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The moisture-dependent flow characteristics of *Canarium schweinfurthii* Engler nuts

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Abstract: The flow characteristics of three varieties of *Canarium schweinfurthii* Engler nuts (*Canarium schweinfurthii* short, *Canarium schweinfurthii* long and *Canarium schweinfurthii* large – $CSHT_{LRG}$) relevant for the design and development of handling and storage systems was studied at three different moisture levels (10.20, 17.23 and 25.06% wet basis). The flow characteristics investigated include the normal stress, the shear stress, the initial shear stress, the coefficient and angle of the internal friction, the coefficient of mobility and the size of the discharge opening. An Instron universal machine at a cross-head speed of 25 mm·min^{-1} was used to obtain the shear force. The results obtained showed that all the flow properties increased with an increase in the moisture content except for the coefficient of mobility. Moreover, the variety of the *C. schweinfurthii* nuts had a significant effect ($P < 0.05$) on the flow characteristics. $CSHT_{LRG}$ had the best ability to flow freely than the other varieties. The hopper side wall angle for all the varieties ranged from 67–70°. Round, square and triangle shapes are all acceptable for the smooth flow of *C. schweinfurthii* nuts.

Keywords: stress; friction; mobility; angle; shapes

Canarium schweinfurthii Engler nut is an extract from its edible fruits. The fruits are obtained from the *C. schweinfurthii* tree that belong to the family of Burseraceae. It is grown mostly in the equatorial forest region of East, West and Central Africa and is popularly called the African bush candle (Orwa et al. 2009). The spindle-like stony nuts contain edible oils that are used domestically for food and industrially to make shampoo, waxes and drugs for the treatment of wounds and microbial infections (Edou et al. 2012). Like most shelled nuts, *C. schweinfurthii* nuts possess great potential for generating energy when they are gasified, are used to store energy in batteries (dry cells) and used as a filter in sewage plants when converted to biochar. The quality of the kernel oil obtained from these nuts at present is of a low standard due to poor conventional storage practices (Abayeh et al. 1999). In addition, an estimate of about 68% of these nuts get wasted annually especially during the harvest, resulting in a scarcity in the off season and a loss of economic benefits. This is due to lack of reliable storage facilities to ensure the all year-round availability of the nuts. An adequate storage facility based on the physical characteristics of these nuts will ensure their availability all year round, reduce losses and encourage high quality kernel oil production. The design and development of a bulk handling facility requires the knowledge of the flow characteristics of the the

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bulk products in order to overcome structural failures and ensure consistent reliable operating conditions (Kamath et al. 1994; Bhadra et al. 2009). Flow is the movement of the bulk materials in a steady and continuous stream. The free flow of the bulk products depends on the moisture content, the angle of internal friction, the outlet shape and geometry along with its surface characteristics (Mazumder et al. 2008). During the bulk flow of the granular materials, the products manifest shear behaviour due to stresses that result from the impressed forces, giving rise to inter-particle friction and cohesion forces between the product surfaces (Weber et al. 2004). The inter-particle forces in the bulk flow granular materials have been measured using shear testing procedures for different agricultural products. Irtwange and Igbeka (2002) investigated the influence of the moisture content on the flow characteristics of two varieties of the African yam bean under different impressed loading conditions. They observed that the products' flow properties are related to the moisture content and various loading conditions in a linear fashion. Rognon et al. (2008) studied the effect of the inter-granular cohesive forces on the dense flow of the cohesive granular materials (grains) using homogenous plain shear flows. They reported that the inter-granular cohesive forces had a strong negative effect on the dense granular flow. Mankoc et al. (2007) considered a wide range of outlet sizes in their study of the flow rates of grains and found that a small size outlet obeys the power law. They also proposed a new law that can be used to predict the mass flow rate through any given orifice size. Rahman and Zhu (2012) investigated the gravity flow of rapeseed through hopper orifices of different shapes (circular, square, rectangular and triangular) of the same orifice area, and reported that the flow rate decreased from the circular to the triangular orifice shapes. The reason was attributed to the inter-particle forces between the products. Ahn et al. (2008) used different flat-plate orifice sizes to investigate the characteristics of a continuous steady granular flow under increasing normal stresses. They observed that before the orifice becomes choked, the discharge rate increased with an increase in the normal stresses, but as the orifice became clogged, the increasing normal stress had no effect on the flow rate. This observation was the same for all the orifices and particle sizes studied. Mort (2015) evaluated the effect of a dimensionless orifice size on the onset of clogging and the flow rate of relatively free flowing granular materials and concluded that the excess friction, the size distribution and the shape encourage the products to clog at the dimensionless orifice. This study, therefore, focuses on the effect of the moisture content on the flow characteristics (normal stress, shear stress, initial shear stress, coefficient and angle of internal friction, coefficient of mobility and size of the discharge opening) of *C. schweinfurthii* nuts and to compare the behaviour of the various varieties.

