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Mechanical behaviour of selected bulk oilseeds under compression loading

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Abstract. Cold pressing or compressive mechanical expression of oil from bulk oilseeds without thermal treatments or appreciable thermal effects facilitates the preservation of quality in expressed oils and enhances their stability in storage. Mechanical response of bulk oilseeds during cold expression which are vital to equipment design vary with crops and are not completely understood. Mechanical behaviours of bulk seeds of camelina, pumpkin and sesame relevant to cold pressing were investigated at moisture contents of 7.04, 8.60 and 6.06% (d.b.), 80 mm pressing depth and a compressive force of 100 kN, applied uniformly at 10 mm min^{-1}. Deformation varied with incremental force and among crops at peak compression. Deformations in Camelina, Sesame and Pumpkin seeds were 40.2, 41.6 and 50.9 mm at peak compression. Oil point pressures of Sesame, Camelina and Pumpkin seeds were 3.83, 7.49 and 8.83 MPa, respectively. Oil recovery at the applied load was similar in Camelina and Sesame but significantly lower in pumpkin seeds. Volume energy requirement for the expression of oil from camelina, pumpkin and sesame seeds were 2.56, 1.72 and 1.46 MJ m^{-3}, respectively. An assessment of the pressed cake after oil expression revealed that the materials were capable of further deformation under compression.

Key words: oilseed, cold pressing, compressive stress, strain, energy.

INTRODUCTION

The main object of cold pressing of oilseeds is extracting oil at temperatures that guarantee the quality of the extracted oil (Kachel-Jakubowska et al., 2015; Ratusz et al., 2016). In large scale screw presses, process temperatures often reach 170 °C at 1,600 bars (Matthäus, 2012). Cold pressed oils are obtained at temperatures below 40 °C (Makała, 2015). Although considerable solvent–free expression is achieved with screw presses (Maurice, 2005), substantial quantities of residual oil are removed using supplemental techniques including solvent, super–critical fluids and temperature assisted processes and optimisation involves establishing combinations of geometrical, process and flow factors at which oil yields are high and quality as indicated by known process parameters is maintained (Voges et al., 2008; Willems et al., 2008; Honarvar et al., 2013). Hydraulic pressing refers to the mechanical expression of oil from bulk sections of oilseeds using compressive force (Mrema & McNulty, 1985; Owolarafe et al., 2008) and seldom involves significant changes in temperature of the pressed material, guaranteeing high oil quality (FAO/WHO, 2015a; 2015b). Different attempts have been made to describe the mechanism of expression of oil from oilseeds using compressive force (Bargale, 1997; Bargale et al., 2000; Savoire et al., 2013). This process has been shown to be a function of several influence factors, including initial produce depths (Herák et al., 2013; Kabutey et al., 2013), moisture and temperature (Santoso & Inggrid, 2014; Kachel-Jakubowska et al., 2015), compressive force (Kabutey et al., 2014) and the rate of its application (Bargale et al., 2000; Santoso & Inggrid, 2014) and size or diameter of the constraining vessel (Kabutey et al., 2013; Owolarafe et al., 2007). Oil pressing indices of interest have also been shown to vary significantly across crop types and varietal lines (Herák et al., 2012; Rusinek et al., 2012). The main indicators of interest during compressive expression of oil from oilseeds have been oil points, oil yield, deformation and deformation energy (Faborode & Favier, 1996; Bargale et al., 2000; Kabutey et al., 2014). Deformation of bulk oilseed sections under compressive force has been described to occur in three phases (Mrema & McNulty, 1985; Faborode & Favier, 1996; Owolarafe et al., 2008). The reciprocal slope transform has been shown to be useful in describing only the initial phase during which reorganisation of seeds and settling–in occurs (Herák et al., 2014). Deformation behaviours in some crops have been described using the tangent–curve descriptor (Herák & Kabutey, 2014). The tangent curve relation provided fitting description of the reported process parameters up to some limit points (Divišová et al., 2014; Sigalingging et al., 2015) beyond which erratic behaviours or serration effects along the force–deformation profiles of different crops were established (Divišová et al., 2014; Kabutey et al., 2014). The limit point in question appears to be the bioyield point and this was not attained in some crops (Herák et al., 2012) with high strain resistance, at the applied force and pressing conditions. The behaviours reported in literature also varied significantly across oilseed crops.

