Compressive loading experiment of non-roasted bulk oil palm kernels at varying pressing factors**

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A b s t r a c t. Compression testing of non-roasted bulk oil palm kernels at different processing factors was performed using a universal compression testing machine and a pressing vessel with a plunger. The purpose of the research was to describe regression models of deformation, deformation energy and percentage kernel oil depending on force, speed and vessel diameter. The tested compression forces were 100, 125, 150, 175 and 200 kN, while the speeds were 5, 10, 15, 20 and 25 mm min^{-1}. Three pressing vessels of diameter 60, 80 and 100 mm were used. Samples were compressed at an initial height of 60 mm. For varying forces and vessel diameters at a constant speed of 5 mm min^{-1}, the values of deformation, deformation energy and percentage kernel oil ranged from 28.47±0.89 to 37.45±0.11 mm, 796±0.82 to 1795±49.01 J and 7.33±0.26 to 25.67±0.39%. At a constant force of 200 kN for different speeds and vessel diameters; the aforementioned determined parameters also ranged from 31.91±1.61 to 37.63±1.21 mm, 1012±26.76 to 1795±49.01 J and 14.66±0.42 to 24.98±1.37%. The results were statistically significant ($p<0.05$) or (F-ratio>F-critical), with high coefficients of determination between 0.74 and 0.99. Thus, higher force at specific speed may be needed to maximally recover kernel oil.

K e y w o r d s: non-roasted oil palm kernels, linear compression, vessel diameters, mechanical properties, regression equations

INTRODUCTION

In-depth knowledge of mechanical properties such as rupture force, deformation at rupture point, deformation ratio at rupture point, energy for rupture, volume energy or toughness and hardness of bulk oilseeds/kernels is essential for designing ultra efficient oil processing technology (Aripin *et al.*, 2012; Galedar *et al.*, 2009; Ozumba and Obiakor, 2011). These properties are influenced by several factors, including force, speed, moisture content, temperature, pressing vessel diameter, varieties of bulk oilseeds or kernels, among others (Deli *et al.*, 2011, Herak *et al.*, 2010).

The rupture force is the minimum force required to break the bulk material. This is a key factor influencing the energy demand of vegetable oil extraction, and determining the optimal force would enhance the oil recovery efficiency by minimizing the energy input (Akinoso and Raji, 2011; Herak *et al.*, 2010; Raji and Favier, 2004). Deformation at rupture point is the deformation at loading direction and is useful for determining the gap size between the surfaces needed for efficiently compressing the kernels for dehulling or shelling. Energy for rupture is the energy required to rupture the bulk material, and can be ascertained from the area under the rupture force and deformation at rupture point. Toughness is the ratio of rupture energy to that of the volume of sample. It is actually the work required to cause a rupture of the bulk material and can be approximated by the area under the force-deformation curve up to the rupture point. Hardness is the ratio of rupture force and deformation at rupture point (Galedar *et al.*, 2009; Karaj and Muller, 2010; Sirisomboon *et al.*, 2007).

The available literature on the compression loading of bulk oil palm kernels mainly evaluated the rupture force, deformation, energy and toughness of a single kernel or seed dependent on temperature, moisture content and loading position (Akinoso and Raji, 2011; Ozumba and Obiakor, 2011). In terms of oil recovery efficiency and energy utilization, the compression of bulk oil material is economically viable compared to a single kernel or seed under compression loading (Karaj and Muller, 2011; Tunde-Akintunde

et al., 2001; Zheng *et al.*, 2003). In view of that, our previously published studies focused on the mechanical behaviour of bulk oilseeds or kernels of rapeseeds, sunflower seeds, jatropha seeds and oil palm kernels in compression loading where the pressing factors such as force, speed and vessel diameter remained constant variables (Divišová *et al.*, 2014; Herak *et al.*, 2012, 2013; Kabutey *et al.*, 2013, 2015; Sigalingging *et al.*, 2014, 2015). Compression loading involves a process where the bulk material is pressed in a vessel or chamber that is placed under a universal compression testing machine. This vessel or chamber has holes that allows the leakage of oil (Herák *et al.*, 2013; Munson-Mcgee, 2014).

Information on the combined effect of the aforementioned pressing factors on the mechanical behaviour of bulk oil palm kernels under compression loading is limited. The present study seeks to remedy this by describing regression models of deformation, deformation energy and percentage oil yield of non-roasted bulk oil palm kernels depending on compressive force, compression speed and vessel diameter.

