Int. Agrophysics, 1995, 9, 131-142

SOME PHYSICAL PROPERTIES AND CRACKING ENERGY OF CONOPHOR NUTS AT DIFFERENT MOISTURE CONTENT

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Accepted September 30, 1994

A b s t r a c t. Freshly harvested conophor fruits (*Tetracarpidium conophorum*) were processed traditionally and the nuts extracted. Physical measurements of axial and radial diameters, nut weight and volume were taken and used to compute the nut's density and sphericity. The energy to crack the nut and release the kernel was obtained using the 'nut cracking energy instrument' for different moisture contents. Visual observation was used to assess the cracking percentage of the nuts.

Results show that the conophor nut (African walnut) has average sphericity of 0.91, radial diameter of 2.90 cm and an axial diameter of 3.19 cm. The density of the fresh nuts (68.8 % moisture content) was found to be about 0.877 g/cm^3 while the nut thickness was 0.067 cm.

Full cracking of nuts increased with decreasing moisture content and increased drop height. The cracking energy was influenced by nut mass and radial diameter as well as shell moisture content. The nut and kernel moisture content have high linear relationship with the shell moisture content.

However, impinging velocity of about 4 m/s was adequate to sufficiently crack conophor nuts of not more than 30 % moisture content and release the kernel.

K e y w o r d s: Conophor nuts, *Tetracarpidium conophorum*, cracking energy, moisture content, physical properties

INTRODUCTION

The physical properties (axial and radial diameters, shell thickness and weight, sphericity, nut weight, volume and density) of agricultural products are some of the parameters which are important in many problems related to the design and function of a particular machine or to the analysis of the behaviour of the products under handling, processing and storage [1,13,28,36].

As it was not reported that the conophor nut cracking machine developed by Makanjuola [25] was designed based on the physical properties of the nuts, the first part of this study was to determine the physical properties of conophor nuts which may help in improving the efficiency of Makanjuola's machine and enable one to find the correlation between the cracking paramters with the physical attributes of nut [9].

Goldsmith [14] and Veluswami *et al.* [42] defined impact as the phenomena of mechanical loading over a range of velocities. Damage to fruits and vegetables resulting from impact forces and sometimes referred to as cracking has been reviewed by several researchers [20,28,30]. The study of impact phenomena has been used to develop design criteria and models for fruit harvesting, grain processing and materials handling equipment applications [5,17,37].

The determination of the maximum allowable load to which biological materials can be subjected without causing objectionable damage [26,29] as in cracking due to drops and other types of impact or static loading, is important to the agricultural engineer. Impact-induced cracking of nuts have been found beneficial for macadamia nuts [21,22], palm nuts [10], peanuts [41] and soybean [11,27,34].

For conophor nuts (*Tetracarpidium conophorum*) the full or complete cracking of the shell will release the kernel for processing into food or for industrial use. However, the force levels and the limits of the impact energy that the nut can withstand or sustain without the kernel being damaged [8] must be known and understood. Also, in order to release the kernel easily, the shell has to get multiple split cracks both longitudinally and transversely [32] which should not extend to the kernel to cause mechanical damage and result in lower quality product [11].

Of the many impact-inducing devices the simple drop test apparatus has been widely used even though the resultant damage is usually measured subjectively [12]. In this apparatus, either the product impacts upon rigid surface or a mass impacts upon the product [10,23,30,44]. It has been observed that the following factors influence cracking in biological products: size, moisture content, orientation, impact velocity, temperature, impact surface, drop height [2,6,11,19,40]. However, researchers have used such impact parameters as impulse energy momentum, force etc. to monitor mechanical damage in fruits and vegetables [3,12,15,33].

Reducing nut or shell moisture content improved kernel recovery [15,22,25,39]. High velocity impact (or high drop height) as related to kernel moisture, shape and size, impact surface and angle of impact surface [11,24,35] improved crackage and shelling in melon seeds and soybean, respectively. Makanjuola [25] stated that the ability of his machine to crack and separate the conophor kernel from the broken shell was influenced by moisture content.