MATERIAL AND METHODS

The three varieties of *C. schweinfurthii* nuts (*C. schweinfurthii* short – $CSHT_S$, *C. schweifurthii* long – $CSHT_L$ and *C. schweinfurthii* large – $CSHT_{LRG}$) used for this study were sourced from the Ebonyi State (6°15'N, 8°05'E) of Nigeria. The experiment was conducted in the Bioresources Engineering Department of McGill University, Macdonald campus, Canada. The nuts were extracted from the fruits and conditioned to three different moisture contents using the oven drying method according to Association of Official Agricultural Chemists AOAC (1995).

The size distribution of the samples. The size distribution of the samples were determined by measuring the principal dimensions (a = major diameter, b = intermediate diameter, c = minor diameter) of the nuts using a digital Vernier calliper (JIS7502; Mitutoyo, USA) of 0.01mm accuracy. The class interval of each sample size was developed and the number of times each class occurred was recorded.

Normal stress and shear stress. The normal and shear stresses were determined using the direct shear method (Mani et al. 2004; Kibar and Öztürk 2009; Hakan et al. 2014). This involves a topless cylindrical container of 0.070 m in diameter and 0.010 m in height, filled with samples and placed under another topless and bottomless smaller cylindrical container of 0.045 and 0.038 m in diameter and in height, respectively (Fig. 1) filled with samples. The smaller container was connected to the Instron universal machine cross-head through a pulley assembly. The cross-head speed during the experiment was 25 mm·min^{-1}. Normal loads of 4.90, 9.81, 14.71, 19.61 and 24.52 N were placed on the

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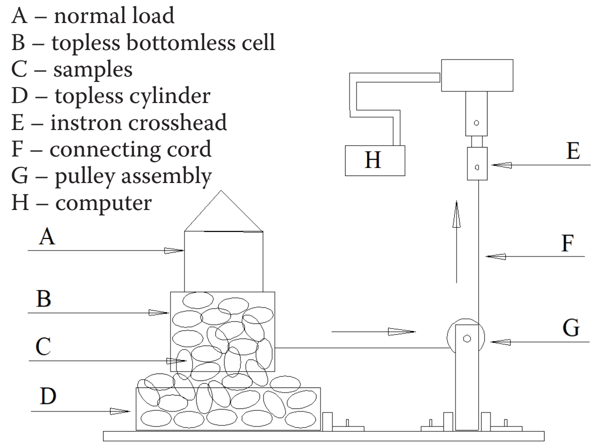