MATERIALS AND METHOD

Bulk oil palm kernels purchased from Afosu/Abirim in the Birim North District in the Eastern Region of Southern Ghana were used for the compression test. The moisture content of the samples was determined using the conventional method (ISI, 1996). From equation Eq. (1) (Blahovec, 2008), the moisture content was calculated to be 9.33 (% w.b.):

$$MC = \left(\frac{m_a - m_b}{m_a} \, 100\right), \qquad (1)$$

where: MC is the percentage moisture content on a wet basis (% w.b.), m_a and m_b are the masses of samples before and after oven drying at a temperature of 105ºC and a drying time of 17 h. A universal compression testing machine (ZDM 50, Czech Republic) and vessels of different diameters with a plunger were used. The initial height of the samples was measured at 60 mm. Two different experiments were carried out. The first was done by varying the forces (F_m, kN) between 100 and 200 kN and vessel diameters (D, mm) between 60 and 100 mm at a constant speed of 5 mm min^{-1}. The second test was done by varying the speeds (R_m, mm min^{-1}) between 5 and 25 mm min^{-1} and vessel diameters (D, mm) at a constant force of 200 kN. All data were subjected to statistical analysis using multiple regression analysis employed in STATISTICA 13 software (Statsoft, 2013).

The percentage kernel oil yield was determined as the ratio of the mass of kernel oil (the difference between mass of initial height of kernels and mass of kernel cake) to that of the initial mass of bulk kernels (measured at an initial height of 60 mm) multiplied by 100 - as given by Eq. (2) (Deli *et al.*, 2011):

$$O_y = \left(\frac{O_w}{O_m} \, 100\right), \qquad (2)$$

where: O_y is the percentage kernel oil (%), O_w is the mass of kernel oil (g) and O_m is the mass of initial pressing height of bulk kernels (g).

The volume of the bulk samples was determined using Eq. (3) (Chakespari *et al.*, 2010; Herak *et al.*, 2012):

$$V = \left[\left(\frac{\pi D^2}{4}\right) H_x\right], \qquad (3)$$

where: V is the volume of bulk kernels (m^3), D is the vessel diameter (mm), H_x is the initial height of bulk kernels (mm). For all vessel diameters, the calculated volume values were 16.97 10^{-5}, 30.16 10^{-5} and 47.13 10^{-5} m^3, respectively.

The deformation energy of the bulk kernels was also calculated using Eq. (4) (Demirel *et al.*, 2017; Herák *et al.*, 2013 ; Kabutey *et al.*, 2014):

$$U = \sum_{n=0}^{n=i-1} \left[\left(\frac{F_{n+1} + F_n}{2}\right) (x_{n+1} - x_n)\right], \qquad (4)$$

where: U is the deformation energy (J), $F_{n+1}+F_n$ and $x_{n+1}-x_n$ are the compressive force (N) and deformation (mm), n is the number of data points and i is the number of sections in which the axis deformation was divided (step measurement was 0.5).

The volume energy, u (J m^{-3}) of the bulk kernels was calculated using Eq. (5) (Chakespari *et al.*, 2010; Gupta and Das, 2000; Łysiak, 2007):

$$u = \frac{U}{V}. \qquad (5)$$

The hardness of the bulk kernels was calculated using Eq. (6) (Chakespari *et al.*, 2010; Herak *et al.*, 2012) which is the ratio of compressive force to that of the kernel maximum deformation:

$$S_x = \frac{F_m}{D_x}, \qquad (6)$$

where: S_x is the bulk kernels hardness (kN mm^{-1}), F_m is the compressive force (kN) and D_x is the bulk kernels maximum deformation (mm).

RESULTS AND DISCUSSION

The results of the study are presented in Tables 1 to 5 and Figs 1 and 2, respectively. For varying forces and vessel diameters at a constant speed of 5 mm min^{-1}, the aforementioned parameters also ranged from 28.47±0.89 to 37.45±0.11 mm, 796±0.82 to 1795±49.01 J and 7.33±0.26 to 25.67±0.39% (Table 1). The deformation decreased with increased vessel diameters, but increased with compression force increase. The deformation energy increased

Table 1. Deformation, deformation energy and oil yield of non-roasted bulk oil palm kernels at varying forces and vessel diameters

