels for the processing machines and equipment, the internal friction coefficient plays an essential role. The equation showing the ackee seed moisture relative to its coefficient of internal friction and the trends are shown in Equation (10) and Figure 3, respectively.

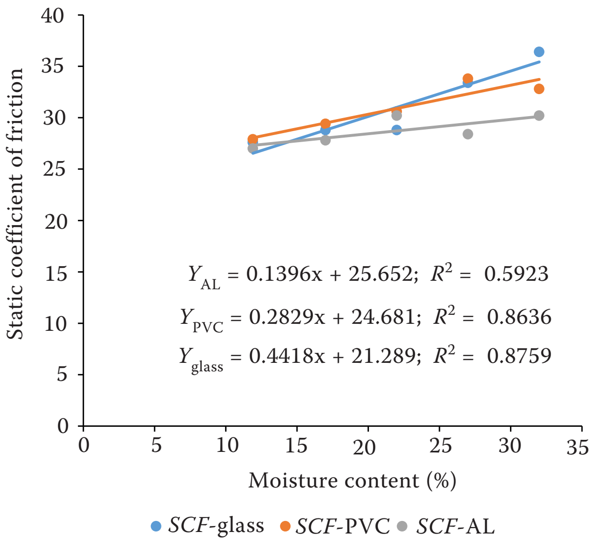

Figure 2. Effect of the ackee seed moisture on its coefficient of static friction on the aluminium, PVC and glass surfaces (*SCF*)

$$\mu_i = -0.0091x + 0.8541 \quad R^2 = 0.9052 \tag{10}$$

where: μ_i – coefficient of internal friction; x – moisture content.

Table 2. Moisture influenced coefficient of internal friction and angle of repose of the ackee seeds

Moisture content (%)	Coefficient of internal friction	Angle of repose (°)
11.9	0.744	28.92
17.0	0.719	28.91
22.0	0.650	24.94
27.0	0.575	24.60
32.0	0.588	22.17
LSD	0.0735*	4.209*

*Significant at $P = 0.05$; LSD – least significant difference

Angle of repose. The dynamic repose angle of the ackee seeds decreased (28.92–22.17°) significantly with an increasing seed moisture of 11.9 to 32% (Table 2). This is because the smoothness of the ackee seed coat and the water film on it causes the seed to be slippery in addition to its ability to roll on surfaces

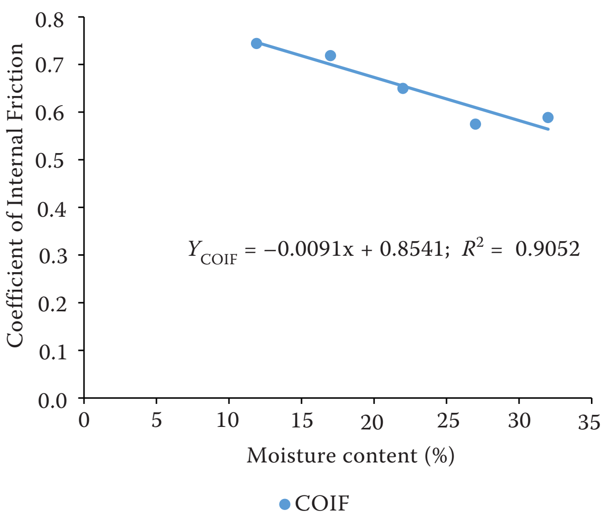

Figure 3. Coefficient of internal friction (COIF) of the ackee seeds as affected by the moisture content

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(sphericity). Therefore, the seeds spread more easily when poured instead of piling, which accounts for the decrease in the repose angle. This property is necessary in designing machines for the grain bulk flow and grain storage structures, especially in the design of hopper angles. Onwe et al. (2020), reported a decreasing repose angle for two varieties of the investigated African star apple while Jaiyeoba et al. (2020) reported the same for nutmeg seeds. The ackee seed moisture and the relationship of the angle of repose with the trends are shown in Equation (11) and Figure 4, respectively.

$$\Theta_{Dynamic} = -0.3546x - 33.701 \quad R^2 = 0.9127 \tag{11}$$

where: $\Theta_{Dynamic}$ – dynamic angle of repose; x – seed moisture.