The African walnut (*Tetracarpiduim conophorum*) is a climber which grows in the tropical rainforest with thick and extensive canopy. The fruit which may contain as many as four nuts, have nuts with hard black shells (Fig. 1a) which must be cracked to release the edible milky white kernels for processing into food or for industrial use.

The kernel is grown for food and contains about 40 % oil and 21.8 % good quality protein. The industrial potential of the kernel is also high. The kernel oil could be used in the manufacture of paints and varnishes or processed into edible vegetable oil. The cake obtained after expressing the oil can be used as food for the disabled and for babies or used as protein for livestock feed or a source of nitrogen fertilizer. The nut shells could be used as fuel on the farm for low cost driers.

The objectives of this study were to:

- determine those physical properties of the conophor nut necessary to characterize it,
- evaluate the effect of drop height, nut radial diameter, nut mass and nut moisture content on the cracking,
- determine the correlation of cracking percentage with some physical atributes of conophor nuts.

MATERIALS AND METHOD

Freshly harvested fruits of African walnut (Conophor nut) were processed traditionally and the nuts obtained were subjected to physical measurements (axial and radial diameters, shell thickness) using a vernier calliper. Because the nut naturally lies on its radial diameter and also a preliminary test showed that impacts to the side resulted in significantly more splits than impacts to the top as reported by Hoki and Pickett [16] and Bartsch *et al.* [3] for navy bean and soybean seeds, respectively the mean of 4 masurements around the nuts middle section (radial diameter) (Fig. 1b) was taken and the nuts grouped into the following size ranges: $d \leq 2.79$ cm; $2.80 < d < 2.99$ cm; $d \geq 3.00$ cm.

The weights of the nut and the shell were determined using an electronic top loading balance and recorded to the second decimal in g, while the volume was determined using the displacement method [28]. Both were used to calculate the density of nut. The sphericity of

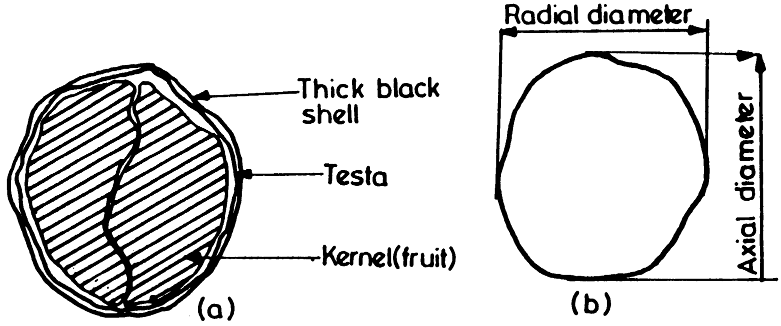

Fig. 1. Cross-section of conophor nut.

the nut, defined as the ratio of the radial to the axial diameter as shown in Fig. 1b [28,38] was also determined. The fresh nut moisture content was determined gravimetrically after drying in an oven at 103 °C for 24 h using Eq. 1. For the above measurements, 300 nuts of different sizes were utilized. Some nuts were cracked, the weights of the shell and kernel taken before and after drying for the determination of both shell and kernel moisture content (MC):

$$MC = \frac{W_1 - W_2}{W_2} \qquad (1)$$

where W_1 - initial weight of nut, W_2 - weight after oven-drying for 24 h.

Another six groups of nuts (100 in each group) were brought out and labelled A to F. Ten nuts of each group were weighed, cracked, the kernels and shells separated and re-weighed as a group. Both the 10 cracked ones and the 90 others in each group were weighed and put in the oven switched to 70 °C. The shells were allowed to dry to 60, 50, 40, 30, 20 and 10 % moisture content (db), respectively before the cracking test. At the appropriate moisture content, the group is taken out of the oven and cooled in a dessicator for 24 h. The cracked group were re-weighed to determine the moisture contents of the shell and kernel while the uncracked nuts were re-weighed for the determination of whole nut moisture content. The uncracked ones were then sorted out into size groups and the physical parameters of each individual nut in each group determined.