Level of factors		Mean ± standard deviation of measured amounts		
Forces (kN)	Vessel diameters D (mm)	Deformation D_x (10^{-3} m)	Deformation energy U (J)	Oil yield O_y (%)
100	60	35.67±0.21	796±0.82	22.16±1.04
	80	32.88±2.09	991±29.46	14.67±0.91
	100	28.47±0.89	1019±27.71	7.33±0.26
125	60	36.91±0.83	871±53.84	22.99±1.44
	80	33.25±2.19	1079±73.37	15.08±2.06
	100	31.37±0.49	1340±12.09	11.90±0.51
150	60	36.65±0.51	912±46.44	23.73±1.44
	80	34.66±1.56	1243±28.69	17.59±0.91
	100	32.41±0.15	1541±41.51	15.07±0.21
175	60	36.62±1.11	1007±15.10	25.30±0.13
	80	34.62±0.74	1353±57.77	19.46±1.23
	100	34.31±1.28	1673±43.19	16.16±0.37
200	60	37.45±0.11	1094±4.13	25.67±0.39
	80	35.23±0.57	1408±43.33	19.36±0.00
	100	34.72±0.45	1795±49.01	17.51±0.09

At a constant speed of 5 mm min^{-1}.

Table 2. Deformation, deformation energy and oil yield of non-roasted bulk oil palm kernels at different speeds and vessel diameters

Level of factors		Mean ± standard deviation of measured amounts		
Speeds R_m (mm min^{-1})	Vessel diameters D (mm)	Deformation D_x (10^{-3} m)	Deformation energy U (J)	Oil yield O_y (%)
5	60	37.37±0.00	1081±22.38	24.98±1.37
	80	35.79±0.22	1420±27.38	18.10±1.77
	100	34.98±0.08	1795±63.86	17.33±0.35
10	60	37.63±1.21	1078±14.26	24.19±0.52
	80	35.48±1.04	1345±10.89	17.84±0.04
	100	31.91±1.61	1720±15.69	16.49±0.37
15	60	36.75±0.71	1026±3.36	22.85±0.21
	80	34.62±2.45	1357±43.18	17.18±0.91
	100	33.84±0.27	1780±68.98	15.59±0.72
20	60	36.38±0.48	1012±26.76	22.31±0.72
	80	34.25±0.18	1357±15.75	16.82±0.76
	100	33.09±1.13	1686±14.05	15.08±0.60
25	60	36.96±0.78	1017±16.91	19.99±0.72
	80	34.31±1.05	1344±1.07	15.18±0.33
	100	32.86±0.31	1717±2.92	14.66±0.42

At a constant force of 200 kN.

Table 3. Repeated measured ANOVA statistical analysis of measured amounts of non-roasted bulk oil palm kernels

Measured variables	R^2	F-ratio	F-critical	p-value
Forces and vessel diameters at a constant speed of 5 mm min^{-1}				
Deformation (mm)	0.78	47.03		<0.05
Deformation energy (J)	0.92	156.6	2.64	<0.05
Kernel oil yield (%)	0.91	134.4		<0.05
Speeds and vessel diameters at a constant force of 200 kN				
Deformation (mm)	0.74	37.73		<0.05
Deformation energy (J)	0.99	979.8	2.64	<0.05
Kernel oil yield (%)	0.85	76.39		<0.05

Significant (p < 0.05 or F_{ratio} > $F_{critical}$). F-ratio is the value of the F test (-), F-critical is the critical value that compares a pair of models (-), p-value is the significance level used for testing a statistical hypothesis (-), R^2 is the coefficient of determination (-).

with both the vessel diameter increase and compression force increase. The percentage kernel oil decreased with increased vessel diameter, but increased with compression force increase. The linear regression models describing the dependence of deformation, deformation energy and kernel oil yield on force (F_m, kN) and vessel diameter (D, mm) are given in Eqs (7), (8) and (9) as follows:

$$D_x = -0.11\ D + 0.03\ F_m + 38.21, \quad (7)$$

$$U = 13.44\ D + 4.97\ F_m - 612.4, \quad (8)$$

$$O_y = -0.26\ D + 0.06\ F_m + 29.42. \quad (9)$$

In contrast, for different speeds and vessel diameters at a constant force of 200 kN; the values of deformation, deformation energy and kernel oil yield ranged from 31.91±1.61 to 37.63±1.21 mm, 1012±26.76 to 1795±49.01 J and 14.66±0.42 to 24.98±1.37% (Table 2). The deformation and percentage kernel oil decreased along with both speed increase and vessel diameter increase, while the deformation energy decreased with increasing speeds but increased with vessel diameter increase. The linear regression relationships explaining the function of deformation, deformation energy and kernel oil yield on speed (R_m, mm min^{-1}) and vessel diameter (D, mm) are shown in Eqs (10), (11) and (12) as follows:

$$D_x = -0.09\ D - 0.06\ R_m + 43.37, \quad (10)$$

$$U = 17.37\ D - 3.35\ R_m + 42.52, \quad (11)$$

$$O_y = -0.18\ D - 0.17\ R_m + 35.19. \quad (12)$$

The determined parameters were statistically significant (p<0.05) or (F-ratio>F-critical) with the coefficients of determination (R^2) between 0.74 and 0.99 (Table 3). This means that the varying pressing factors: speed, force and vessel diameter being the independent variables under
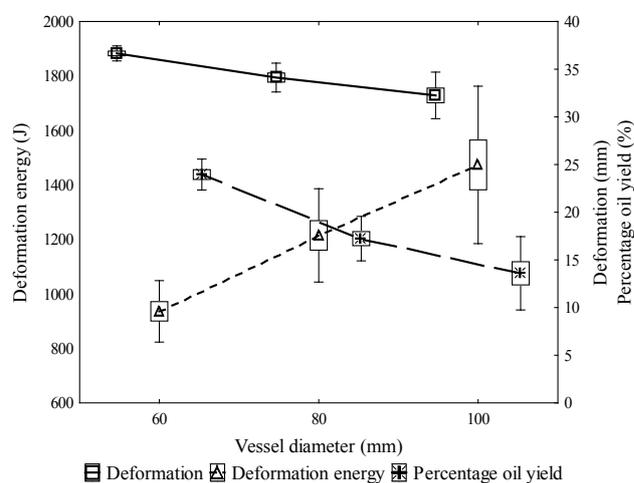
Fig. 1. Box plot of deformation, deformation energy and percentage oil yield versus vessel diameter.

consideration, influenced the dependent variables, namely, the deformation, deformation energy and kernel oil yield. Figure 1 shows the box plot of the dependencies of deformation, deformation energy and percentage kernel oil versus vessel diameter.

The volume energy and hardness are given in Tables 4 and 5. These parameters were not specifically dependent as described in Eqs (5) and (6), and the varying speeds had no significant effect. Contrarily, volume energy significantly decreased with increasing vessel diameters, while hardness increased. Furthermore, the volume energy increased along with the compression forces, while it decreased with the vessel diameter increase. The hardness, however, increased with increasing compression forces and increasing vessel diameters, respectively. We also observed that the kernels after compression did not achieve permanent deformation in relation to the applied loads and speeds. This suggests that more kernel oil could be obtained at a force greater than 200 kN. Generally, the volume energy and hardness represent the toughness or rigidity of the bulk material (Chakespari *et al.*, 2010; Łysiak, 2007; Gupta and Das, 2000).

**Table 4.** Hardness and volume energy of non-roasted bulk kernels at varying forces and vessel diameters

Forces D (kN)	Vessel diameters D (mm)	Volume energy u (10^6 J m^{-3})	Hardness S_x (kN mm^{-1})
100	60	4.69±0.05	2.80±0.02
	80	3.29±0.11	3.05±0.19
	100	2.16±0.06	3.51±0.11
125	60	5.14±0.32	3.39±0.08
	80	3.58±0.24	3.77±0.25
	100	2.84±0.03	3.99±0.06
150	60	5.38±0.27	4.09±0.06
	80	4.12±0.11	4.33±0.19
	100	3.27±0.09	4.63±0.02
175	60	5.93±0.09	4.78±0.15
	80	4.49±0.10	5.06±0.11
	100	3.55±0.09	5.11±0.19
200	60	6.45±0.02	5.34±0.02
	80	4.67±0.10	5.68±0.09
	100	3.81±0.10	5.76±0.08

At a constant speed of 5 mm min^{-1}.

Table 5. Hardness and volume energy of non-roasted bulk kernels at varying speeds and vessel diameters

Speeds R_m (mm min^{-1})	Vessel diameters D (mm)	Volume energy u (10^6 J m^{-3})	Hardness S_x (kN mm^{-1})
5	60	6.45±0.02	5.34±0.02
	80	4.67±0.14	5.68±0.09
	100	3.81±0.10	5.76±0.08
10	60	6.36±0.08	5.32±0.17
	80	4.46±0.04	5.64±0.17
	100	3.65±0.03	6.28±0.31
15	60	6.05±0.02	5.44±0.11
	80	4.51±0.14	5.79±0.41
	100	3.78±0.15	5.91±0.05
20	60	5.96±0.16	5.49±0.07
	80	4.50±0.05	5.84±0.03
	100	3.58±0.03	6.05±0.21
25	60	5.99±0.10	5.41±0.11
	80	4.46±0.00	5.83±0.18
	100	3.64±0.01	6.09±0.06