Normal and shear stresses. The effect of the ackee seed moisture on its normal stress (for 200, 300 and 400 g loads) and its shear stress (for 200 g load) was significant at $P = 0.05$ (Table 3). The shear stress

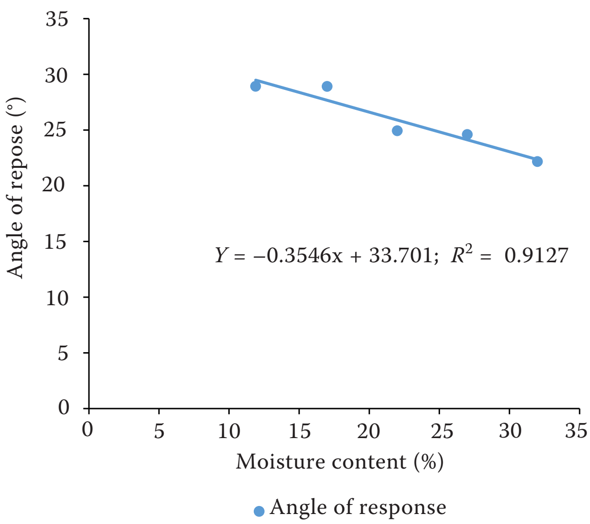

Figure 4. Dynamic repose angle of the ackee seeds as influenced by the seed moisture

for the 300 and 400 g loads was not significantly different. The normal stress increased linearly as the ackee seed moisture increased across all the loads (200 to 400 g). The difference in the means was significant ($P < 0.05$) as shown in Table 3. The highest normal stress values for the 200, 300 and 400 g loads were 8.994 (27%), 11.851 (27%), and 14.708 g·cm^{-2} (27%), respectively. Equations (12–14) show the relationship between the moisture content and normal stress at the specified loads. The trends are also shown in Figures 5, 6 and 7.

$$\Lambda_{200} = 0.0124x + 8.576 \quad R^2 = 0.7908 \tag{12}$$

$$\Lambda_{300} = 0.0099x + 11.501 \quad R^2 = 0.6735 \tag{13}$$

$$\Lambda_{400} = 0.0153x + 14.213 \quad R^2 = 0.8281 \tag{14}$$

where: Λ_{200} – normal stress at the 200 g load; Λ_{300} – normal stress at the 300 g load; Λ_{400} – normal stress at the 400g load; x – moisture content.

The shear stress reduced linearly with an increasing ackee seed moisture under the 200 g load. The difference in means at the 200 g load was significant ($P < 0.05$). At the 300 and 400 g loads, the shear stress also reduced with an increasing seed moisture, but not significantly. The highest value in the shear stress at the 200 g load was 1.620 (11.9%). This implies that the dry ackee seeds will exert more force on the interior walls of the storage facility when stored than the wet or moist ackee seeds. The slippery surface of the wet ackee seeds could be responsible for this phenomenon. The shear stress is important in the design consideration of storage facilities or parts of the machines that carry or convey seeds, for example conveyors and hoppers. It is also vital in choosing materials to construct the storage

Table 3. Normal and shear stresses of the ackee seeds at different moisture contents (g·cm^{-2})

Moisture content (%)	Normal stress			Shear stress		
	200 g	300 g	400 g	200 g	300 g	400 g
11.9	8.72	11.64	14.37	1.62	1.92	2.61
17.0	8.79	11.64	14.50	1.57	1.84	2.57
22.0	8.81	11.66	14.52	1.52	1.82	2.51
27.0	8.99	11.85	14.71	1.39	1.80	2.40
32.0	8.93	11.79	14.65	1.25	1.79	2.35
LSD	0.0935*	0.1348*	0.0981*	0.1727*	NS	NS

*Significant at $P = 0.05$; NS – not significant; LSD – the least significant difference

