Deformation energy of *Jatropha curcas* L. seeds under compression loading

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Abstract

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The present research is a follow-up of the previous studies on mechanical behaviour of *Jatropha curcas* L. seeds under compression loading. The research describes in detail the deformation energy which was determined from the area under the force-deformation curve. The compression device ZDM 50-2313/56/18 with a chart recorder and pressing vessel of diameter 76 mm were used to record the force-deformation functions of varying moisture content between 8.46% and 36.50% w.b. of *Jatropha curcas* L. seeds. Under the force-deformation curve, three main descriptions namely the increasing function (smooth curve), wave-effect characteristics (serration effect) and whole area under the force-deformation curve were analysed. For each of the force-deformation curve descriptions, it was found that moisture content influenced the values of compressive force, deformation, deformation energy and seed hardness. Interestingly, the research findings conclude that moisture content is a primary factor contributing to the wave-effect characteristics on the force-deformation curve.

Keywords: seed moisture content; compressive force; deformation curve; smooth curve; serration effect

Jatropha curcas L. is an energy crop which is used as a feedstock for biodiesel production (Heller 1996). The crop can be grown on degraded and marginal lands and under drought conditions (Brittaine, Lutaladio 2010). The plant and seeds are non-edible to both humans and animals due to the presence of toxic substances such as curcine and deterpine (Heller 1996; Martinez et al. 2006). Since jatropha oil is a potential biodiesel feedstock, the study of the physical and mechanical properties of the crop has become very important especially for optimization of mechanical oil extraction method involving screw presses or extruders. However, literature information on the physical properties and notably mechanical behaviour of jatropha crop are limited (Sirisomboon, Kitchaiya 2009) compared to other oil-bearing crops such as sunflower, rape, flax, peas and others (Gupta, Das 2000; Lysiak 2007).

In the present research the mechanical properties of jatropha crop with respect to the exact value

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of compressive force, deformation, deformation energy, seed hardness and behaviour of force-deformation curve in relation to moisture content were investigated.

Generally, agricultural materials and food products deform in response to applied forces and the amount of force required to produce a given amount of deformation varies widely among different materials (Stroshine, Hamann 1994 cit. in Zareiforoush et al. 2010). The dependence between compressive force and deformation of a given oil-bearing crop can also be used to estimate the energy which is characterized by the area under the force-deformation curve (Lysiak 2007).

From the previous study on behaviour of different moisture content of *Jatropha curcas* L. seeds under compression loading (Kabutey et al. 2011), it was found that the whole area under the force-deformation curve, deformation and deformation energy of *Jatropha curcas* L. seeds increased with increasing moisture content. Similar results were also reported by (Burubai et al. 2007) for the effect of temperature and moisture content on the strength properties of African nutmeg (*Monodora myristica*). Further, the results of the previous study (Kabutey et al. 2011) revealed that at low moisture content the force-deformation curve showed smooth curve without the wave-effect characteristic or serration effect which is caused by high moisture content.

However, the previous study did not describe the different pressing areas under the force-deformation curve with respect to the amount of compressive force, deformation, deformation energy, seed hardness and specifically, the pressing area under the force-deformation curve where the wave-effect characteristic actually starts. This information is relevant for determining the correct amount of compressive force required for obtaining the oil (Herak et al. 2010). The "wave-effect characteristic" is when the deformation of plant seeds during compression becomes a trigonometric function instead of a linear function (Herák et al. 2012).

The objective of this present research was to describe the different pressing areas under the force-deformation curve of *Jatropha curcas* L. seeds. These pressing areas included the increasing function area, pressing area with wave-effect and the whole pressing area under the curve by examining the effect of moisture content on pressing force (N), deformation (mm), deformation energy (J), seed hardness (N/mm) and volume energy (J/m^3).

