MECHANICAL BEHAVIOUR OF BULK SEEDS OF SOME LEGUMINOUS CROPS UNDER COMPRESSION LOADING*

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The behaviours of constrained bulk columns of seeds of 3 important leguminous feed crops under compressive force applied at a uniform rate of 10 mm min^{-1} up to 100 kN at ≈ 9% moisture content (in dry basis) were studied to establish parameters which are relevant to the design of equipment for achieving product densification. Deformation varied significantly ($P < 0.02$) with crop type and was the highest in lupine seeds. Feed pea had the highest strain resistance value. Both deformation energy and volume energy requirements varied significantly ($P < 0.0001$) with crop type. Moduli of deformation of compressed feed pea, lupine, and soybean at an applied force of 100 kN were 269.7, 306.3, and 455.2 MPa, indicating the proportionate resistance of the crop materials to compressive strain. Precisely 4.43, 3.76, and 3.15 MJ m^{-3} are required to achieve 56.7, 77.0, and 67.7% or 461.7, 539.3, and 500.4 kg m^{-3} gains in bulk density in feed pea, lupine, and soybean, respectively. Deformation and volume energy demands correlated negatively ($r = -0.934$ and $r = -0.78$) with lipid presence. Crops with more oil appeared to deform more easily under compressive force. Higher deformations and lower energy demands may be possible at optimal combinations of force, product moisture, and depth.

strain, bulk density, porosity, compression, deformation, energy

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INTRODUCTION

Compression of bulk materials is carried out in order to improve their bulk and energy densities (Miao et al., 2015). Compressive forces are often used in combination with other forces to cause failure of seed and grain materials and are normally directed at overcoming bonds within the elements of these materials (Wilhelm et al., 2004), including their strengths and resistance to shear. The effectiveness with which this can be accomplished is arguably a function of the behaviours of these crops under compression (Babic et al., 2013). Quasi-statically compressed single seed sections, for example, have been shown to yield variously at different moisture levels and geometrical orientations (Altuntas, Yıldız, 2007; Tavakoli et al., 2009; Putri et al., 2015). Both fractionation and densification of plant materials are complex processes (Tumuluru et al., 2011) and the properties which characterize them vary under different forces as well as different geometrical and moisture conditions (Altuntas, Demirtola, 2007; Aremu et al., 2014).

Different methods for determining mechanical response parameters of plant materials with respect to size reduction and densification are described in literature (Shelef, Mohsenin, 1967; Laskowski et al., 1998; Laskowski, Lysiak, 1999; Herák et al., 2012; Padureanu et al., 2013; Kulig et al., 2015). Often the real scenarios are of bulk section presentations in departure from basic assumptions or considerations for unconstrained single-kernel compres-

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sion tests which form the bulk of currently reported works (Laskowski, Lysiak, 1999; Rybinski et al., 2014; Kulig et al., 2015).

Five critical points may be defined along the force-deformation profiles of most biological materials, namely the limits of elasticity, plasticity, biological resistance, point of rupture and collapse threshold, in that order as deformation progresses (Laskowski, Lysiak, 1999). The most significant of these appears to be deformation to rupture (Laskowski, Lysiak, 1999). Herak et al. (2012) described the occurrence of a local maximum which coincides with limit deformation in uni-axially compressed bulk plant seed sections based upon which computations of the total and unit strain energies could be done. Energy input during the compression of seeds depends on their deformation energies and would vary with feed crops and conditions, which are often moisture related (Arif et al., 2015).

Feed pea, white lupine, and soybean are important feed industry crops (Jezierny et al., 2010; Bhardwaj, 2002) which are used to provide livestock with vital nutrition (Hickling, 2003; Moss et al., 2001) either in comminuted or densified forms. Although studies are reported on energy demands during impact milling and densification of ground seeds of feed pea and lupine (Laskowski, Lysiak, 1999; Andrejko, Grochowicz, 2007), very little (Herak et al., 2012) is reported on mechanical behaviours of bulk sections of these crops under compressive forces. Bulk compression of these seeds are important as a means of achieving products of higher bulk, nutrient, and calorific energy densities which are easier to transport and store. Bulk compression also offers a means for establishing a database on mechanical behaviours of these crops which are necessary for predicting energy requirements and process efficiencies in related extrusion based densification activities.