Thereafter nuts with no shell cracks, no shell damage and within the weight range of 8 to 17 g were selected for impact tests. The nut weight was an important consideration since impact forces are directly related to the weight of the impacted body [31]. The percentage of rejected nuts due to shell cracks and disfigurement was found to be 3, 5, 8, 12, 17 and 20 at 60, 50, 40, 30, 20 and 10 % moisture content, respectively. The damaged or initially cracked nuts were sorted out by visual inspection [43]. With the percentage of wastages about 20 %, enough good and sound nuts were available for running the impact tests. Fifteen nuts were used in each sample. One hundred fresh nuts were allowed to dry in the sun for 96 h which brought their moisture content to 68.6 % with only 2 % discards. They were used as fresh nuts.

The laboratory device used to impact the nuts operated in a way similar to the nut cracking energy instrument used by Wright and Splinter [44], Fluck and Ahmed [12] and Dienagha and Ibanichuka [10]. The instrument (Fig. 2) consisted of a hammer (200 g) constrained to more vertically in an open-ended metal cylindrical container which rests on a flat base plate. The hammer was raised to various heights by means of a rope attached to the hammer through a small pulley. The thickness of the flat plate is 6 mm. A graduated scale (ruler) placed in the container measures the height through which the hammer falls to

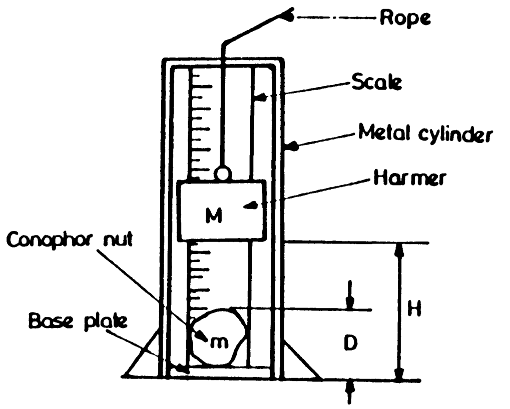

Fig. 2. Nut cracking energy instrument showing components and placement nut and measured dimensions.

crack the nut placed at the middle of the base plate and lying on its side. The heights used were 5, 6, 7, 8, 9, 10, 11 and 12 cm from the base plate.

System energy balance for cracking

The concept of energy balance has been used to describe the impact phenomenon [4,12,23]. In the drop test system whereby the hammer falls vertically onto a static nut on a hard surface, the energy balance equation is:

$$E_i = E_h + E_r \qquad (2)$$

where E_i, E_h and E_r are the initial potential energy (equal to the kinetic energy at impact), the energy dissipated during contact (net energy), and the kinetic energy remaining in the nut, respectively. If the moving velocity V_i at the initiation of impact, and the final velocity V_f at the termination of impact are known, the net energy absorbed at impact termination is [44]:

$$E_{net} = E_h = \frac{1}{2} M (V_i^2 - V_f^2) + Mgd_t \qquad (3)$$

where d_t is the remaining nut deformation at termination of impact. A greater amount of energy than this net energy absorbed is applied to the nut during impact, but as the hammer rebounds, some of the energy applied is returned to the hammer from the nut. As the hammer is heavier than the conophor nuts, there are no rebounds of the hammer. The maximum energy applied during impact is at the point where final velocity V_f is zero and deformation d_t is maximum [12]:

$$E_{net} = \frac{1}{2} MV_i^2 + Mgd_{max} \qquad (4)$$

The initial potential energy E_i is proportional to the mass M of hammer and hammer drop height H:

$$E_i = Mg\,(H - d) \qquad (5)$$

where d - radial diameter of nut. So:

$$E_i = E_{net} \qquad (6)$$

There is always some loss in energy of the system during impact [30]. However, considering the mass of the nut, m, that absorbs the impact energy the energy dissipated in the system is used to crack the shell, i.e., to deform it to d_{max}. However, if this energy is excessive, it will not only crack the shell and release the kernel but also damage or wound the kernel.