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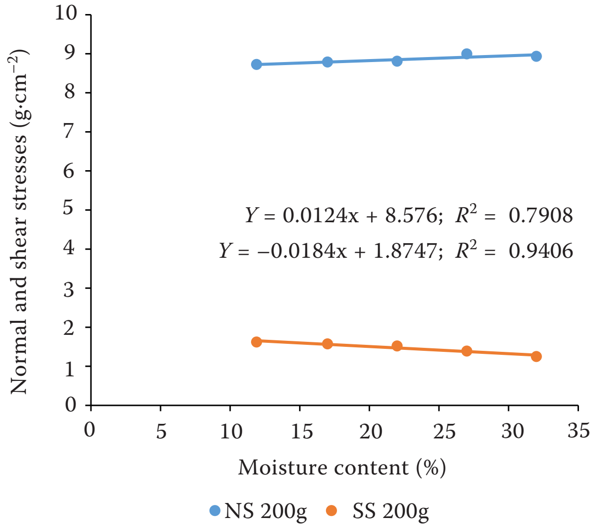

Figure 5. Normal stress (NS) and shear stress (SS) mean values at the different moisture levels under the 200 g load

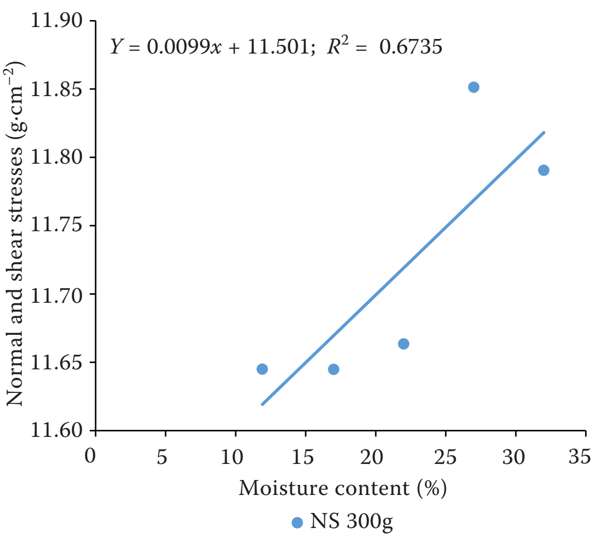

Figure 6. Normal stress (NS) mean values at the different moisture levels under the 300 g load

facilities. The relationship between the shear stress and moisture content at the 200 g load and the trend is shown in Equation 15 and Figure 5, respectively.

$$\lambda_{200} = 0.0184x + 1.8747 \quad R^2 = 0.9406 \tag{15}$$

where: λ_{200} – shear stress at the 200 g load; x – moisture content.

CONCLUSION

(*i*) There were significant changes in most of the friction properties of the ackee apple seeds because of the changes in the seed moisture content.

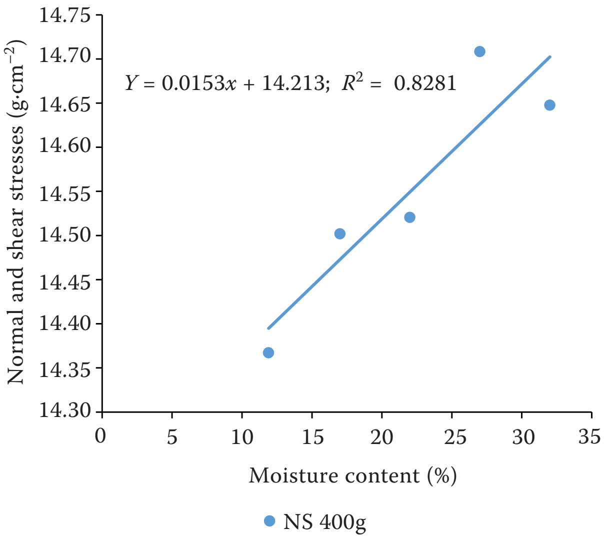

Figure 7. Normal stress (NS) mean values at the different moisture levels under the 400 g load

(*ii*) Regression models for predicting ackee seeds behaviour with respect to the increase in their moisture levels were generated.

(*iii*) Primary data vital to the development of the processing machines and equipment for ackee apple seeds were developed.

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