Fig. 1. The experimental set up for the flow characteristics of the *Canarium schweinfurthii* Engler nut

samples in the small container before engaging the cross-head. With the help of the inbuilt computer software connected to the Instron by the manufacturer, the cross head pushes the top container with the samples against the lower one until shear is initiated, returns the cross head to its initial position and automatically records the force that initiated the movement at the interface. The normal stress (τ_N) and shear stress (τ) were determined as shown in Eqs 1 and 2 (Irtwange, Igbeka 2002):

$$\tau_N = \frac{W_1 + W_2}{A} + \rho h \quad (1)$$

where: W_1 – mass of the cell (kg); W_2 – mass due to the normal load on top of the samples (kg); A – area of the cell (m^2); ρ – density of the samples (kg·m^{-3}); h – height of the samples in the cell (m)

$$\tau = \frac{F_s\left(1 - f\sqrt{2}\right)}{A} \quad (2)$$

where: F_s – shear force that initiated the movement of the sample and the normal load (N); f – coefficient of friction of the pulley, $f = 0.5$

The initial shear stress (τ_0) was taken as the intercept of the straight line obtained by plotting the shear stress against normal stress.

The coefficient and angle of the internal friction. The coefficient of internal friction (μ) is the resistant characteristics of the sample surfaces against each other during the flow operation. It influences the flow of the sample materials through the outlet chutes and hoppers and was determined as the slope of the plot of the shear stress versus the normal stress. The angle of internal friction – θ (°) was calculated as in Eq. 3 (Kibar et al. 2014):

$$\theta = \tan^{-1}\mu \quad (3)$$

The angle of the internal friction of any given product is very essential in determining the lateral and vertical pressures on the silo walls. This aids in the material's selection to avoid failures.

The coefficient of mobility and the hopper wall slope. The coefficient of mobility represents the freedom of movement of the individual or bulk agricultural products during the flow. It is inversely related to the coefficient of friction so that the higher the friction is the lower the mobility of the product is, hence leading to the larger size of the opening and the steeper slope of the hopper side wall. The coefficient of mobility of the products and the angle of inclination of the hopper side wall are very important in designing and developing bulk solid handling structures to achieve complete sliding and avoid a blockage in the chute outlet (non-arching) during the flow. Two methods (the direct (Eq. 4) and approximate – m_p (Eq. 5) methods) were used to determine the coefficient of mobility of the *C. schweifurthii* nuts as shown in Equations 4 and 5 (Elaskar et al. 2001; Irtwange, Igbeka 2002; Adejumo, Abayomi 2012):

$$R_{dm} = 1 + 2\mu^2 - 2\mu\sqrt{\left(1+\mu^2\right)} \quad (4)$$

where: R_{dm} – coefficient of mobility

$$m_p = \frac{0.18}{\mu} \quad (5)$$

The hopper incline angle (φ) for the smooth flow of the nut was calculated as in Eq. 6:

$$\varphi \leq 45° + \frac{\theta}{2} \quad (6)$$

The shape and size of the opening. The importance of considering the shape and size of the opening in the design and development of the discharge outlets is to overcome arching which block the outlet during the flow operation. The size of the opening – P (m) for the different shape types (square, triangle, rectangle, round, slot and wedge) was calculated as shown in Eq. 7 (Irtwange, Igbeka 2002):

$$P = \frac{2\tau_0\left(1 - \sin\ \theta\right)}{z\rho} \quad (7)$$

where: ρ – bulk density of the sample (kg·m^{-3}); z – constant factor for the different shapes: for the square, triangle and round ones: $z = 0.5$, for the slot and wedge

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ones: $z = 1$, for the rectangular shape one: $z = l/(x + l)$: $z = 0.6670$ when the rectangle ratio is $l/x = 2$, $z = 0.750$ when the rectangle ratio is $l/x = 3$; x – square side, the circular diameter or the short side of a rectangle; l – long side of a rectangle

The data obtained from the experiment was analysed using the MS Excel (Version 14.0), SPSS (Version 21.0) and Genstat (Version 19.1) statistical packages.

