# A DEVICE TO MEASURE WALL FRICTION DURING UNIAXIAL COMPRESSION OF BIOMATERIALS

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***Abstract***
*A device is reported for the acquisition of the effects of friction between compressed biomaterials along the interface between the material and the wall, parallel to the axis of compression. Results of equipment calibration test as well as uniaxial compression tests on a selected food powder are reported. Wall friction had highly significant effect on transmissibility of pressure in the compressed material and significantly affected effective utilisation of the input energy. The results are of importance with respect to the densification, handling and storage of food materials of the type described.*

***Key words:*** *wall friction; food powder; effective pressure.*

## INTRODUCTION
Friction along the internal walls of product compression dies or large storage facilities for related feedstock and products has profound effect *(Cheng, Zhang, Yan, & Shi, 2015; Tien, Wu, Huang, Kuo, & Chu, 2007)*, especially on longitudinal transmissibility of pressure *(Briscoe & Rough, 1998; Michrafy, Haas, Kadiri, Sommer, & Dodds, 2006)* – which determines the degree of achievable deformation *(Li, Liu, & Rockabrand, 1996)* and uniformity of the distribution of density *(Adams, Briscoe, Corfield, Lawrence, & Weert, 1998)* along the lengths of compressed products – and the magnitude of radially transmitted pressure. Dissipation of energy, severe barrel wear and failure of machine elements are some of the effects of friction during food processing *(Adams et al., 1998; Tumuluru, Wright, Kenny, & Hess, 2010)*. Wall friction is therefore an important factor considered during the design and operation of product densification and storage schemes. Available studies document some of these effects in relation to bulk storage of biomaterials *(Horabik & Molenda, 2002; Molenda & Horabik, 2005*). The effect of wall friction during product densification is however scantily reported, especially in relation to high pressure uniaxial compression. Instrumented bins and dies have been employed in various ways to sense both applied and transmitted loads *(Bek, Gonzalez-Gutierrez, Moreno Lopez, Bregant, & Emri, 2016; Rusinek & Molenda, 2007)* and to estimate internal friction parameters for bulk materials in storage *(Molenda et al., 2006; Rusinek & Molenda, 2007)*. Similar constructs *(Jiří Blahovec & Kubat, 1987)* may be employed to sense frictional drag along the walls of product densification devices. This study reports one such technique.

## MATERIALS AND METHODS
### Description and working principles of the test apparatus
The device (Fig. 1) consists of a stepped cylindrical ring supported on four slender columns rising from a base ring which is supported in a groove on a flat, circular solid base. A base plug whose smaller end fits in a product compression vessel sits on the base plate and maintains a clearance with the slender arms along its circumference. The product compression vessel sits on the stepped ring. During product compression, friction drag along the internal wall of the die is sensed through deflections in the support arms while reaction to the applied compression force is offered through the plug. Deflections in the support arms are sensed through strain gauges affixed at midpoints on their outer faces. The signals are subsequently relayed and amplified using a data acquisition unit which is

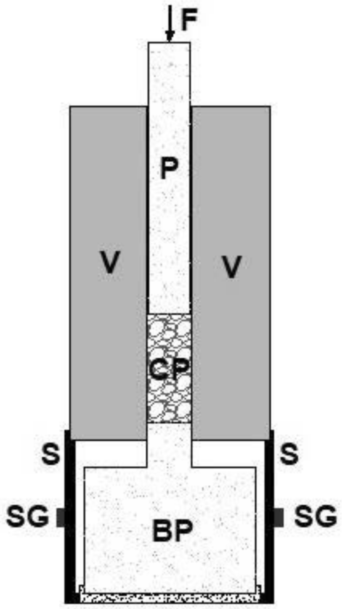


**Fig. 1** Schematic layout of the friction drag sensing and data acquisition device indicating the applied force (F), piston (P), compression vessel (V), compressed product (CP), base plug (BP), vessel support (S) and strain gauge (SG)

connected to a personal computer. As shown in the setup (Fig. 1), the small end of the plug is designed to fit in the compression vessel only partially; sufficient clearance is maintained between the bottom of the compression vessel and the stepped face of the base plug. The plug acts as a stationary base while the piston moves vertically downwards during compression. Axially applied pressure induces radial transmission of stress through the material, normal to the face of the wall of the compression vessel. Deformation of the compressed material implies reduction in its volume which progresses mainly axially (downwards), relative to the wall of the die. Drag is thereby imposed on the internal wall of the compression vessel, due, chiefly, to frictional resistance. A threshold magnitude of this resistance is sensed as static friction. Consequently, a dynamic phase is established within which kinetic friction dominates, which is wall friction. The compression vessel is mounted on the support (S) whose slender arms deflect accordingly as a result of frictional drag. Strain transducers are mounted on the four arms in full bridge configuration with compensation for transverse strain in two of the arms to sense the drag. Output analog signals are fed to an amplifier and subsequently through a microprocessor control unit to the input/output devices. The signal gain employed was 20. A user interface (Radlice v.1.1.0.0), developed at the Czech University of Life Sciences was used.

