Mechanical behaviour of several layers of selected plant seeds under compression loading

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Abstract

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This article is focused on the determination of the mechanical behaviour of several layers of plant seeds namely; garden pea (*Pisum sativum* L.), common bean (*Phaseolus vulgaris* L.), common sunflower (*Helianthus annuus* L.) and jatropha (*Jatropha curcas* L.) seeds under compression loading. The results from the experiment showed that during compression plant seeds may change their mechanical behaviour that is deformation characteristic ceases to be a function of growing and beginning to resemble that of trigonometric functions and this behaviour is called the "wave effect". Also the strain value at which there is no further change of the mechanical behaviour is actually a local maximum of deformation characteristic and this is called the limit deformation. Exceeding this value can cause vibration of the presser including other negative factors which influences the process of pressing. The amounts of the limit deformation, strain energy and volume energy for jatropha, common bean, common sunflower and garden pea were determined in this experiment. From the calculated amounts of the volume energy, garden pea had the best resistance to change in the mechanical behaviour due to the fact that its change in the mechanical behaviour was not discovered. The other plant seeds; common beans, common sunflower and jatropha with respect to resistance to change in the mechanical behaviour followed in that order of magnitude.

Keywords: jatropha; common bean; garden pea; common sunflower; pressing; wave effect

In oil extrusion with usual extruders used in industrial practice, there is non-linear compression of pressed mixture incurred during the processing. This means that the compression is combination of translational movement moving and rotational movement. For better understanding of mechanical behaviour of plant seeds under compression loading, it is necessary first to understand mechanical behaviour of one free placed seed and one layer of seeds with limited deformation and also mechanical behaviour of more layers of the seeds. Earlier experiments conducted with plant seeds, namely jatropha, palm oil, sunflower and knotweed, showed that the specific strain energy required for deformation of one free placed seed was much greater than for pressing the same seeds layer (Fomin 1978; Blahovec, Řezníček 1980; Herák et al. 2007). There is a dynamic effect on plant tissue and thus higher cell damage (Addy et al. 1975), which is arising due to radial pressure during pressing, the gradual deformation of seeds, seeds of mutual friction and friction of the seed on the pressing vessel. There is also a required gradient of pressing pressure, and thus if the pressure gradient is increased the volume strain energy decreases. High pressure gradients also occur on the edges of holes when the input material is forced through (Danilov 1976). Pressure gradient is provided by the movement of fluid from inside the material on its surface. Liquid and solid phases are mixture of different phases which are not strongly bound to each other. The pressed material is viscoelastic and its mechanical properties generate greater stresses for dynamic loading than for static loading at the same energy consumption (Blahovec, Řezníček 1980).

During mechanical loading, the cells behave like thin-walled shell structures (Koegel et al. 1973). For the desired deformation, it is therefore necessary to produce the frictional force acting on the tangential stress. When the layer of cells is pressed, the pressure of fluid in the cells increases and the cells expand in width. The pressure fluid is not the same in all cells. The largest pressure is in the middle layer and it decreases gradually toward the edges (Fomin 1978). A breach wall cell occurs at the edge of the layer which again is the largest pressure gradient. In compression of more layers of materials, cumulating deformation energy occurred in the compressed material during the process of compression. In rupturing some of the cells, the stress of this cell is transmitted to other cells with only small losses of energy consumed to displace liquid from broken cells. There is a stress gradient not only in the radial direction but also in the axial direction (Blahovec, Řezníček 1980). The pressure gradient thus causes a change in the mechanical behaviour of plant seeds during pressing. To some extent, however, the pressing force or volume energy and the deformation characteristics are globally (strictly) monotonic increasing functions (Faborode, Favier 1996; Očenášek, Voldřich 2009; Tavakoli et al. 2009; Herák et al. 2010; Herák et al. 2011); thus, if the pressing force is increased the deformation increases. In the same way, with some value of the pressing force, volume energy and the deformation characteristics are the local monotonic functions, and thus if the deformation is increased, the pressing force remains constant or decreases. This effect is denoted as "wave effect" in this article. In fact, the mechanical properties of pressed plant seeds as well as temperature of pressed mixture of plant seeds can also be changed (Resende et al. 2007; Kabutey et al. 2011). In some cases, the initial temperature of the pressing mixture is higher than ambient temperature and it occurs when there is a heat transfer between the mixture, the pressing device and the environment. The aim of this experiment was to determine deformation characteristics for several layers of selected plant seeds, namely common sunflower, common bean, garden pea and jatropha, under compression loading, and also to determine the amount of volume energy at which there is no occurrence of "wave effect" characteristic (Kabutey et al. 2011). From previous experiments (Fomin 1978) it is known that the change in mechanical behaviour of plant seeds under compression loading is generally affected by moisture content. The moisture contents of the plant seeds were determined by artificially soaking the seeds in water and the values obtained were higher than the natural conditions.