Camelina, sesame and pumpkin seeds are emerging oilseed crops whose oils have received attention with regard to their qualities and potentials as food, biofuel and health oils (Tunde-Akintunde & Akintunde, 2004; Fruhwirth & Hermetter, 2007; Berti et al., 2016). In this study, the behaviours of these important oilseeds under compressive force were investigated and parameters essential to the expression of oil from them were determined.

MATERIALS AND METHODS

Samples

Whole and cleaned seeds of camelina (*Camelina sativa* (L.) Crantz), pumpkin (*Cucurbita pepo* L.) and sesame (*Sesamum indicum* L.) purchased in Czech Republic were used for this study.

Experimental setup and tests

A schematic view of the oil expression apparatus is shown in Fig. 1. It consisted of an 80 mm internal bore cylindrical steel pressing vessel with a 20 mm thick circular base plate stepped inwards diametrically at 10mm depth, 8mm from its circumference and 10 lateral orifices (ϕ3 mm) equispaced along the circumference of the pressing vessel, 15 mm from its base. The vessel had a close fitting solid piston, stepped 1mm, 30 mm from its base. The vessel is mounted on the bed of a Tempos ZDM 50 model test universal test rig and loaded compressively using a spherical base, flat topped disc. Bulk columns of camelina, sesame and pumpkin seeds at 7.04, 8.60 and 6.06% moisture contents (d.b.), respectively, each 80mm deep and constrained within the pressing vessel were gradually compressed at 10 mm min-1 to a maximum force of 100 kN under laboratory condition of 20 °C. Each test was repeated three times. The experiment was considered as a completely randomised design. Test data were electronically logged using the Mark Mitchell Engauge Digitizer software (Version 4.1, 2002). Moisture measurements were conducted using the oven drying method as described in the ASAE standards S352.2 for moisture determination in unground grains and seeds. Each 15 g sample was oven dried in a Gallenkamp Memmert type hot air oven at 103 ± 2 °C. The masses of the samples used in the course of this study were weighed using the Kern 440–35N (Kern & Sohn GmbH, Stuttgart, Germany) weighing balance. The capacity of the standard calibrated cylinder used for initial bulk density measurement was 230 mm^3.

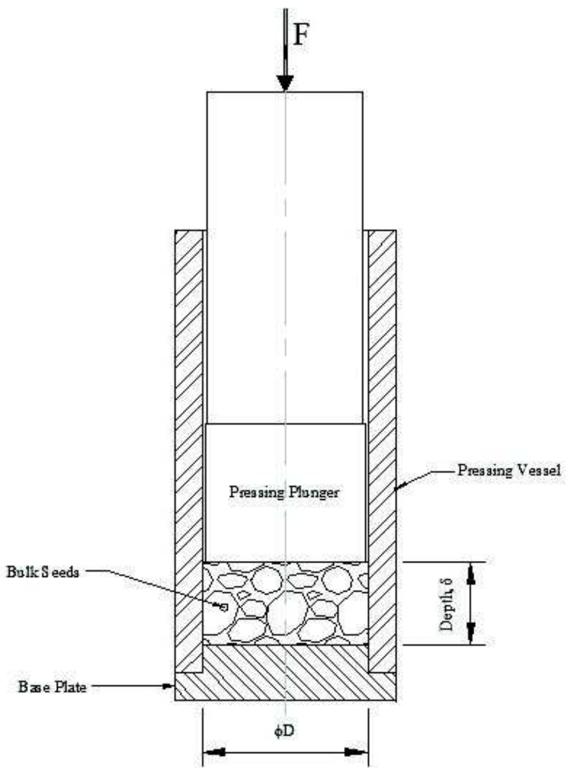

Figure 1. Schematic view of the oil expression apparatus.