By examining the amount of crackage done on the nut and dropping the nut from certain heights unto the hard surface to cause the same amount of crackage, the impacting velocity of the nut V could be determined:

$$\frac{1}{2} mV^2 = Mg\,(H - d) \qquad (7)$$

$$V = \left[\frac{2Mg(H-d)}{m}\right]^{\frac{1}{2}} \qquad (8)$$

Assessment of cracking

Visual inspection methods which have been widely used by other researchers [7,16,43] were used here for the evaluation and assessment of cracking. It was assessed at the end of impacting a sample of 15 nuts in each treatment combination.

Nuts fully cracked with undamaged kernels released (FC) were removed first followed by those fully cracked with wounded kernels (FCW), then those with cracked unreleased in-shell nuts (VC) and those that were smashed (SM). After separation, their percentages of the sample were recorded as cracking percentage. Linear and multiple regression equations were developed between the assessed cracking percentage, the calculated cracking energy and the various treatments and some of the physical attributes of conophor nuts.

RESULTS AND DISCUSSION

Physical measurements of shape and size

The axial and radial diameters of each of the 1 000 nuts were analysed and used to calculate their sphericity. The mean and standard deviation of each physical parameter is given in Table 1. It was observed that the axial diameter was 3.19 ± 0.21 cm and the radial diameter was 2.90 ± 0.18 cm. The sphericity of conophor nuts was found to be 0.912 ± 0.035. All the above parameters increased with increase in the size of the nuts and about 54 % of the nuts fall within the medium size range of 2.80<d<2.99 cm. The smallest and the largest sizes had 25 % and 21 % of all the nuts within them. With the average sphericity as about 0.91, it may be said that compared to other fruits and seeds [28], the conophor nuts could be treated as a sphere for design purposes since sphericity was not significantly different among nut sizes. It was also interesting to observe that there was no significant difference in the thickness of the shell measured at the top, middle and bottom of the nut for the different size groups. The mean value of the nut thickness was found to be 0.067 ± 0.008 cm.

Table 2 shows the values of the weight, volume, moisture content (db) and density of the nuts as well as the weight of the shell for each size group. While all the measured parameters increased with increase in nut sizes, only weight and volume of nut and weight of shell were significantly different at 5 %. Not only was it observed that the nut density was not significantly different among nut sizes, which is an important engineering design attribute, but that the nuts have density less than unity, i.e., lighter than water. The average nut

Table 1. Some physical measurements of conophor nut

Size range (cm)	Total number	Axial diameter (cm)	Radial diameter (cm)	Thickness of shell (cm)	Percentage sphericity
d≤2.79	250	3.07 ± 0.06	2.72 ± 0.07	0.066 ± 0.01	88.8 ± 3.1
2.80<d<2.99	540	3.14 ± 0.10	2.88 ± 0.06	0.067 ± 0.01	91.7 ± 2.7
d≥3.00	210	3.42 ± 0.31	3.17 ± 0.17	0.069 ± 0.008	92.9 ± 4.3
Mean values		3.19 ± 0.21	2.90 ± 0.18	0.067 ± 0.009	91.2 ± 3.5
LSD 0.05		0.12	0.09	ns	ns

ns - not significant.

Table 2. More physical measurements of conophor nut

Size range (cm)	Total number	Nut weight (g)	Nut volume (cm^3)	Nut density (g/cm^3)	Nut moisture content (%)	Shell weight (g)
d≤2.79	106	10.22 ± 1.60	11.78 ± 1.74	0.8688 ± 0.0693	68.3 ± 11.4	2.30 ± 0.33
2.80<d<2.99	204	11.49 ± 1.65	13.27 ± 2.05	0.8688 ± 0.0644	68.5 ± 10.1	2.44 ± 0.24
d≥3.00	90	14.77 ± 1.23	16.51 ± 2.01	0.9005 ± 0.0707	69.0 ± 6.4	3.14 ± 0.33
Mean values		11.76 ± 2.18	13.48 ±2.43	0.877±0.0234	68.6 ± 8.0	2.61 ± 0.44
LSD 0.05		0.69	1.04	ns	ns	0.25

moisture content of 68.6 % db compared with Makanjoula's [25] value of about 60 % wb at harvest.