MATERIAL AND METHODS

Cleaned *Jatropha curcas* L. seeds originally from North Sumatera, Indonesia but obtained from the Farmet a.s., Česká Skalice, Czech Republic were used for the experiment. The standard hot air oven method with a temperature setting of 105°C and a drying time of 17 h (ISI 1966) was used to determine the initial moisture content. In order to investigate the effect of moisture content on the force-deformation curve and other parameters, the jatropha seeds were moistened and placed in a refrigerator at 5°C for varying moistening time periods between 6 and 24 hours. The laboratory temperature condition was 20°C. Electronic balance (Kern 440-35; Kern & Sohn GmbH, Balingen, Germany) having an accuracy of 0.001g was used to weigh the samples and the different moisture content values obtained from the samples were calculated from Eq. (1) given by Blahovec (2008).

$$MC_{\text{w.b.}} = \left[\frac{M_i - M_c}{M_i}\right] \times 100\% \qquad (1)$$

where:

$MC_{\text{w.b.}}$ – moisture content on wet basis (%)

M_i – weight of the sample in the initial state (g)

M_c – weight of the sample after oven drying (g)

The moisture content determinations were repeated three times and mean values were used in subsequent calculations. The obtained results were interpreted using the Statistica Software (OK 74104; Statsoft Inc, Tulsa, USA).

Compression test. Compression device ZDM 50-2313/56/18 with a chart recorder (VEB, Dresden, Germany) and pressing vessel (steel; Czech University of Life Sciences Prague, Prague, Czech Republic) of diameter 76 mm was used to compress the varying moisture content of jatropha seeds ranging between 8.46% and 36.50% wet basis (w.b.). Compression was done under the temperature of 20°C, pressing rate of 1mm/s and compressive force of 100 kN being the min. limit of the compression device. After pressing, the force-deformation characteristic curves obtained directly from the chart recorder were analysed again using the software programme Engauge Digitizer 4.1 (Mitchell 2002) to obtain the geometry information on the curve with respect to values of pressing force and deformation, respectively.

Deformation energy. The deformation energy which is the area under the force-deformation curve (Lysiak 2007) was calculated using Eq. (2) (Herak et al. 2010).

$$E = \sum_{n=0}^{n=i-1} \left[\left(\frac{F_{n+1} + F_n}{2} \right) \times \left(x_{n+1} - x_n \right) \right] \tag{2}$$

where:
E – deformation energy (J)
F_n, F_{n+1} – values of compressive force (N)
X_n, X_{n+1} – values of seed deformation (m)

Pressing seed volume. Seed volume was determined using Eq. (3):

$$V = \frac{\pi \times D^2}{4} \times H \tag{3}$$

where:
V – pressing seed volume (m^3)
D – diameter of pressing vessel, 76 mm
H – height of seeds in the pressing vessel which was measured at the height of H = 50 mm for all respective seed moisture content

The pressing seed volume using Eq. (3) was found to be 2.26 × 10^{-4}m^3 which was constant for all moisture content of the *Jatropha curcas* L. seeds.

Energy per unit volume. The volume energy, also known as the toughness, is the ratio of the deformation energy and pressing seed volume Eq. (4), (Gupta, Das 2000):

$$e = \frac{E}{V} \tag{4}$$

where:
e – volume energy (J/m^3)
E – deformation energy (J)
V – pressing seed volume (m^3)

Seed hardness. The hardness (S_H; N/mm) calculation was determined using Eq. (5) which is defined as the ratio of pressing force (P_F; N) to that of the seed max. deformation (D; mm):

$$S_H = \frac{P_F}{D} \tag{5}$$

RESULTS AND DISCUSSION

The results of the study are given in Tables 1 and 2 and Figs 1–4. The study considered the deformation energy of *Jatropha curcas* L. seeds of

Table 1. Average values (± standard deviation) of measured parameters under the pressing area in relation to moisture content