In this study, bulk seeds of feed pea, lupine, and soybean, which were constrained in a cylindrical vessel, were compressed uni-axially with a view of establishing their compression behaviours and energy consumption during the process.

MATERIAL AND METHODS

Samples

Cleaned whole seeds of feed pea (*Pisum sativum* L.), white lupine (*Lupinus albus* L.), and soybean (*Glycine max* (L.) Merr.) obtained in the Czech Republic were used for testing. These samples were purchased at 14.7, 15.7, and 14.8% moisture contents (dry basis) and left to dry naturally in the laboratory. At the time of the test, feed pea, lupine, and soybean showed moisture contents of 9.39, 9.39, and 8.96% (dry basis), respectively.

Experimental setup and tests

A schematic view of the experimental setup is shown in Fig. 1. Bulk columns of feed pea, lupine, and soybean constrained within cylindrical steel vessels 60 mm in diameter were subjected to compressive forces on a ZDM50 (TEMPOS, Czech Republic) model test rig at 20°C laboratory condition in order to compress these seeds. Replicated samples of feed pea, lupin, and soybean at 9.39, 9.39, and 8.96% moisture contents (dry basis), respectively were simultaneously placed in the constraining vessel to depths of 30 mm and gradually compressed at a displacement rate of 10 mm min^{-1} to a maximum force of 100 kN. Each test was repeated three times. The experiment was considered as a completely randomized design. Test data were electronically logged. Moisture contents of the crops were determined 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 type hot air oven (Memmert GmbH, Germany) at 103 ± 2°C for 72 h. 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.

Evaluation of crop properties and compression parameters

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

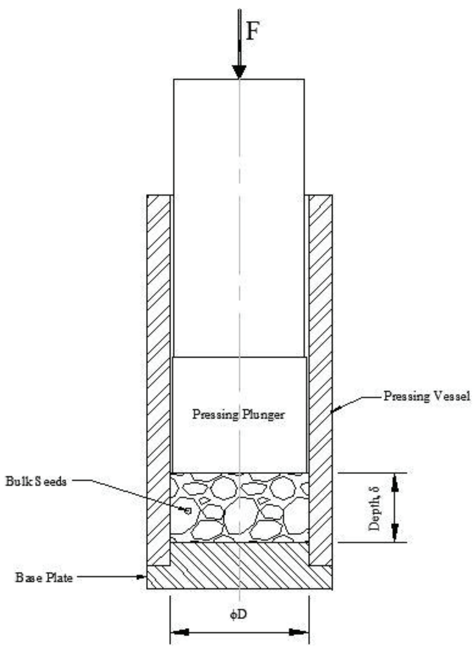

Fig. 1. Schematic view of the experimental setup

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

Crop	Mass (g)	Initial volume (104 mm^3)	Porosity (%)	Bulk density (kg m^{-3})	True density (kg m^{-3})
Feed pea	69.1 ± 4.8	8.49 ± 0.30	36.1 ± 2.1	814.5 ± 66.3	1275 ± 66
Lupine	59.5 ± 4.2	8.49 ± 0.30	48.9 ± 2.9	700.8 ± 58.9	1372 ± 69
Soybean	62.7 ± 4.6	8.49 ± 0.30	45.8 ± 2.7	739.2 ± 60.1	1362 ± 68

SD = standard deviation

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

where:
ρ_b (kg m^{-3}) = bulk density
ρ_t (kg m^{-3}) = true density
of each crop, respectively. Bulk densities were determined using a standard technique (Sirisomboon et al., 2007) as the ratio of the mass of a sample to the known free-fill volume it occupies without compaction. True densities were determined using moisture-dependent relationships (Altuntas, Demirtola, 2007; Wandkar et al., 2012; Werby et al., 2013) determined using the method of the pycnometer and toluene (Mirzabe et al., 2015).