Cracking assessment of conophor nuts

Fresh conophor nuts at 68.6 % moisture content

Figure 3 shows that drop height had a linear relationship with cracking percentage for the different assessment criteria. However, while the percentage of nuts with visible cracks (VC) decreased with hammer drop height, those in the FC, FCW and SM assessment criteria increased. Their linear regression coefficients (Table 3) show high significance at the 5 % level of probability. The regression equation is given by:

$$CP = a + bH \tag{9}$$

where CP - cracking percentage, H - hammer drop height, a and b are constants.

For hammer drop heights 8 cm and above, the percentage of FC was greater than that of the other assessment criteria. The low percentage of FC was due partly to the tough testa - shell attachment and partly to the high moisture content of the in-shell kernel. These made cracking and separation difficult and also explains

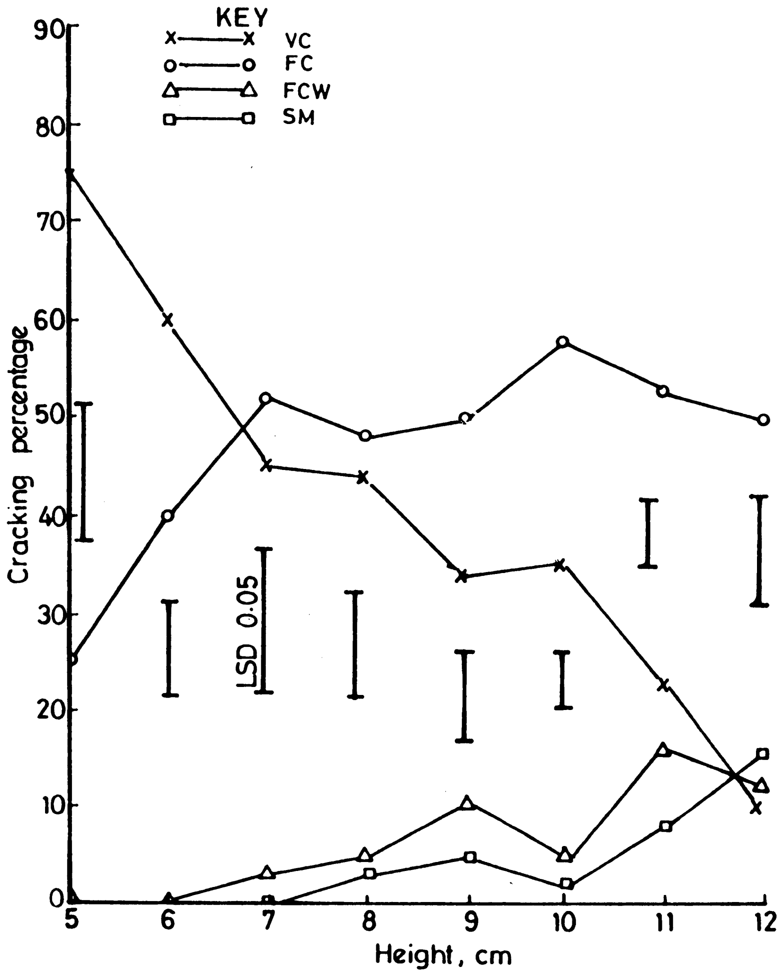

Fig. 3. Percentage cracking efficiency for fresh conophor nuts at various test heights (n=290).

Table 3. Linear regression coefficients of the effect of drop height (cm) on cracking percentage of fresh conophor nuts at 68.6 % moisture content

Assessment criteria	Coefficients		
	a	b	r
VC	109.54	-8.11	-0.974
FC	15.09	3.89	0.853
FCW	-112.85	2.32	0.862
SM	-11.77	1.89	0.850

the low overall percentage of SM (4.3 %) nuts. Others VC, FC and FCW accounted for 40.6 %, 48.2 % and 6.9 %, respectively, of all fresh nuts tested.