RESULTS AND DISCUSSION

The size distribution of the samples

The size distribution for all the varieties of the *C. schweinfurthii* nut presented in Fig. 2 showed that the major (a, mm), intermediate (b, mm) and minor (c, mm) diameters ranged from 29.00–34.90, 14.11–17.41 and 14.04–17.24 mm, respectively, for the large variety; 33.21–40.9, 11.50–14.44 and 11.49–14.14 mm, respectively, for the long variety and, 22.00–26.92, 9.52–12.46 and 9.45–11.48 mm, respectively, for the short variety. The intermediate and minor diameters of all the varieties are relatively similar indicating that the fruits can roll. The major diameter of the long variety was greater than that of the large and short varieties by 12.14 and 36.95%, respectively, while the intermediate and minor diameters of the large variety were also higher than that of the long and short varieties by an average of 17.88 and 32.96%, respectively.

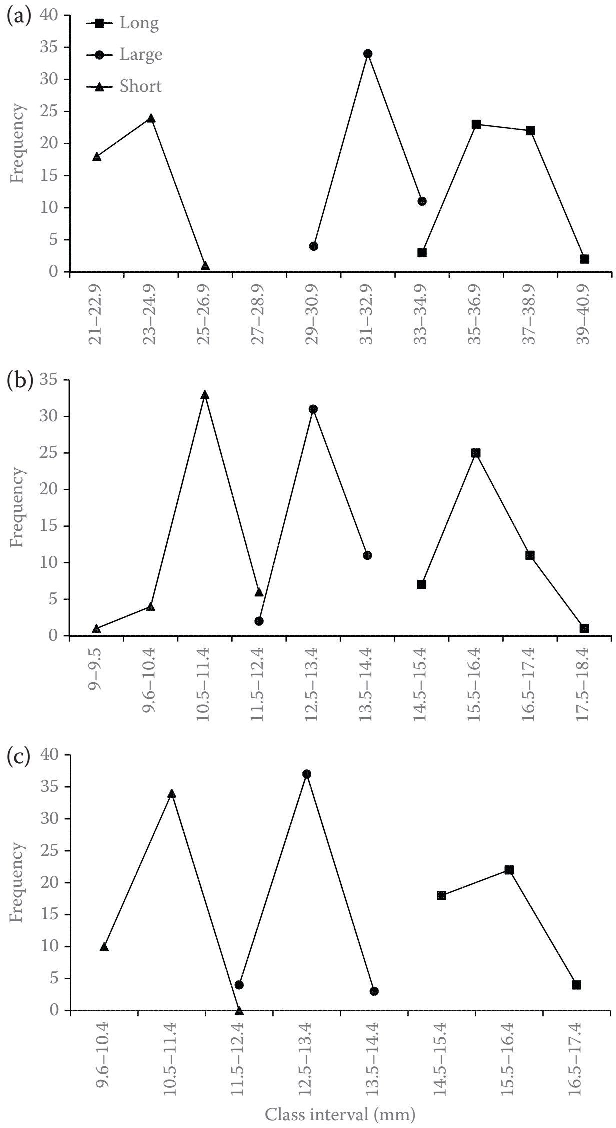

Fig. 2. The plot of the frequency against the class interval of the major (a), intermediate (b) and minor (c) diameters of the *Canarium schweinfurthii* Engler nut varieties

The normal stress, shear stress and initial shear stress

The results of the shear stress, normal stress and initial shear stress of the *C. schweinfurthii* nut varieties at various moisture contents and normal loads studied are shown in Figs 3a–c and Table 1. The figures revealed that the shear stress and normal stress of all the varieties increased with an increase in the normal loads and moisture contents (10.20–25.06% wet basis). The initial shear stress also increased with the moisture content for the large and short varieties. This is because of the increase in the bulk density of the nuts resulting from the increase in the mass with relatively no change in the bulk volume of the nuts. The increase in the shear, normal and initial shear stresses with the increase in the normal load has been reported for the African yam bean and Raya seeds at moisture ranges of 5–16 and 4–15.7% (wet basis), respectively (Sethi et al. 1992; Irtwange, Igbeka 2002). The ANOVA summary presented in Tables 2 and 3 revealed the high significant ($P > 0.05$) effect of the moisture content, the variety and the normal load on both nut types of stresses. Moreover, the initial shear stress was not significantly ($P < 0.05$) affected by the moisture content, although it increased with the increase