The highest value of deformation which was achieved for a crop at any given load was defined as δ_c (mm). The strain in the compressed material ϵ_l (–) is given by Eq. 2:

$$\epsilon_l = \frac{\delta_c}{\delta_o} \quad (2)$$

where:
δ_o (mm) = initial height of pressed bulk seeds

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

$$V = \frac{\pi D^2}{4} \times \delta_o \quad (3)$$

where:
D (mm) = inside diameter of the constraining cylindrical steel vessel

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. 4). This is the area beneath the force-deformation curve and is numerically computable as follows:

$$E = \sum_{n=0}^{n=i-1} \left[\left(\frac{F_{n+1} + F_n}{2}\right) \times (\delta_{n+1} - \delta_n)\right] \quad (4)$$

where:
i = number of subdivisions of the deformation axis in this case done in step measurements of 0.01 mm, as logged by the test equipment and as set forth by Herak et al. (2012)
F_n (N) = compressive force for a known deformation δ_n (mm),
E (J) = deformation energy

Volume deformation energy, (N mm^{-3}) is a function of the induced volumetric strain and is determinable by Eq. 5

$$e = \frac{E}{V} \quad (5)$$

The Modulus of deformation, M_n (MPa) was determined using Eq. 6:

$$M_n = \left[\frac{4 \times \delta_0}{\pi \times D^2}\left(\frac{F_{n+1} - F_n}{\delta_{n+1} - \delta_n}\right)\right]_{n=0}^{n=i-1} \quad (6)$$

Data analysis

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

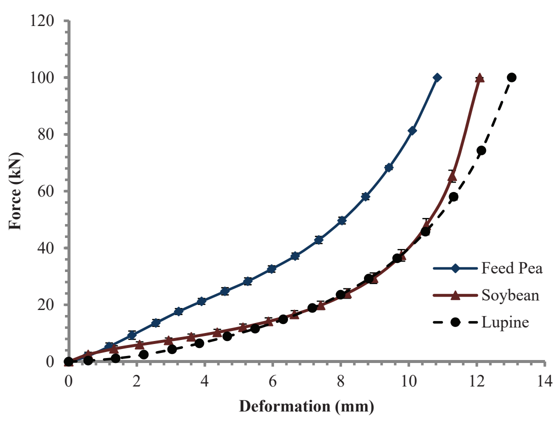

Fig. 2. Measured mechanical characteristics of the selected crops at moisture contents of ≈ 9% (dry basis) and crushing depths of 30 mm

Table 2. Measured and calculated mechanical parameters of selected bulk feed crops uni-axially loaded to 100 kN at 10 mm min-1 and 9% moisture content (mean ± SD)

Crop	δ (mm)	δ_V (10^4 mm^3)	ϵ_l (–)	*E* (J)	*e* (MJ m^{-3})	ρ (kg m^{-3})
Feed pea	10.8 ± 0.4	3.07 ± 0.12	0.361 ± 0.017	375.5 ± 6.21	4.43 ± 0.07	1276.2 ± 33.3
Lupine	13.0 ± 0.5	3.69 ± 0.15	0.434 ± 0.021	319.2 ± 8.48	3.76 ± 0.10	1240.2 ± 48.6
Soybean	12.1 ± 0.6	3.42 ± 0.18	0.403 ± 0.027	267.2 ± 3.22	3.15 ± 0.04	1239.7 ± 55.1

δ = Deformation, δ_V = Volume deformation, ϵ_l = Strain, E = Deformation energy, e = Volume deformation energy, ρ = Bulk density of compressed seeds, SD = standard deviation

RESULTS

Some physical properties of feed pea, soybean, and lupine are presented in Table 1. Force-deformation profiles of the three crops are presented in Fig. 2. There were significant differences ($P = 0.019$) between maximum deformations of 30 mm deep bulk sections of feed pea, soybean, and lupine compressed to a force of 100 kN at about 9% product moisture content. Deformation ranged between 10.3–11.2, 11.3–12.83, and 12.6–13.8 mm in feed pea, soybean, and lupine, respectively. The least mean deformation occurred in feed pea, followed by deformations in soybean and lupine seeds, in that order (Table 2).

Values of strain induced in bulk sections of feed pea, lupine, and soybean ranged between 0.342–0.373, 0.420–0.459, and 0.375–0.427 or 0.361, 0.434, and 0.403 on the average, respectively (Table 2).

Significantly high differences ($P < 0.0001$) were observed among energy demands for the deformation of bulk sections of the three crops considered. Deformation energy varied between 367.3–382.2, 311.1–331.0, and 262.7–270.0 J, respectively for feed pea, lupine, and soybean seed samples, respectively. The least mean energy consumption was recorded during the compression of soybean and was 267.2 J; energy expenditure during the compression of lupine was significantly higher at 319.2 J. Energy expended to compress feed pea was the highest, being 375.5 J (Table 2).