MATERIAL AND METHODS

Sample

Materials used were intact and undamaged seeds of common bean (*Phaseolus vulgaris* L.), garden pea (*Pisum sativum* L.), common sunflower (*Helianthus annuus* L.), and jatropha (*Jatropha curcas* L.). Ten samples from each compressed plant seeds were laid-out and their physical properties are presented in the Table 1. The cleaned plant seeds were soaked in water for 3 days in a refrigerator at 5°C and their moisture contents before soaking Mcb (% d.b.) and after soaking Mca (% d.b.) were determined using the ASTA 1985 method (Olaniyan, Oje 2002), the weight of the samples m_s (g) was determined using equipment Kern 440–35N (Kern & Sohn GmbH, Stuttgart, Germany) and the porosity P_f (%) for the soaked seeds was calculated from bulk and true densities using the relationship given by porosity Eq. (1) (Sirisomboon et al. 2007).

$$P_f = \left(1 - \frac{\rho_b}{\rho_s}\right) \times 100 \qquad (1)$$

where:

P_f – porosity (%)

ρ_b – bulk density (kg/m^3) it was determined as the weight of the sample divided by volume of pressing vessel 3.627 × 10^{-4} m^3

ρ_t – true density (kg/m^3) it was determined for average moisture content of each sample from the previously experiments as jatropha 971 kg/m^3 (Sirisomboon et al. 2007), common sunflower 885 kg/m^3 (Isik, Izli 2007), garden pea 1,150 kg/m^3 (Yalcin et al. 2007), common bean 1,370 kg/m^3 (Ozturk et al. 2009)

Table 1. Determined physical properties of selected pressed samples (mean ± SD)

Plant seeds	Weight of the sample m_s (g)	Porosity of the sample P_f (%)	Moisture content before soaking Mcb (% d.b.)	Moisture content after soaking Mca (% d.b.)
Jatropha	132.6 ± 5.2	62.18 ± 0.32	5.39 ± 0.65	26.22 ± 0.77
Common sunflower	146.7 ± 6.6	51.46 ± 1.23	8.45 ± 0.56	28.49 ± 0.87
Common bean	262.8 ± 3.2	48.38 ± 1.62	9.15 ± 0.23	31.34 ± 0.93
Garden pea	278.6 ± 6.5	36.83 ± 0.73	10.3 ± 0.45	32.60 ± 0.38

Pressing force

To determine the development of the relationship of the pressing force and linear deformation, the ZDM 50 – 2313/56/18 (VEB, Dresden, Germany) pressing device was used to record the course of deformation function in an exact and analogical manner. A pressing plunger and pressing vessel with inner diameter D = 76 mm (Fig. 1) were also used. The pressed seeds were placed into pressing vessel and height of the seeds layers was H = 80 mm. The seeds were pressed under the temperature of 20°C. The pressing speed was v = 1 mm/s. The experiment was repeated for each mixture of plant seeds 10 times. The measuring range of force was from the value 0 N up to 250 kN, in which the test was stopped. Individual points of measurement were digitally recorded and analysed with each new addition of deformation of 0.5 mm. The amount of the limit deformation δ (mm) was determined by the measured value of the first local maximum deformation characteristic. This limit deformation is a coordinate of the origin of the "wave effect". Generally, it can be described as the relationship between pressing force F (N) and deformation x (mm) using Eq. (2), where the pressing force is a function of deformation