At various moisture contents

The effect of shell moisture content on cracking percentage (Fig. 4) showed high correlation for the VC and FC assessment criteria (Table 4). Only percentage FC decreased with increase in shell moisture content [3] and percentage SM was not affected by moisture content. At shell moisture content of 30 % and below, conophor nuts recorded an average 85 % FC for all drop heights. From 40 to 60 % shell moisture content there was no significant difference between percentage FC (46 %) and VC (42 %) on one hand and FCW (11 %) and SM (4 %) on the other. This may be due to the thickness of the shell (Table 1) which allowed most drying to first occur on it without much moisture removed from the kernel (Table 5). The moisture difference between the shell and the kernel here was greater than 10 %. This made the testa-shell attachment strong thereby affecting the cracking assessment criteria. Minimum percentages of FCW and SM occurred at between 10 and 20 % shell moisture content where the difference between kernel and shell moisture contents were less than 7 %.

Table 6 shows the coefficients of the linear regression equations between the assessment criteria and hammer drop heights for different shell moisture contents. Percentage of visible cracks (VC) decreased with the increase in hammer drop height and increased with the increase in shell moisture content.

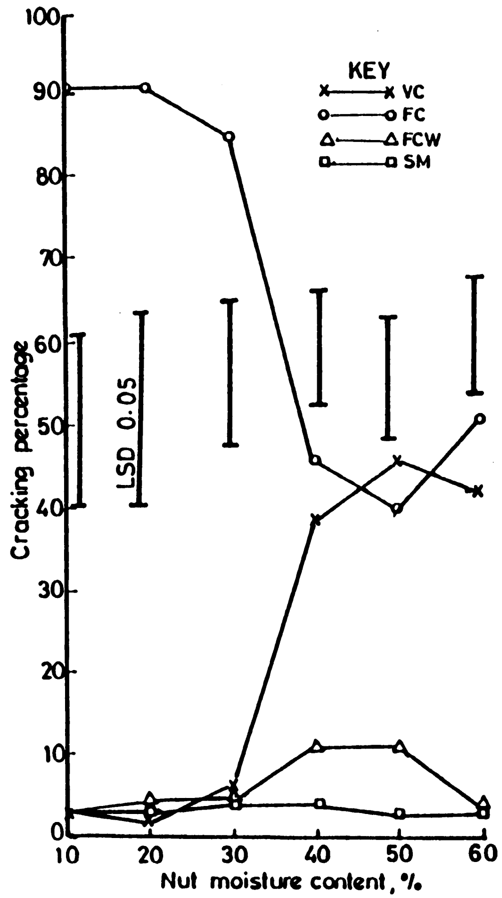

Fig. 4. Effect of conophor nut moisture content on percentage cracking efficiency for all test heights (n=600).

Table 4. Linear regression coefficients of the effect of shell moisture content (%) on cracking percentage of conophor nuts for all drop height tested

Assessment criteria	Coefficients		
	a	b	r
VC	-13.0	1.03	0.902
FC	106.5	-1.12	-0.870
FCW	3.13	0.09	0.466
SM	3.33	5.71^{-12}	2.07^{-10}nr

nr - no linear relationship.

At 20, 30 and 60 % shell moisture content, all assessment criteria were significantly affected by hammer drop height. At 40 % shell moisture content the percentage FC had no significant linear relationship with hammer

Table 5. Relationship between shell, nut and kernel moisture contents (%)

Shell	10.0	20.0	30.0	40.0	50.0	60.0
Nut	11.9	23.0	33.8	45.4	56.5	68.6
Kernel	13.3	24.6	36.9	50.5	62.4	76.8

Table 6. Linear regression coefficients of the effects of drop height on the assessment criteria of conophor nuts for different shell moisture contents

Shell moisture (% db)	Assessment criteria	Coefficients		
		a	b	r
10	VC	10.0	-1.0	-0.3536
	FC	77.0	2.0	0.3536
	FCW	20.5	-2.5	-0.8839
	SM	-7.5	1.5	0.5303
20	VC	18.0	-2.0	-0.7071
	FC	119.0	-3.5	-0.6187
	FCW	-20.0	3.0	0.8660
	SM	-17.0	2.5	0.8839
30	VC	42.0	-4.0	-0.9701
	FC	112.0	-3.0	-0.6000
	FCW	-31.0	4.0	0.8944
	SM	-23.0	3.0	0.8660
40	VC	74.0	-5.0	-0.8839
	FC	42.5	0.5	0.1889
	FCW	-6.5	2.5	0.9449
	SM	-10.0	2.0	0.7559
50	VC	110.0	-8.0	-0.9428
	FC	-16.0	7.0	0.9439
	FCW	15.0	-0.5	-0.1889
	SM	-9.0	1.5	0.8660
60	VC	154.5	-12.5	-0.9791
	FC	-7.5	6.5	0.7941
	FCW	-27.5	3.5	0.8489
	SM	-19.5	2.5	0.8839