Energy consumption per unit volume of compressed material varied significantly ($P < 0.0001$) among crop types ranging between 4.32–4.50, 3.67–3.90, and 3.09–3.18 MJ m^{-3} for feed pea, lupine, and soybean, respectively (Table 2). Soybean and lupine required 3.15 and 3.76 MJ of energy per unit volume (m^3) of material compressed. Compressing feed pea required the most amount of energy per unit volume of material, being 4.43 MJ m^{-3} (Table 2).

The change in volume energy demand with incremental deformation is presented in Fig. 3. Each profile is a curvilinear form with a positive slope. Volume energy demands appeared to be within similar range for soybean and lupine. Feed pea had the highest volume energy demand for each amount of deformation (Fig. 3).

Results of the moduli of deformation of bulk seeds of feed pea, lupine, and soybean and their variation with incremental deformation during compression are presented in Fig. 4. For every incremental deforma-

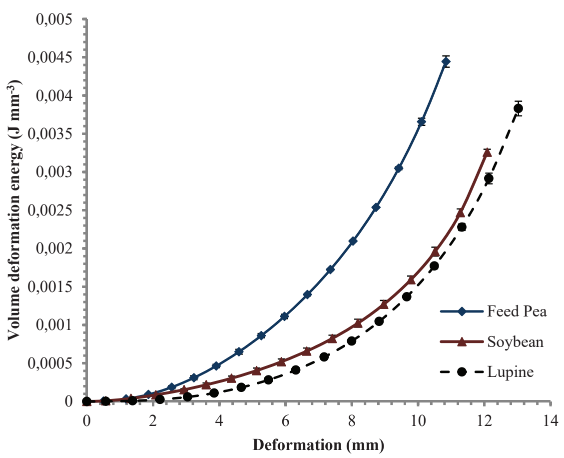

Fig. 3. Changes in volume energy demands with incremental deformation of bulk feed pea, lupine, and soybean seeds at ≈ 9% moisture content, loaded gradually to 100 kN

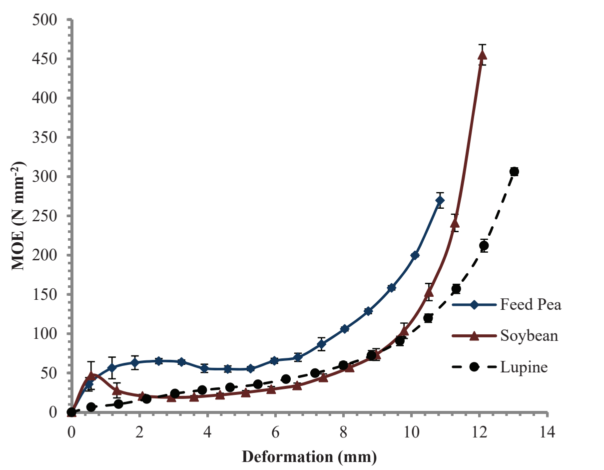

Fig. 4. Moduli of deformation of feed pea, soybean, and lupine at 9% moisture content, gradually compressed to 100 kN

tion during compression, feed pea had higher modulus of deformation than each of the other crops (Fig. 4). There were no marked variations between the changes in moduli of deformation of soybean and lupine within the 2–10 mm deformation range. A sharp contrast however exists beyond that range (Fig. 4). Moduli of deformation of feed pea, lupine, and soybean after compression at an applied force of 100 kN and 9% moisture content (dry basis) were 269.7, 306.3, and 455.2 MPa, respectively indicating the proportional resistance to strain offered by each of these crop materials under the specified force and conditions.

Porosities or packing factors of feed pea, lupine, and soybean at ≈ 9% moisture contents prior to compression were 36.1, 48.9, and 45.8%, respectively (Table 1).

Bulk densities of feed pea, lupine, and soybean in the undisturbed state prior to compression were 814.5, 700.8, and 739.2 kg m^{-3}, respectively. When the crops were compressed, feed pea, lupine, and soybean acquired mean bulk densities of 1276.2, 1240.2, and 1239.7 kg m^{-3}, respectively. The respective gains in bulk densities by these products were 461.7, 539.3, and 500.4 kg m^{-3}. The range of bulk densities of compressed feed pea, lupin, and soybean were 1238.1–1299.6, 1207.6–1296.1, 1182.4–1292.2 kg m^{-3}, respectively (Table 1).