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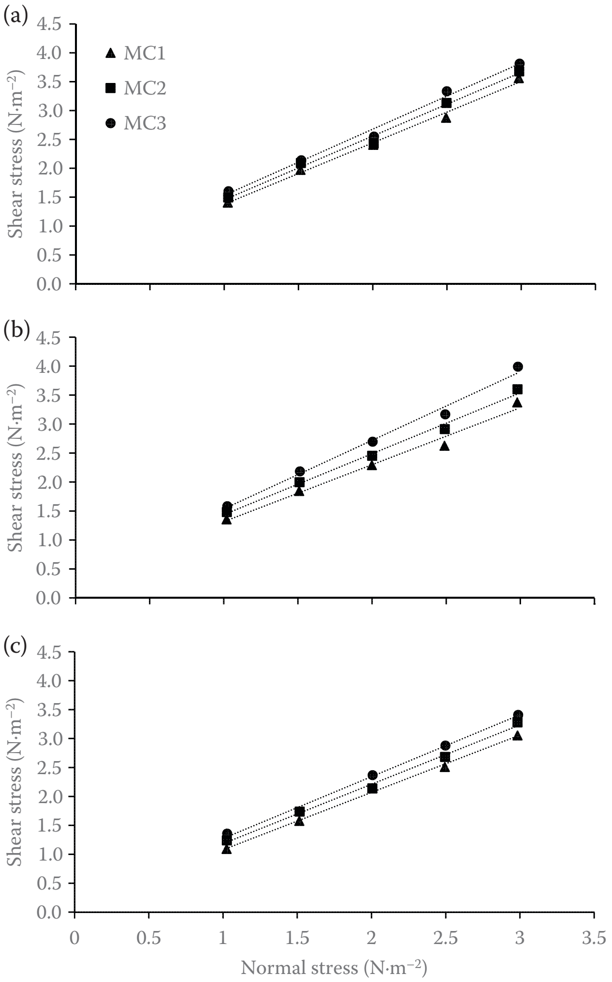

Fig. 3. The plot of the normal versus the shear stress for the *Canarium schweinfurthii* Engler nut large (a), long (b) and short (c) varieties at various moisture contents (MC)

MC 1 = 10.20%; MC 2 = 17.23%; MC 3 = 25.06%

in the moisture content. The varietal differences in the initial stress are significant ($P > 0.05$) with $CSHT_S$ being the highest at a moisture content of 25.05% (wet basis) while $CSHT_{LRG}$ had the least at a moisture content of 10.20% (wet basis). The low values of the initial shear stress observed for all the varieties showed that the *C. schweifurthii* nut surfaces have fine grains, hence, they manifest very low resistance to flow especially at a low moisture level. This also means that the cohesion between the nuts is approximately zero. The regression equations for predicting the shear and normal stress of the *C. schweifurthii* nut varieties at a given moisture content and normal load are presented in Table 4.

The coefficient and the angle of the internal friction

Table 1 summarises the coefficient and the angle of the internal friction of various *C. schweinfurthii* nut varieties at a moisture range of 10.20–25.06% (wet basis). The ANOVA summary is also shown in Table 2. The values of coefficient and angle of internal friction increased as the moisture content rises from 10.20–25.06% (wet basis). A similar trend was reported by Unuigbe et al. (2013) for a dika nut at a moisture content of 8.25–18.98% (dry basis). This behaviour can be attributed to the cohesive properties of water on the nut's surface which tends to gum the nuts together. The coef-

Table 1. The coefficient of internal friction and the coefficient of mobility of *Canarium schweinfurthii* Engler nuts at various moisture contents