drop height depicting a transition conophor nut moisture content where the shell could crack and the kernel sustaining some wound without releasing the kernel.

Multiple regression equations of cracking percentage on hammer drop height and shell moisture content for the different assessment criteria showed no relationship in the SM criteria. For the others, their equations and regression coefficients are given below:

$$\begin{aligned} &VC: CP=60.76-10.24\,H+1.26\,MC\ (R^2=0.9893)\\ &FC: CP=3.38+14.31\,H-1.44\,MC\ (R^2=0.9708)\\ &FCW: CP=-20.78+5.12\,H-0.40\,MC\ (R^2=0.5780) \end{aligned} \quad (10)$$

where H - hammer drop height (cm) and MC - shell moisture content (%). Equation 10 shows that for FC and FCW the cracking percentage increased as drop height increased and shell moisture content decreased [34,35]. However, it was observed that conophor nuts were better cracked at shell moisture contents below 30 % and hammer drop heights of between 8 and 10 cm. More visible cracks were obtained at decreasing drop heights and increasing shell moisture contents.

Considering the effect of hammer drop height on the cracking percentage of the assessment criteria for all shell moisture contents only VC decreased with increasing drop

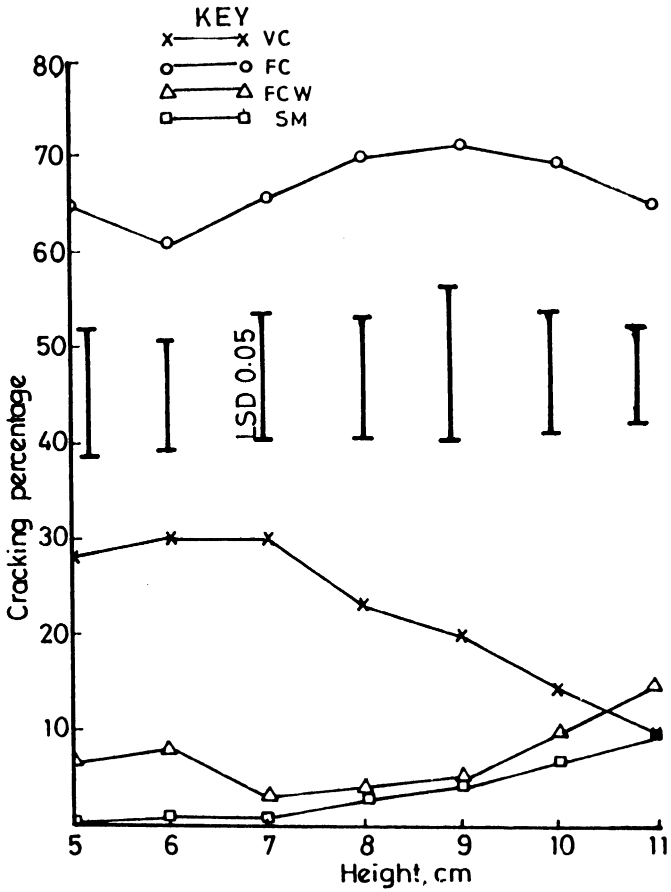

Fig. 5. Effect of various test heights on cracking efficiency of conophor nuts for all moisture contents (n=600).

height (Fig. 5). The linear correlation coefficient was highest in SM (0.9469) and lowest in FC (0.4570) (Table 7). However, the quadratic equation (9) relating cracking percentage to hammer drop height slightly improved the regression coefficient for the FC assessment criteria to r=0.6989 or R^2=0.4884.

$$CP=-13.303+20.423\,H-1.226\,H^2 \quad (r=0.6989) \qquad (11)$$

It also showed that cracking percentage in FC decreased with the square of drop height of the impacting hammer. The maximum percentage FC of about 70 % was obtained between the drop heights of 8 and 10 cm.