DISCUSSION

There is a positive relationship between compression force and deformation. This means that when compression force increases, deformation also increases. Similar deformation trends were observed in lupine and soybean as shown in Fig. 2. A marked resistance to strain was indicated in feed pea compared to the other crops as shown in Fig. 2. This can be attributed to the strength of this crop in compression. Some studies show that feed pea seed possesses more strength in rupture than lupine and soybean (Bormuth, 1994; Tavakoli et al., 2009; Werby et al., 2013). When compared with an earlier work (Herak et al., 2012), the results indicate that the crops are capable of deforming more at higher loads, irrespective of the relative effects of the initial depth and moisture contents of the seeds. For a compression force of 250 kN, Herak et al. (2012) reported deformations of between 32.1–33.5 mm in compressed green pea sections for an initial seed depth of 80 mm and 10.35% moisture content (dry basis) and these were not limit deformations. The local maxima and wave-like effects observed in some crops by Herak et al. (2012) were not observed for the crops in this study, at the stated conditions. This indicates that further deformations are possible for each of the crops under modified loading conditions.

The values of bulk densities observed for feed pea, lupine, and soybean prior to the application of compressive forces are within the ranges reported in literature for undisturbed bulk seed sections which were not exposed to compressive force (Yalcın et al., 2007; Kibar, Ozturk, 2008). and initial produce depth may contribute significantly to changes in bulk density of the compressed product (Divisova et al., 2014).

Deformation energy rose from 267.2 J for soybean to 319.2 J for lupine. On the average, 375.5 J was expended to deform feed pea samples. More energy per m^3 of material was required for compressing feed pea compared to lupine and soybean. Mean energy requirement for compressing lupine seeds appears to compare relatively with values reported for pelletizing smaller quantities of ground lupine seeds at 10 kN and a similar speed and moisture content (Andrejko, Grochowicz, 2007). Also, deformation and volume energy requirements appear to reduce with increasing lipid presence, as may be observed with the crops in this study. Lipid contents of feed pea, lupine, and soybean range between 0.8–6.1, 5–10, and 12–27%, respectively (Breene et al., 1988; Murcia, Rincon, 1991; Suchy et al., 2008; Aldal'in et al., 2012; Khodapanahi et al., 2012). These values correlate negatively with strain and volume specific energy demands of the test crops (r = –0.934 and –0.78, respectively). One study indicated that soybean seeds showed susceptibility to rupture based on the relative fat contents of their cultivars (Kuzniar et al., 2016). Some authors have correlated rupture strength of some non-leguminous crops to physico-chemical properties other than lipid presence (Hruskova, Svec, 2009; Baslar et al., 2012).

There are indications from this and other existing studies (Andrejko, Grochowicz, 2007; Herak et al., 2012) that deformation, strain energy, and volume specific energy requirements would be significantly affected by the interactions of compression force, initial produce depth, and crop moisture contents. It would be possible therefore to achieve large deformations at lower forces and higher crop moisture contents and deeper bulk sections. Studies on single-seeded specimen (Laskowski, Lysiak, 1999) seem to suggest that deformation reduces when compression force and moisture content are lowered.

The implications of these findings are that it is possible to achieve efficiently failure of the material structure and densification of bulk seeds using optimal combinations of the important influence factors. This will result in lower energy demand during the process. The results will be translatable in the design and optimization of extrusion and related densification equipment components and processes.

CONCLUSION

In this study, tests were conducted to determine resistance to strain and energy requirement during the compression of bulk seeds of feed pea, lupine, and soybean at ≈ 9% moisture contents (dry basis), 30 mm depth of seeds, and a compressive force of 100 kN applied at a uniform rate of 10 mm min^{-1}. Deformation, resistance to strain, and deformation energy varied significantly among crop types. Energy requirements to deform unit volumes of soybean, lupine, and feed pea at ≈ 9% product moisture contents and 100 kN were 4.43, 3.76, and 3.15 MJ m^{-3}, respectively. Moduli of deformation of densified feed pea, lupine, and soybean at an applied force of 100 kN were 269.7, 306.3, and 455.2 MPa, respectively showing that compressed soybean had the greatest stiffness upon densification. Higher resistance to strain and higher energy demand per unit volume of compressed material were indicated in feed pea than in other crops. There are indications that the relative contributions of the force, crop moisture content, and depth of seedbed on deformation, imposed strain, and energy requirements are interactive in nature and should form the focus of future studies.

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