Species variety	Moisture content (% wb)	Initial shear stress ($N \cdot m^{-2}$)	Coefficient of internal friction	Angle of internal friction (°)	Coefficient of mobility	
					direct method	approximate method
$CSHT_{LRG}$	10.20	0.3134	1.06	46.77	0.1569	0.1692
	17.23	0.3507	1.10	47.82	0.1484	0.1631
	25.06	0.3867	1.15	48.87	0.1407	0.1572
$CSHT_L$	10.20	0.3318	0.9835	44.52	0.1756	0.1830
	17.23	0.3841	1.05	46.45	0.1596	0.1711
	25.06	0.3560	1.18	49.77	0.1352	0.1523
$CSHT_S$	10.2	0.0650	0.991	44.74	0.1738	0.1816
	17.23	0.1580	1.03	45.72	0.1656	0.1755
	25.06	0.2765	1.05	46.25	0.1612	0.1723

$CSHT_{LRG}$ – *Canarium schweinfurthii* large; $CSHT_L$ – *Canarium schweinfurthii* long; $CSHT_S$– *Canarium schweinfurthii* short; wb – wet basis

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Table 2. The ANOVA summary of the flow characteristics of *Canarium schweinfurthii* Engler nuts

Source of variation	*df*	Coefficient of internal friction	Initial shear stress	Coefficient of mobility
Moisture content	2	0.0659^{ns}	0.1549^{ns}	0.0379^{*}
Variety	2	0.1410^{ns}	0.0168^{*}	0.0089^{**}
Error	4	0.0016	0.0026	3.2E-05

$P < 0.05$; *df* – degree of freedom; ns – not significant; *significant; **highly significant

Table 3. The ANOVA summary of the normal and shear stress of *Canarium schweinfurthii* Engler nuts

Source of variation	*df*	Normal stress	Shear stress
Normal load	4	$<0.001^{**}$	$<0.001^{**}$
Moisture content	2	$<0.001^{**}$	0.0220^{*}
Variety	2	$<0.001^{**}$	$<0.001^{**}$
Interaction	10	1.00^{ns}	0.9290^{ns}

$P < 0.05$; *df* – degree of freedom; **highly significant; ns – not significant; *significant

Table 4. The regression equations for the determination of the shear and normal stress of *Canarium schweinfurthii* Engler nuts

Stress	Variety	Model equation	R^2	RMSE
Shear	$CSHT_L$	$0.3031 + 0.0304M + 1.15L$	0.96	0.0213
	$CSHT_{LRG}$	$0.4241 + 0.0288M + 1.05L$	0.98	0.0605
	$CSHT_S$	$0.3334 + 0.0217M + 1.00L$	0.99	0.0374
Normal	$CSHT_L$	$0.7982 - 0.0131M + 0.9147L$	0.90	0.0047
	$CSHT_{LRG}$	$0.3306 + 0.0068M + 1.0127L$	0.98	0.01228
	$CSHT_S$	$0.5313 + 0.0003M + 0.9800L$	1	5.92E-5

$CSHT_L$ – *Canarium schweinfurthii* long; $CSHT_{LRG}$ – *Canarium schweinfurthii* large; $CSHT_S$ – *Canarium schweinfurthii* short; M – moisture content (wet basis); L – normal load (N); R^2 – coefficient of determination; RMSE – root mean square error

ficient and the angle of the internal friction of the various varieties studied at varying moisture contents are not significant ($P < 0.05$); however, $CSHT_L$ had the highest (1.18) and lowest (0.9835) values of friction at a moisture content of 25.06 and 10.20%, respectively.

The coefficient of mobility

The mean values of the coefficient of mobility obtained through two calculation methods in the moisture range of 10.20–25.06% (wet basis) for the various varieties studied are presented in Table 1. The coefficient of mobility decreased with an increase in the moisture content. The values of the coefficient of mobility for the $CSHT_L$, $CSHT_{LRG}$ and $CSHT_S$ nut varieties decreased by 10.33, 23.00 and 7.25% and, 7.09, 16.78 and 5.12% for the direct calculation method and the approximate method, respectively. Seithi et al. (1992) and Irtwange and Igbeka (2002) reported a similar trend for the African yam bean and Raya seeds in the moisture ranges of 4–16 and 4–15.71% wet basis, respectively. This result is attributed to the increase in the coefficient of internal friction caused by the high moisture content, which reduces the movement of the nut over another nut. Methods of calculating the coefficient of mobility varied significantly ($P > 0.05$) with the approximate method having the highest values. The approximate method is preferred for these nuts because it will aid in taking a good safety factor into account during the design of the flow channel to avoid blocking. The coefficient of mobility of the varieties differ significantly while