$$F(x) = f(x) \tag{2}$$

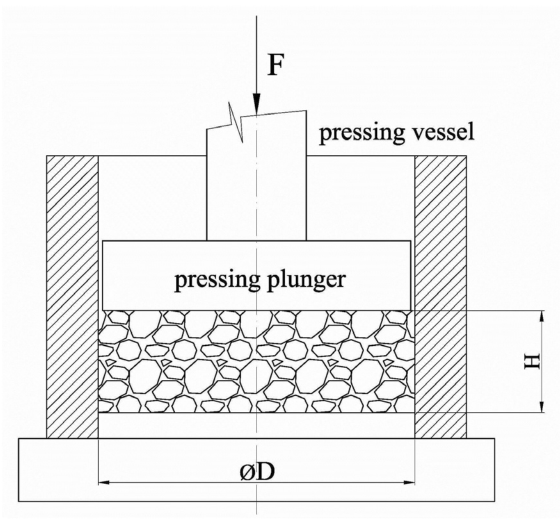

Fig. 1. Scheme of the pressing equipment

Strain energy

If the relationship between the pressing force and deformation in Eq. (2) is integrated on the interval from zero deformation to limit deformation the amount of the limit deformation energy using Eq. (3) can be determined. This energy will not change the mechanical behavior of the seeds when the "wave effect" characteristic has not displayed.

$$E = \int_0^{\delta} F(x)\,dx \tag{3}$$

Volume energy

Volume energy is the amount of the strain energy Eq. (3) divided by deformed volume Eq. (4) (V, mm^3) which is the cross-section of pressing vessel multiplied by limit deformation;

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

then the amount of the limit unit volume energy in Eq. (5) (e, 10^{-3} × J/mm^3) can also be calculated.

$$e = \frac{E}{V} \tag{5}$$

RESULTS AND DISCUSSION

Pressing force

Results from the experiment showed that there are different dependencies between compressive force and deformation for each pressed mixture of plant seeds. The average values from the data measured

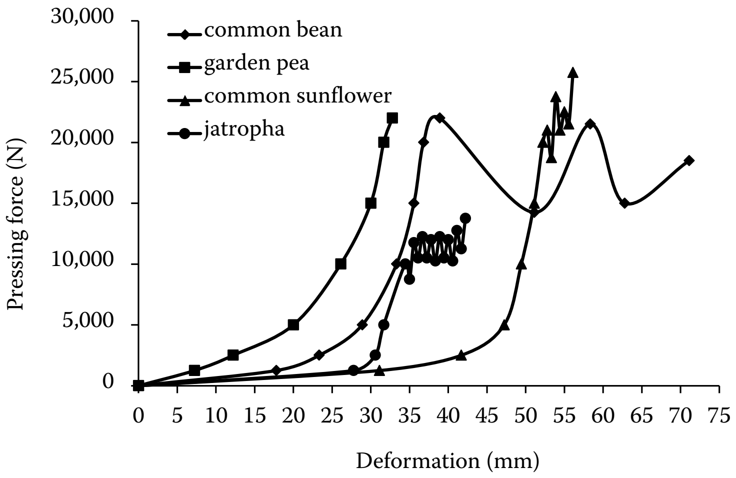

Fig. 2. Measured mechanical characteristics of selected seeds

during the experiment are graphically displayed in the graph (Fig. 2). The figure of the general shape of deformation characteristic (Fig. 3) shows that the characteristics of pressed plant seed appeared from zero deformation into the first limit deformation as the dependencies that can be replaced by function similar to tangent curve (Herák et al. 2010, 2011). From the Fig. 3 it is clear that this region is essentially the increasing function area and from this first limit deformation to the second limit deformations the characteristics can be replaced by functions similar to trigonometric functions and this region is the "wave effect" area.

From the results of the deformation characteristic and with the measured value of the first local maximum deformation characteristic, the amounts of the limit deformation δ (mm) for all measured seeds were determined and are presented in Table 2.

Strain energy

The amounts of limit strain energy using Eq. (6) were determined by both Eq. (3) and pressing force Eq. (2). These values were calculated from zero deformation to the limit deformation for each plant seeds. In actual sense, strain energy is the size of the area under the deformation curve, which can be set as the sum of the squares Eq. (6).

$$E = \sum_{n=0}^{n=i-1}\left[\left(\frac{F_{n+1}+F_n}{2}\right)\times\left(x_{n+1}-x_n\right)\right] \tag{6}$$

where:

i – number of sections in which the axis deformation was divided (step measurement was 0.5 mm)

F_n – compressive force for deformation x_n (mm) (N)

E – strain energy (J × 10^{-3})

The calculated amounts of the limit strain energies are presented in Table 2.