Moisture content (% w.b.)	Pressing force (N)	Deformation (mm)	Deformation energy (J)	Hardness (mm)	Volume energy (10^6 J/m^3)
Parameters with increasing function					
8.46	97,938 ± 140.00	34.56 ± 0.97	438.66 ± 16.91	2,835.33 ± 81.91	1.93 ± 0.07
28.57	63,014 ± 1807.06	27.88 ± 0.73	232.87 ± 4.57	2,260.73 ± 84.22	1.02 ± 0.02
32.02	57,289 ± 6211.02	28.86 ± 0.21	231.10 ± 18.98	1,984.63 ± 212.84	1.01 ± 0.08
34.05	41,186 ± 2437.86	27.38 ± 0.75	160.85 ± 11.17	1,504.33 ± 92.93	0.71 ± 0.05
36.50	39,447 ± 5274.65	26.87 ± 1.76	158.23 ± 19.42	1,463.59 ± 99.51	0.69 ± 0.09
Parameters with wave-effect					
8.46	0.00	0.00	0.00	0.00	0.00
28.57	34,711 ± 1,555.89	2.69 ± 0.47	233.93 ± 3.91	13,125.08 ± 1,800.71	1.03 ± 0.01
32.02	40,683 ± 6,151.48	3.79 ± 0.54	285.72 ± 23.12	10,716.63 ± 105.18	1.25 ± 0.10
34.05	56,545 ± 2,150.82	5.44 ± 0.41	369.34 ± 25.53	10,420.89 ± 58.77	1.62 ± 0.11
36.50	58,226 ± 5,332.77	5.02 ± 1.05	394.02 ± 20.65	11,777.64 ± 1,370.45	1.73 ± 0.09
Parameters under the whole pressing area					
8.46	97,938 ± 140.00	34.56 ± 0.97	438.67 ± 16.90	2,835.33 ± 81.91	1.93 ± 0.07
28.57	97,725 ± 264.82	30.57 ± 1.12	466.80 ± 4.76	3,199.31 ± 116.21	2.05 ± 0.02
32.02	97,672 ± 110.21	32.65 ± 0.55	516.82 ± 7.26	2,991.49 ± 51.47	2.27 ± 0.03
34.05	97,731 ± 320.88	32.82 ± 0.53	530.20 ± 17.42	2,977.68 ± 49.17	2.33 ± 0.07
36.50	97,673 ± 188.91	31.89 ± 0.97	552.26 ± 24.44	3,063.92 ± 90.58	2.43 ± 0.11

Table 2. Statistical analysis of determined parameters of *Jatropha curcas* L. seeds force deformation curve descriptions, while $F_{critical}$ = 5.31

Force deformation curve description	Determined parameters	Equation	R^2	F	P <
Increasing function (Smooth curve)	compressive force (N)	–2,049MC + 116,984	0.95	62.19	0.05
	seed deformation (mm)	–0.27MC + 36.69	0.95	59.19	0.05
	deformation energy (J)	–10.04MC + 524.79	0.97	119.27	0.05
	hardness (N/mm)	$-2.83MC^2 + 74.64MC + 2,407.64$	0.96	27.75	0.05
Wave-effect characteristics (Serration effect)	compressive force (N)	$55.88MC^2 - 368.93MC - 895.52$	0.97	46.98	0.05
	deed deformation (mm)	0.18MC – 1.77	0.91	30.81	0.05
	deformation energy (J)	13.32MC – 120.24	0.97	108.66	0.05
	hardness (N/mm)	–26.8MC – 1,585MC + 11,438	0.95	21.96	0.05
Whole area under the force-deformation curve	compressive force (N)	–9.41MC + 98,010	0.92	39.37	0.05
	seed deformation (mm)	$0.02MC^2 - 0.74MC + 39.73$	0.83	5.21	> 0.05
	deformation energy (J)	$0.31MC^2 - 9.58MC + 497.36$	0.97	40.13	0.05
	hardness (N/mm)	$-1.06MC^2 + 52.85MC - 2,467.72$	0.65	1.92	> 0.05

MC – moisture content (% w.b.) of *Jatropha curcas* L. seeds; R^2 – coefficient of determination (–); F – value of F test that compares a pair of models (–); P – hypothesis value of the study outcomes significant level (–); $F_{critical}$ – critical value that compares a pair of models (–)

varying moisture content between 8.46 and 36.50% w.b. The deformation energy is the energy which is characterized by the area under the force-deformation curve (Lysiak 2007). Three different pressing areas were described under the force-deformation curve by examining the effect of moisture content on pressing force (N), deformation (mm), deformation energy (J), seed hardness (N/mm) and energy per unit volume (J/m^3) of *Jatropha curcas* L. seeds.