Evaluation of properties of oilseeds and compression parameters

The porosity, P_f (%) of each batch of crop was calculated using the relationship given below (Eq. 1) (Mohensin, 1970; Sirisomboon et al., 2007):

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

where ρ_b (kg m^{-3}) and ρ_t (kg m^{-3}) are the bulk and true densities of each crop, respectively. Bulk densities of oilseeds prior to expression were determined as the ratio of the mass of a sample to the known free–fill volume it occupies without compaction, as outlined in literature (Mohensin, 1970; Sirisomboon et al., 2007; Arozarena et al., 2012). True densities were determined using a solvent displacement technique – the method of the pycnometer and toluene, as described by Mohsenin (1970). True densities were computed (Eq. 2) as:

$$\gamma_S = \left(\gamma_T \times \frac{m_S}{m_{TD}}\right) \tag{2}$$

γ_S and γ_T are specific gravities of the crop and of the batch of toluene used while m_S and m_{TD} are masses of the sample and of the displaced quantity of toluene, respectively.

The highest value of deformation which was achieved for each crop at any given load was defined as δ_c (mm). Where δ_o (mm) is the initial height of pressed bulk seeds, the strain in the compressed material ϵ_l (–) is given by Eq. 3

$$\in_l = \frac{\delta_c}{\delta_o} \tag{3}$$

The initial volume of compressed material, V (mm^3) is given by Eq. 4

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

where, D (mm) is the inside diameter of the constraining cylindrical steel vessel.

Bulk density of the compressed oilseed material, ρ_{bc} (kg m^{-3}) after oil expression was determined as a function of the mass (m_c) and volume (V_c) of the final product volume following compression (Eq. 5)

$$\rho_{bc} = \frac{m_c}{V_c} \tag{5}$$

The final volume of the compressed material, V_c (mm^3) is given by Eq. 6

$$V_c = \frac{\pi \times D^2}{4} \times \delta_f \tag{6}$$

where, δ_f (mm) is the final height of the compressed oilseeds in the constraining. Oil yield, OY (%) was determined as a function of the ratio of expressed oil to the total seed mass (Eq. 7)

$$OY = \frac{m_o}{m_{ss}} \times 100 \tag{7}$$

where, m_O (g) is the mass of expressed oil and m_{ss} (g) is the mass of seeds pressed

Deformation energy E (J) is the energy required to achieve a given deformation of the compressed product mass, at the specified force and conditions (Eq. 8). This is the area beneath the force–deformation curve and is numerically computable as

$$E = \sum_{n=0}^{n=i-1} \left[\left(\frac{F_{n+1} + F_n}{2}\right) \times (\delta_{n+1} - \delta_n)\right] \tag{8}$$

i represents the number of subdivisions of the deformation axis, which in this case was done in step measurements of 0.01 mm, as logged by the test equipment and as set forth by Herák *et al.* (2012), F_n (N) being the compressive force for a known deformation, δ_n (mm) and E (J) the deformation energy. Volume deformation energy, e (N mm^{-3}) is a function of the induced volumetric strain and is determinable by Eq. 9

$$e = \frac{E}{V} \tag{9}$$

The Modulus of Elasticity of the compressed bulk material, M_n (MPa) was obtained as the slope of or stress and strain or deformation curve at the specified force, numerically computed using Eq. 10.

$$M_n = \left[\frac{4 \times \delta_o}{\pi \times D^2} \times \left(\frac{F_{n+1} - F_n}{\delta_{n+1} - \delta_n}\right)\right]_{n=0}^{n=i-1} \quad (10)$$

Data analysis

All test data were subjected to the analysis of variance using the generalised linear model in Minitab®, release 17. Numerical computations and graphical plots were carried on the MS Excel platform. Main treatment effects were compared using the Duncan's multiple range test.

RESULTS AND DISCUSSION

Some physical properties of the bulk camelina, pumpkin and sesame seeds relevant to oilseed pressing are presented in Table 1. Marked differences ($p < 0.0001$) were observed among mean values of these parameters for the three crops. Porosity, bulk and true densities ranged between 6.67–7.73%, 1,058.7–1,070.9 kg m^{-3} and 1,144.4–1,149.8 kg m^{-3}, 28.6–30.1%, 590.8–603.2 kg m^{-3} and 839.6–850.6 kg m^{-3} and 3.96–10.2%, 991.3–1,060.0 kg m^{-3} and 1,101.5–1,105.0 kg m^{-3} in bulk seeds of camelina, pumpkin and sesame, respectively. Packing factor was greatest in pumpkin seeds compared to the other oilseeds (Table 1). These observed physical properties were found to be comparable with those reported in literature (Tunde-Akintunde & Akintunde, 2004¸Darvishi, 2012; Khodabakhshian, 2012). There are however observable variations that are due mainly to the varieties of the crops reported and moisture contents at which the tests were conducted (Milani et al., 2007; Tunde-Akintunde & Akintunde, 2007). Physical and mechanical properties of biological materials have been shown to vary with crops, their varieties and moisture levels.