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Table 5. The flow opening type and sizes at various moisture contents

Species variety	Moisture content (% wb)	Size of different opening types (m)				Side wall slope (°)
		round, square, triangle	slot, wedge	rectangular		
				z = 0.667	z = 0.750	
$CSHT_L$	10.20	0.3080	0.1540	0.2310	0.2060	68.39
	17.23	0.3310	0.1650	0.2480	0.2210	68.91
	25.06	0.3670	0.1840	0.2750	0.2450	69.44
$CSHT_{LRG}$	10.20	0.3480	0.1740	0.2610	0.2320	67.26
	17.23	0.3910	0.1950	0.2930	0.2610	68.23
	25.06	0.3570	0.1780	0.2680	0.2380	69.89
$CSHT_S$	10.2	0.2106	0.1053	0.1579	0.1404	67.37
	17.23	0.2500	0.1233	0.1848	0.1644	67.86
	25.06	0.4100	0.2052	0.3076	0.2736	68.13

$CSHT_L$ – *Canarium schweinfurthii* long; $CSHT_{LRG}$ – *Canarium schweinfurthii* large; $CSHT_S$ – *Canarium schweinfurthii* short; wb – wet basis; z – constant factor for the different shapes

Table 6. The ANOVA summary of the size of the flow opening for the *Canarium schweinfurthii* Engler nuts

Source of variation	*df*	Size of opening
Type of opening	3	1.92E-03**
Moisture content	2	0.2257^{ns}
Variety	2	1.69E-03**

P < 0.05; *df* – degree of freedom; **highly significant; ns – not significant

$CSHT_{LRG}$ and $CSHT_L$ had the highest and lowest values, respectively.

The shapes and size of the opening

The summary of the size of the opening required for the easy flow of the nuts through various opening shapes is presented in Table 5 while the ANOVA summary showing the effect of the moisture content, variety and shape on the size of the flow opening is presented in Table 6. For all the opening shapes of all the varieties, the size of the opening increased with an increase in the moisture content. The same behaviour was reported for the African yam bean and Raya seeds at the moisture ranges of 5–16 and 4–15.7% wet basis, respectively (Sethi et al. 1992; Irtwange, Igbeka 2002). The round, square and triangular opening sizes are higher than the other shapes for all the varieties studied. The shape of the opening as well as the size of the opening differ significantly with one another. This result suggests that each nut variety requires a different design specification for the easy flow operation.

The aforementioned results are very essential in the design and development of storage bins, hoppers, flow channels as well as estimating the behaviour of the nuts under static or dynamic loading conditions.

CONCLUSION

From the study of moisture content and the variety effect on the flow characteristics the of *C. schweifurthii* nut, it can be concluded that:

(*i*) The shear stress, normal stress and initial shear stress values of the *C. schweinfurthii* nuts increased with an increase in the moisture content and normal load;

(*ii*) The high moisture content increases the coefficient and the angle of the internal friction and, decreases the coefficient of mobility of the nuts;

(*iii*) The coefficient of internal friction and mobility, the shear stress, normal stress and initial shear stress of the *C. schweinfurthii* nut varieties are statistically different (P > 0.05);

(*iv*) $CSHT_L$ requires a higher force to overcome the initial resistance to the flow while $CSHT_S$ needs a wider opening size when compared with the other varieties;

(*v*) The same hopper side wall slope can be used for all the varieties;

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(*vi*) The major diameter is higher than the intermediate and minor diameters of all the varieties.

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