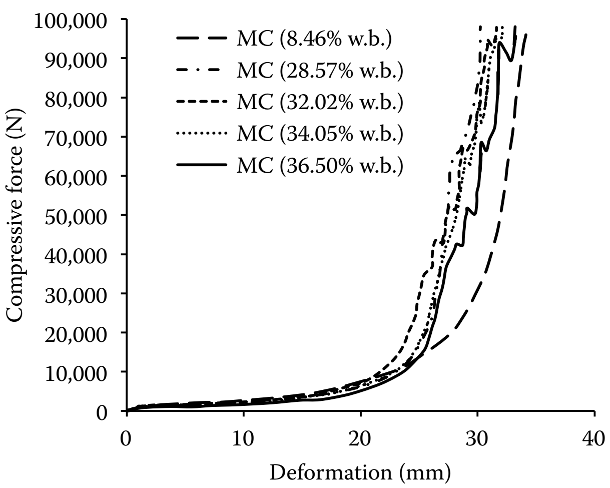

Fig. 1. Dependency between compressive force and deformation in relation to varying moisture content (MC) between 8.46 and 36.50% w.b. of *Jatropha curcas* L. seeds

Statistical analysis of determined parameters under the increasing function area without serration or wave-effect characteristics were significant at 5% probability level which indicates that an increase in moisture content linearly decreased the pressing force, deformation, deformation energy and seed hardness as shown in Fig. 2. It was observed during the compression test that at high moisture content the crude jatropha oil contained in the seed can only be obtained within this pressing region. This limit area confirms the statement that if the actual compressive force is determined for compression of oilseeds, higher oil recovery efficiency can be achieved with min. energy (Herak et al. 2010).

Beyond the increasing function area until compression was fully completed is the pressing area with wave-effect characteristic or serration effect (Fig. 1). This effect on the force-deformation curve increased with increasing moisture content. But, other pressing factors such as compressive force and internal friction between the seeds and the inner walls of the pressing vessel could likely cause serration or wave-effect and these factors would be considered in detail in future research. There was no oil flow under the area with wave-effect. Obviously,

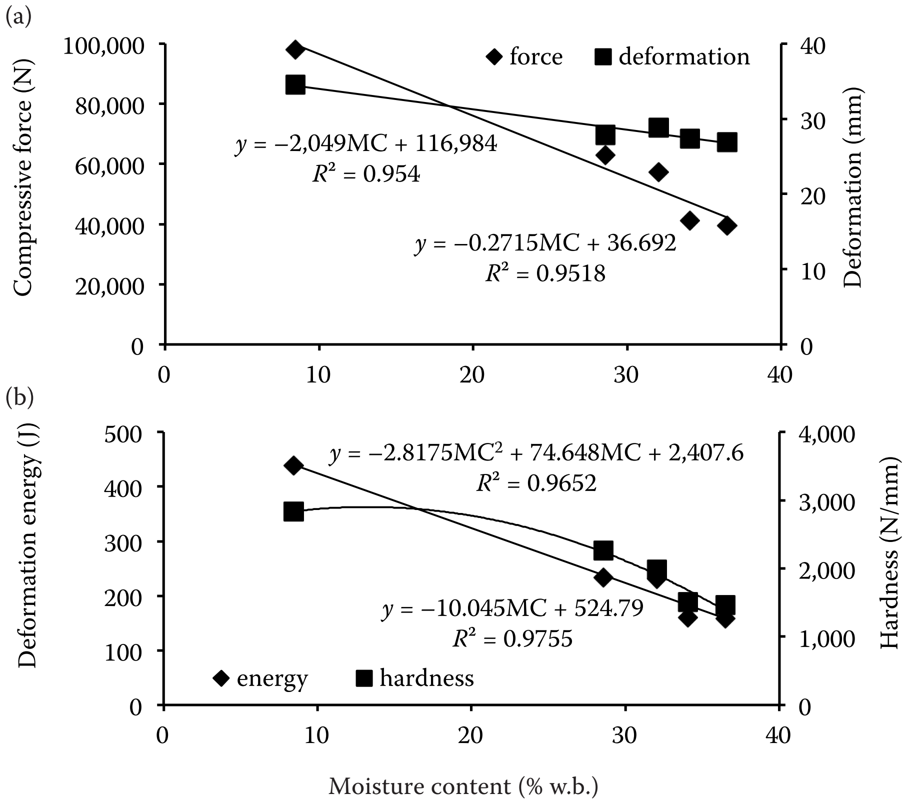

Fig. 2. Effect of moisture content (MC) of *Jatropha cucrcas* L. seeds on (a) compressive force (N) and deformation (mm) and (b) deformation energy (J) and hardness (N/mm) under the force-deformation curve with increasing function (smooth curve)