Table 1. Physical properties of bulk seeds (*Mean* ± *SD**)

Crop	Moisture content (%, d.b.)	Mass (g)	Porosity (%)	†Bulk density (kg m^{-3})	True density (kg m^{-3})
Camelina	7.04 ± 0.06	240.9 ± 3.6	8.73 ± 1.38	1,047.3 ± 15.9	1,147.4 ± 2.8
Pumpkin	8.60 ± 0.15	141.4 ± 3.5	27.25 ± 1.79	614.8 ± 15.2	845.1 ± 7.8
Sesame	6.06 ± 0.36	230.9 ± 5.3	9.05 ± 2.09	1,003.7 ± 23.0	1,103.6 ± 1.9

*SD = standard deviation. †n = 20.

Force–deformation diagrams of bulk sections of camelina, pumpkin and sesame seeds loaded gradually to 100 kN are presented in Fig. 2. Curvilineal trends were observed in the buildup of deformation forces with incremental deformation, in all the oilseeds. The observed trends were positive. Deformation varied significantly ($p < 0.0001$) among the three oilseeds with each incremental addition of force, as did the peak deformations when compressed to 100 kN. The least deformation at peak load occurred in camelina seeds, followed by sesame. The greatest deformation occurred in pumpkin seeds (Table 2). Pumpkin has a comparatively higher packing factor than the other seeds and this accounts for the relative amount of rearrangement that may be necessary in its bulk section prior to pronounced induction of stresses to cause actual failure of the oil bearing material.

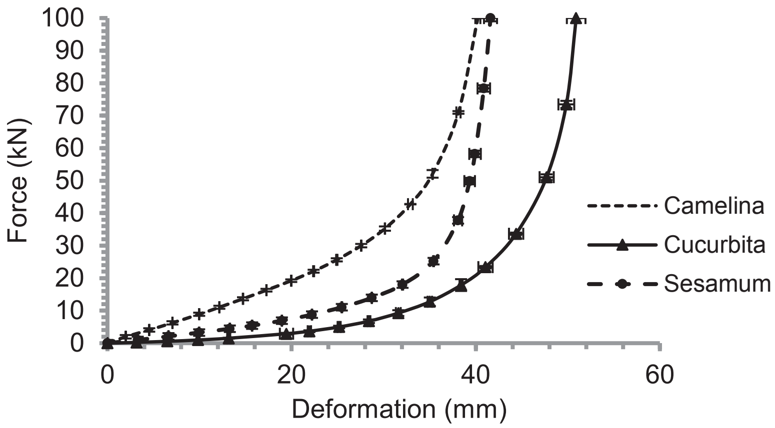

Figure 2. Measured mechanical characteristics of the selected oilseeds at pressing depths of 80 mm.

Table 2. Measured and calculated mechanical parameters of the selected bulk oilseeds uni-axially loaded to 100 kN at 10 mm min^{-1} and 9% moisture content (*Mean* ± *SD**)

Crop	Deformation (mm)	Volume deformation (10^4 mm^3)	Strain (-)	Deformation energy (J)	Volume deformation energy (MJ m^{-3})
Camelina	40.2 ± 0.3	20.2 ± 0.1	0.503 ± 0.003	1,027.3 ± 10.0	2.56 ± 0.02
Pumpkin	50.9 ± 1.0	25.6 ± 0.5	0.636 ± 0.013	693.3 ± 20.5	1.72 ± 0.05
Sesame	41.6 ± 0.7	20.9 ± 0.4	0.520 ± 0.009	585.2 ± 28.7	1.46 ± 0.07

* *SD* = standard deviation.