Table 7. Linear regression coefficients of the effects of drop height on the assessment criteria of conophor nuts for all moisture regimes

Assessment criteria	Coefficients		
	a	b	r
VC	49.22	-3.39	-0.9259
FC	60.95	0.71	0.4570
FCW	-0.83	1.04	0.5591
SM	-9.35	1.64	0.9469

Cracking energy and impacting velocity

The cracking energy of conophor nuts was found to be influenced by nut mass, radial diameter, and shell moisture content. For fresh conophor nuts, cracking energy increased with the increase in both nut mass and nut diameter as shown in Eq. (12):

$$CE=-0.552+7.172^{-03}M+0.026\,D\ (R^2=0.9238) \quad (12)$$

where CE - cracking energy (J), M - nut mass (g), and D - nut radial diameter (cm).

For conophor nuts at different shell moisture contents the cracking energy equation was found to be:

$$CE=4.53+0.076M-1.67D-8.96^{-03}MC\ (R^2=0.9074) \quad (13)$$

where MC - shell moisture content (%).

Equation 13 shows that cracking energy decreased with the increase in shell moisture content and nut radial diameter but increased with nut mass. When compared with Eq. (12) it is observed that shell moisture content plays an important role in the cracking of conophor nuts. However, the equation seems to connote that less cracking energy is required when the radial diameter and moisture content are high. This may not be true since all the three parameters of mass, diameter and moisture content should be taken together. And the equation relates only to the range of values obtained during the work. Also, it is observed from Eqs (12) and (13) that the nut mass was consistently positively correlated with cracking energy, showing that nut mass is an important factor when considering the cracking of nuts.

Cracking energy correlated positively with impacting velocity required to crack the conophor nuts and release the kernels. When the nuts are fresh the relationship between the cracking energy and impacting velocity was found to be:

$$CE = 0.064 + 0.012V \quad (r = 0.9294) \quad (14)$$

where V - impacting velocity (m/s).

However, for the nuts at various moisture contents, the linear regression equations were:

$$CE = 0.039 + 0.017\,V \ (r = 0.8835) \quad (15)$$

$$V = 2.055 + 0.063\,MC \ (r = 0.9825) \quad (16)$$

Showing that as cracking energy increased with increasing impacting velocity, the velocity also increased with shell moisture content. High shell and kernel moisture contents make nut cracking and kernel releasing difficult. However, as the nuts dry out, the kernel shrinks and its adherence to the shell weakens making its release from the cracked shell easy [25]. Cracking percentage of conophor nuts as well as their cracking energy and impacting velocities were all significantly influenced by shell moisture content.

CONCLUSIONS

1. The physical properties of the conophor nuts have been used to characterise them.
2. The nut cracking energy instrument is useful for generating energy data for the design of the conophor nut cracking machines.
3. Shell moisture content played an important part in the cracking of conophor nuts. Full cracking (FC) increased as shell moisture content decreased.
4. Full cracking (FC) increased with increase in drop height.
5. Cracking energy increased with nut mass and radial diameter of fresh conophor nuts but when regressed together with different shell moisture contents cracking energy decreased with increased moisture content and radial diameter.
6. Cracking energy increased with increased impacting velocity which increased with shell moisture content of the conophor nuts.
7. The nut and kernel moisture contents have high linear relationship with the shell moisture content given by the following equations:

$$MC_n = 0.31 + 1.13\,MC_s \ (r=0.9999)$$

$$MC_k = 0.37 + 1.27\,MC_s \ (r=0.9994)$$

where MC_n , MC_s and MC_k are moisture contents for nut, shell and kernel, respectively.

ACKNOWLEDGEMENT

The author is grateful to the Director, Institute of Erosion Studies, Federal University of Technology, Owerri for permission to use the Institute's laboratory and for Mr. Emmanuel and his technical assistance.

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