At a constant force of 200 kN.
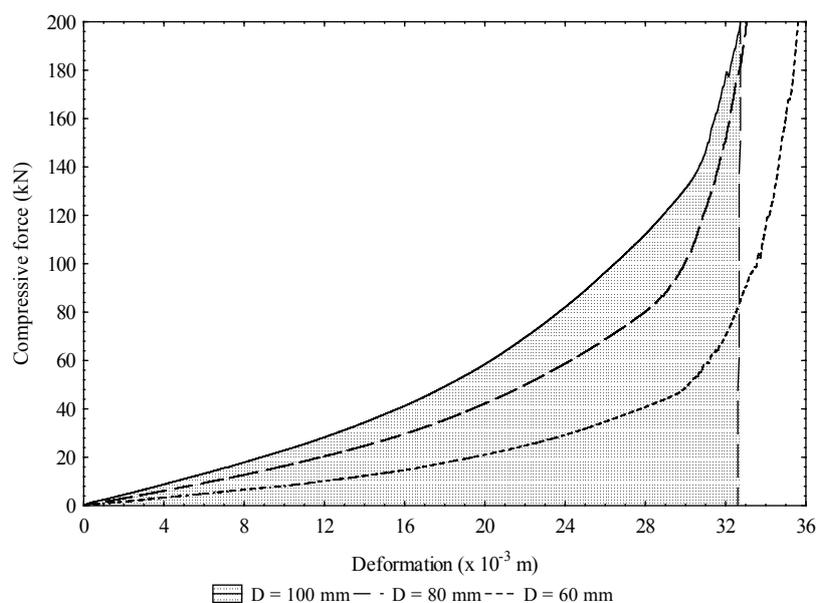
Fig. 2. Dependency between compressive force and deformation curves of non-roasted bulk oil palm kernels in relation to the vessel diameters (D).

The force-deformation curves from the compression test of non-roasted bulk oil palm kernels are illustrated in Fig. 2. The area under the curve represents the deformation energy (Łysiak, 2007; Gupta and Das, 2000) required for obtaining the kernel oil. In the literature, the force-defor-mation characteristic curve can also be employed to assess the damage during harvesting and handling of grains, seeds, fruits and vegetables, as well as other food products (Raji and Favier, 2004; Stroshine, 1998).

In a broader perspective, the results presented here are related to the findings of Deli *et al.* (2011) who compared pressure and oil yield of *Nigella sativa* L. seeds in response to two screw shafts of diameter 8 and 11 mm. The authors indicated that the pressure towards the seeds in the smaller shaft increased, resulting in higher percentage of oil recovered, while the bigger space provided by the bigger shaft needed a higher speed to give optimum pressure towards the seeds in order to achieve maximum oil yield.

Other studies (Beerens, 2007; Karaj and Muller, 2011) also indicated that lower energy input results in higher oil residue in seed-cake and higher material throughput since less time is available for oil leakage from the solids. Karaj and Muller (2011), also reported that the speed influences the energy and the processing time necessary for obtaining the maximum amount of oil. In addition, the viscosity thus remains lower at a higher speed resulting in less pressure and more oil content in press cake. In oil extraction involving the mechanical screw press, the general hypothesis is that higher pressure will result in higher temperature generation and higher oil recovery efficiency (Willems *et al.*, 2008; 2009). For optimizing the mechanical screw press, the pressing factors: force or pressure, speed and diameter of pressing chamber (among others) are important for consideration in compression loading experiments.

CONCLUSIONS

1. Linear regression models were described for non-roasted bulk oil palm kernels deformation, deformation energy and percentage kernel oil yield depending on speed, force and vessel diameter.

2. The models were statistically significant ($p<0.05$) or (F-ratio>F-critical), with high coefficients of determination between 0.74 and 0.99.

3. Higher percentage kernel oil was observed with the vessel diameter of 60 mm than the vessel diameters of 80 and 100 mm.

4. Percentage kernel oil yield decreased with the increase in speed.

5. For all the vessel diameters, at a maximum compressive force of 200 kN and a minimum speed of 5 mm min^{-1}, the bulk oil palm kernels did not achieve permanent deformation. This indicates the presence of oil residue in the kernels which might require a much greater force and/or a lower speed to recover.

Conflict of interest: The Authors do not declare conflict of interest.

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