Oil point pressure (OPP), oil yield and bulk density of the pressed seeds after oil expression are presented in Table 3. At peak application of compressive force, slightly more oil was expressed from sesame than camelina; the least amount of oil was expressed from pumpkin seeds (Table 3). Pumpkin also attained the least bulk density after compression, indicating capacity for further densification (Table 3). Some studies reported slightly higher oil yields under at similar pressures through thermal conditioning of the oilseeds between 40–103 °C (Ajibola et al., 1993; Willems et al., 2008). Compressive oil expression has been correlated with applied pressure and strong interactions between this factor, moisture and temperature have also been reported (Min & Jeong, 1995). The show of oil was attained in pumpkin seeds at higher pressure than the other oilseeds. This indicates higher resistance of its oil bearing material to strain; sesame had very low OPP, the first show of oil being at 3.83 MPa. The oil point pressure for camelina observed in this study is lower than that reported in an earlier study which documented oil point pressures (Rusinek et al., 2012).

When deformation at peak load was compared with the relative yield of oil from each crop (Table 3), no particular trend could be inferred. Whereas the largest amount of deformation was observed in pumpkin seeds, the percent yield of oil with respect to total seed mass was low, compared to the other oilseeds (Table 3). It does appear however that a better correlation exists between relative yield of oil and oil point pressure in each oilseed (Table 3). The show of oil and therefore the onset of actual expression of oil from the oilseeds appeared to be slower in pumpkin compared to the other oilseeds. It may be inferred therefore that much of the deformation observed in pumpkin seeds at the applied force of 100 kN is attributable to rearrangement or packing in the oilseed material prior to actual occurrence of failure in the oilseed material, delaying the onset of oil.

Table 3. Oil expression and compression parameters (*Mean* ± *SD**)

Crop	Oil Point Pressure *(MPa)*	Oil Yield *(%)*	Bulk density of compressed seeds *(kg m^{-3})*
Camelina	7.49 ± 0.04	13.08 ± 0.26	1,220.9 ± 8.8
Pumpkin	8.83 ± 0.40	4.01 ± 0.22	1,125.5 ± 26.1
Sesame	3.83 ± 0.10	14.56 ± 0.58	1,180.5 ± 10.3

* *SD* = standard deviation.

Induced strains at maximum deformation ranged between 0.500–0.508, 0.619–0.646 and 0.512–0.533 in camelina, pumpkin and sesame seeds, respectively (Table 2). Similar amounts of strain and volumetric deformations were observed in camelina and sesame. Strain resistance is a property of the oilseed material. Some single seed quasi–static studies revealed higher rupture force requirement for pumkin than sesame seeds being in the ranges of 20.1–102.4 N and 9.10–10.6 N, respectively (Darvishi, 2012; Khodabakhshian, 2012).

The amounts of energy expended during the compression of the three oilseeds varied significantly ($p < 0.0001$) ranging from 1,016.0–1,040.3, 671.1–720.6 and 522.3–622.3 J in camelina, pumpkin and sesame seeds, respectively. The least amount of energy was expended during the compression of sesame seeds, being 585.2 J; energy expended during the compression of pumpkin was 693.3 J. The most amount of energy was expended during the compression of camelina seeds, being 1,027.3 J (Table 2).

When the volumes of oilseeds compressed were considered (Fig. 3), significant differences ($p < 0.0001$) were observed in the amount of energy expended per unit volume of compressed material. Volume energy demand ranged between 2,526–2,587, 1,669–1,792 and 1,373–1.548 MJ m^{-3} for the compression of camelina, pumpkin and sesame seeds, respectively. The mean volume energy requirement was 1.72 and 1.46 MJ m^{-3}, for pumpkin and sesame, respectively. The most amount of energy was required for the compression of Camelina being 2.55 MJ m^{-3}. This is lower than the value (8.3 MJ m^{-3}) reported by Rusinek et al. (2012) for spring camelina.Variations in the volume energy demands of the three oilseeds as deformation progressed can be seen in Fig. 3. For every measure of deformation, more energy was required to deform a unit volume of camelina seeds, compared to the other crops. This was followed by energy demand for the deformation of unit volumes of sesame seeds, which was higher than that required for pumpkin seeds.