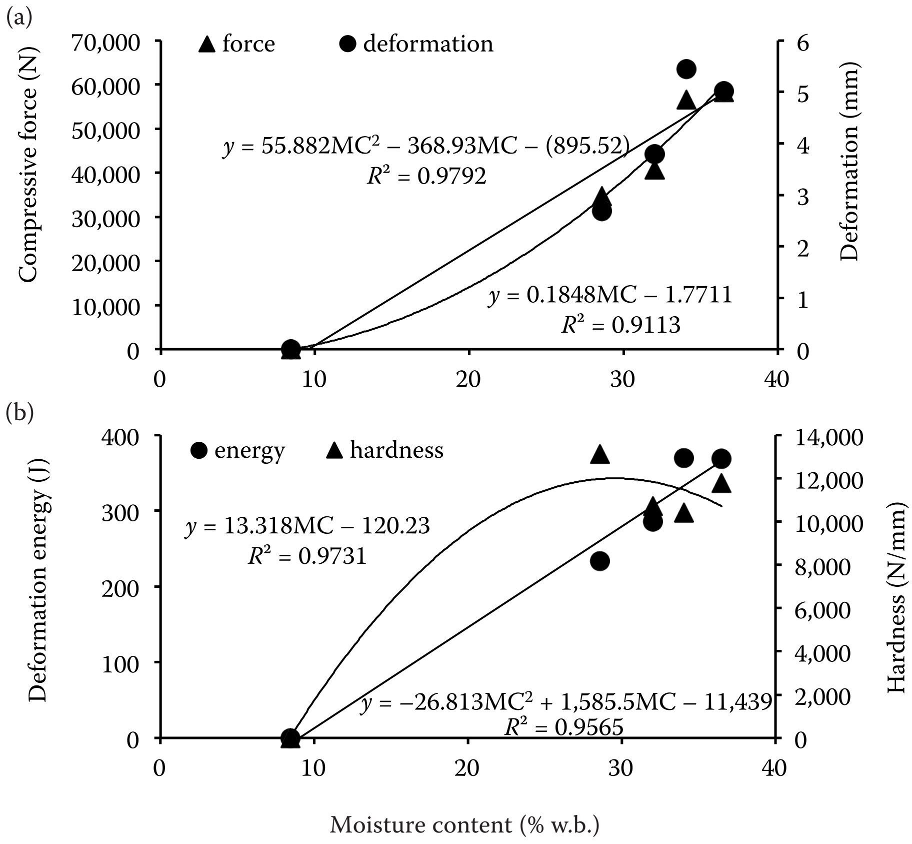

Fig. 3. Effect of moisture content (MC) of *Jatropha cucrcas* L. seeds on (a) compressive force (N) and deformation (mm) and (b) deformation energy (J) and hardness (N/mm) under the force-deformation curve with wave-effect characteristics (serration effect)