Volume energy

The limit deformation volumes for each crop were determined using Eq. (4) and are displayed in Table 2. Also the amounts of limit volume energy are calculated by Eq. (4) using the values of limit strain

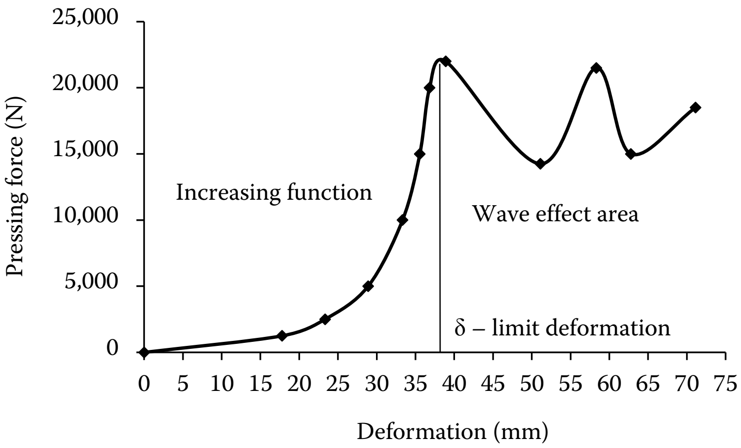

Fig. 3. General shape of mechanical characteristics

Table 2. Measured and calculated amounts of selected seeds (mean ± SD)

Plant seeds	Limit deformation δ (mm)	Strain energy E (J)	Deformed volume V ($10^{-4} \times m^3$)	Volume energy e ($10^5 \times J/m^3$)
Jatropha	35.1 ± 0.8	63.25 ± 2.76	1.592 ± 0.036	3.97 ± 0.81
Common sunflower	53.2 ± 1.2	149.57 ± 3.65	2.413 ± 0.054	6.12 ± 0.29
Common bean	38.4 ± 1.5	192.43 ± 1.87	1.742 ± 0.068	11.05 ± 0.56
Garden pea	32.8 ± 0.7	198.10 ± 3.25	1.488 ± 0.032	13.31 ± 0.52

energy. The calculated values are presented in Table 2. It was found from the calculated values that the seeds of garden peas had the largest value of strain energy that is the energy in which the "wave effect" characteristic did not occur. The rest, namely the common beans, common sunflowers and jatropha obtained the minimum strain energy. These strain energy values correspond to the maximum energy that can be inserted to the pressing process. Exceeding this value can cause vibration of the presser including other negative factors, which also influences the process of pressing (Yao et al. 1997; Zhu et al. 2005). Considering the resistance to change of mechanical behaviour of the plant seeds, it was necessary to compare the values of volume energy to that of the amount of deformed volume for all the plant seeds during compression. The calculated amount of the volume energy for garden pea showed the best resistance to change in the mechanical behaviour. Common beans, common sunflowers and jatropha followed in that order of magnitude to change in mechanical behaviour. These results also correspond to the visual analysis of measured amounts displayed in Fig. 2. From the calculated amounts of porosity, moisture content (Table 1) and the determined volume energy (Table 2) it was found that the resistance to change in mechanical behaviour of the plant seeds depends on porosity. Higher amount of porosity means less resistance to change in mechanical behaviour of the plant seeds and lower amount of limit volume energy. It was also evident that the moisture content of the plant seeds has an influence on volume energy. Higher amounts of moisture content means higher resistance to change in mechanical behaviour of the plant seeds and higher amount of limit volume energy with respect to moisture content before and after soaking. Some factors such as moisture content, temperature and variety of the seeds (Murthy, Bhattacharya et al. 1998; Braga et al. 1999; Herák et al. 2010; Raji, Favier 2004) may change the shape of the curve and strain or even hasten the change in mechanical behaviour, the so-called "wave effect".

CONCLUSION

The experiment on the mechanical behaviour of several layers of selected plant seeds in which limit volume energy was determined including other parameters. It is evident that the garden pea has the best resistance to change in mechanical behaviour while the other plants, common bean, common sunflower and jatropha, followed in that order of magnitude of change in the mechanical behaviours. The porosity and moisture content of the pressed seed samples influenced the amount of limit volume energy. Higher amounts of porosity and moisture content showed lower and higher resistance to change in mechanical behaviour of the plant seeds, respectively. It was also noticed that a change in mechanical behaviour is influenced by physical properties of the pressed seeds as seed dimensions, seed density, porosity, moisture content and mechanical properties such as ultimate strength and yield strength of the pressed seeds.

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