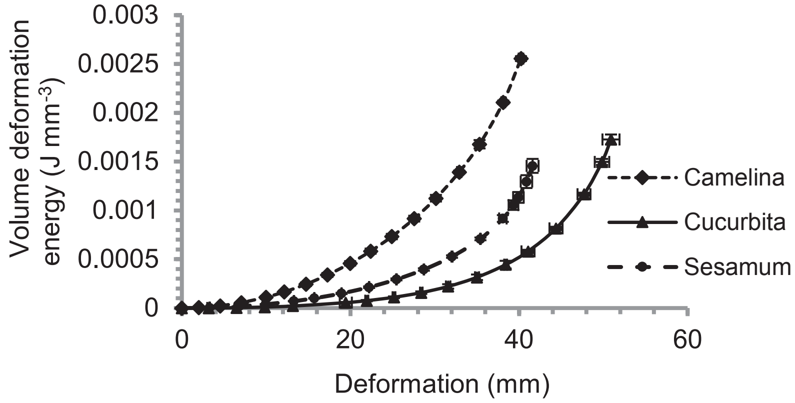

Figure 3. Changes in volume energy demands with incremental deformation of bulk camelina, pumpkin and sesame seeds loaded gradually to 100 kN.

Mean moduli of elasticity attained by the compressed oilseed materials at peak deformation, given the applied force are presented in Table 2. Fig. 3 shows the relative buildup of strain in each oilseed material, given the induced state of stress. At peak deformation and with respect to the applied force, pumpkin seeds offered the highest resistance to strain. This translated to a very low oil yield (Table 3).

Given its low oil yield at 100 kN, bulk pumpkin seeds appear to be capable of considerable amounts of increased deformation at higher stresses which would result in better oil yield.

Mean moduli of elasticity attained by the compressed oilseed materials at peak deformation, given the applied force are presented in Table 2. Fig. 4 shows the relative buildup of strain in each oilseed material, given the induced state of stress. At peak deformation and with respect to the applied force, pumpkin seeds offered the highest resistance to strain. This translated to a very low oil yield (Table 3). Given its low oil yield at 100 kN, bulk pumpkin seeds appear to be capable of considerable amounts of increased deformation at higher stresses which would result in better oil yield.

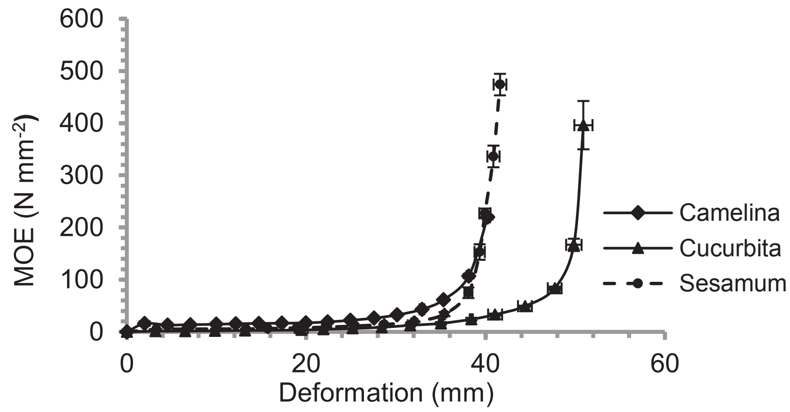

Figure 4. Moduli of elasticity of bulk camelina, pumpkin and sesame seeds gradually compressed to 100 kN.

CONCLUSIONS

Mechanical response of three important and emerging oilseed crops relevant to cold expression were determined at 80 mm pressing depth using a compressive force of 100 kN applied uniformly at 10 mm min^{-1} in an 80 mm diameter pressing vessel. Deformation, resistance to strain and deformation energy varied significantly among the three crops. Porosity, deformation and resistance to strain were greatest and mean oil recovery least in pumpkin seeds. Camelina, pumpkin and sesame had oil point pressures of 7.49, 8.83 and 3.83 MPa and volume deformation energy requirements of 2.56, 1.72 and 1.46 MJ m^{-3}, respectively, given the imposed pressing conditions. An assessment of the bulk densities of the seeds after compression indicated that the seeds are capable of further deformation under compression.

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