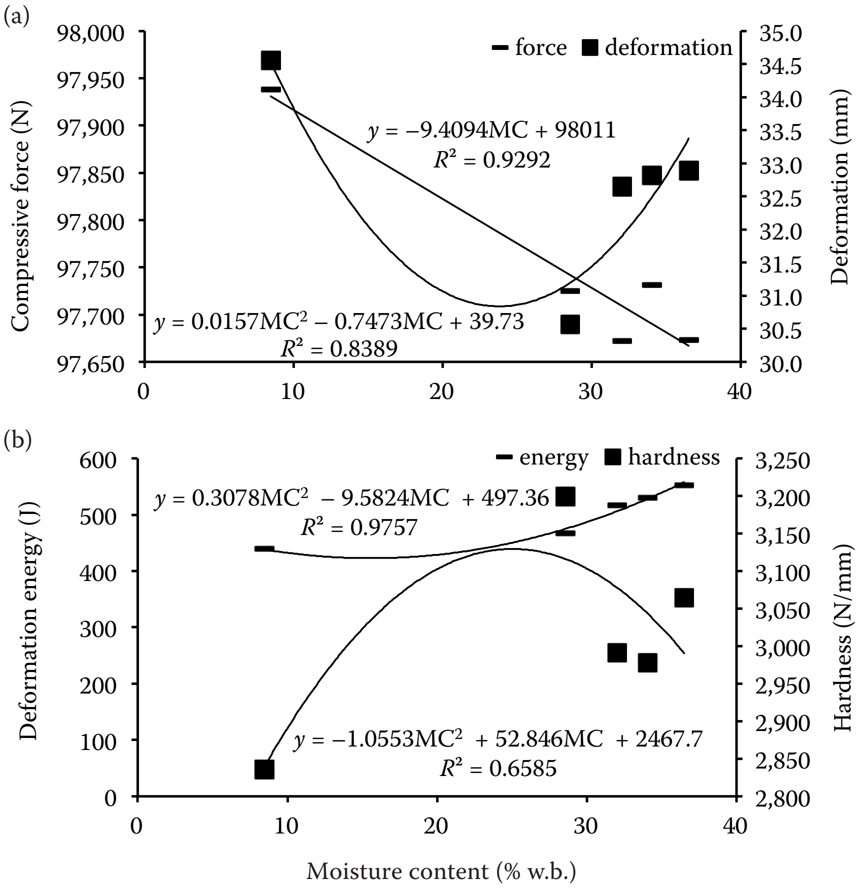

Fig. 4. Effect of moisture content of *Jatropha cucrcas* L. seeds on (a) compressive force (N) and deformation (mm) and (b) deformation energy (J) and hardness (N/mm) under the whole area of the force-deformation curve

the display of the wave-effect behaviour on the force-deformation curve was followed by the ejection of the kernel cake through the holes of the pressing vessel. Additionally, it was observed that at low seed moisture content the force-deformation curve showed smooth characteristics without wave-effect behaviour which agrees with the previous results published by the authors (Kabutey et al. 2011). All measured parameters were statistically significant ($P < 0.05$) whereby linear function best fitted the compressive force and deformation energy in relation to moisture content while polynomial function best suited the relationship between seed deformation and moisture content as well as seed hardness and moisture content (Fig. 3).

For the whole pressing area under the force-deformation curve (Fig. 4) which is a combination of both the increasing function area and the area with wave-effect, statistical analysis of determined parameters showed both significant ($P < 0.05$) and non-significant ($P > 0.05$) results. Increase in moisture content influenced the compressive force and seed deformation. Similar results were obtained from studies conducted by Gupta and Das (2000) and Burubai et al. (2007) on sunflower seeds and nutmeg respectively. The deformation energy and seed hardness were not statistically significant in relation to the effect of moisture content as indicated (Table 1). However, the increase in seed deformation was as a result of the plasticizing effect of the seeds moisture content as explained by (Lysiak 2007) while the increase in deformation energy was attributed to the whole pressing area under the curve with or without wave-effect behaviour, meaning that the bigger the pressing area under the force-deformation curve the greater the deformation energy and vice versa. Furthermore, when there is wave-effect behaviour as a result of moisture content, the seed deformation as well as the deformation energy directly increases as reported in the previous study (Kabutey et al. 2011).

Finally, the present study results showed that mechanical properties and behaviour of the force-deformation characteristic curve of *Jatropha curcas* L. seeds were greatly influenced by moisture content. Similarly, as reported by (Singh et al. 2002) the seed moisture content affects residual oil content and oil recovery efficiency in case of screw presses; that is, higher moisture content increases plasticity and thereby reduces the level of compression and contributes to low oil recovery. Also higher moisture content acts as a lubricant resulting in insufficient friction during pressing.

CONCLUSION

The study results showed that two main pressing areas can be described under the force-deformation curve in relation to moisture content. These are the increasing function area and the area with serration effect. The increase in moisture content of *Jatropha curcas* L seeds was found to be the cause of serration effect on the force-deformation curve. However, other pressing factors such as compressive force and friction are likely to contribute to similar behaviour and this investigation would be considered in future research. Compressive force, deformation, deformation energy and seed hardness were influenced by the increase in moisture content. The results obtained herein would be useful for designing suitable equipment for processing of oil from oil bearing crops.

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