**Equipment calibration**
The assembled apparatus was mounted on a Labor Tech® LabTest 6.50 electromechanical universal test rig (LABORTECH s.r.o., Opava, Czech republic.) on which calibration tests were done for replicate measures of applied forces acting on the support as would net friction loads. The forces were applied through the top face of the compression vessel. During the test, applied forces were logged against output voltage readings on a multi-meter, connected separately to the data acquisition unit.

**Test procedure**
Compression tests were carried out on a Tempos ZDM 50 universal test rig (TEMPOS, spol. s.r.o., Czech Republic). Dry powder of *Ceratonia siliqua* L. (carob) at moisture content of 4.51%, in dry basis, was fed into the compression vessel for a product aspect ratio of 1.0. The internal diameter of the vessel was 25 mm. The apparatus (Fig. 1) was mounted on the test rig and axial force applied on the piston through a hemisperical disc at a deformation rate of 10 mm/min. The force was increased steadily from 0 N to a peak force of 10 kN, corresponding to an applied pressure of 20 MPa. Compression data were logged using the TiraTest software (TIRA GmbH, Schalkau, Germany) while friction data were separately logged using the Radlice v.1.1.0.0 software. Both data sets were subsequently

synchronised using their logged time data. The tests were repeated three times. Product moisture content was determined according to ISO 712:2009 *(International Organization for Standardization, 2009)* with the aid of a Gallenkamp type hot air oven (Memmert GmbH, Germany). Product masses were weighed using the Kern 440–35N (Kern & Sohn GmbH, Stuttgart, Germany).

**Evaluation of the indices of densification**

Procedures and equations employed for evaluating the relevant indices of densification presented here are well reported in literature *(Akangbe, Blahovec, Adamovský, Linda, & Hromasova, 2019; Akangbe & Herak, 2017)*. For a measure of product deformation, gross energy input may be computed using equation (1).

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

where $n$ refers to subdivisions of the deformation axis or incremental deformation, as logged by the test equipment *(Akangbe & Herak, 2017)* and $F_N$ (N) is force applied for an observed deformation, $\delta_n$ (mm). With respect to the mass of the material compressed, specific energy demand, $E_m$ (J.kg$^{-1}$) was calculated as shown in equation (2).

$$E_m = {}^{E}\!/_{m} \quad (2)$$

where $m$ (kg) is the mass of the material compressed. The specific power, $\dot{E}$ (J.kg$^{-1}$.s$^{-1}$) was subsequently calculated as the time rate of expenditure of this energy, using equation (3).

$$\dot{E} = {}^{E_m}\!/_{t} \quad (3)$$

where $t$ is deformation time, s. The effective deformation force ($F_{net}$), net specific energy demand and net specific power requirement were computed using equations (1) – (3), having deducted the measured frictional drag from the applied compression force and replacing $F_N$ (above) with the net force, $F_{net}$ (N), such that

$$F_{net} = F_N - f_N \quad (4)$$

where $f_N$ (N) is the attendant frictional drag. Deformation moduli were established as ratios of applied and effective compressive stress to the strains obtaining. Bulk density of the compressed material was determined as a function of the established material volume upon compression.

**Data analysis**

Regression analysis was run on calibration data and treatment means for the test data as well as other ancillary statistics were established using the MS Excel platform.

**RESULTS**

From the calibration tests conducted, frictional drag along the wall of the compression vessel was found to be related to the output voltage parabolically as presented in equation (5). This relationship was found to be a fitting representation of the interaction of the two parameters ($p<0.001$) and provided estimates of a significant proportion of the system's behaviour ($R^2 = 0.999$) appropriately.

$$f = 776.09V^2 + 2984.1V \quad (5)$$

where $f$ is frictional drag (N) and V is output voltage (Volts).

Force and deformation profiles of the compressed food material are presented in Fig. 2. Frictional resistance progressed in a pattern similar to that observed with the steadily applied force. Both trends were curvilineal and appeared to be transcendantal. This means that as the applied force increased, friction along the wall of the vessel also increased, attaining a peak value at the maximum applied force. As a result of this, the effective force acting to compress the powdery material was significantly reduced compared to the applied force (Fig. 2). This net force however exhibits curvilineal trend similar to those of the interacting forces producing it. An intersection of the profiles of wall friction and the effective compressive force is apparent at about 3027.75 N or a deformation of 8.05 mm. Beyond this point (Fig. 2), effective compressive force was lower than the magnitude of friction along the material-wall interface. This means that a substantial proportion of the force applied beyond the indicated point of interaction, at the given magnitude of applied pressure, is absorbed as frictional resistance. At the applied pressure of 20 MPa and strain of 0.368, induced at a rate of 0.007 $s^{-1}$, the effective compressive pressure on the powdery material was 8.53 MPa (Fig. 3). This means that, for the gross energy demand of 2.58 $kJ.kg^{-1}$, the net energy utilised for deforming the material was 1.46 $kJ.kg^{-1}$. It may be inferred, therefore, that friction energy uptake during the compression of the product

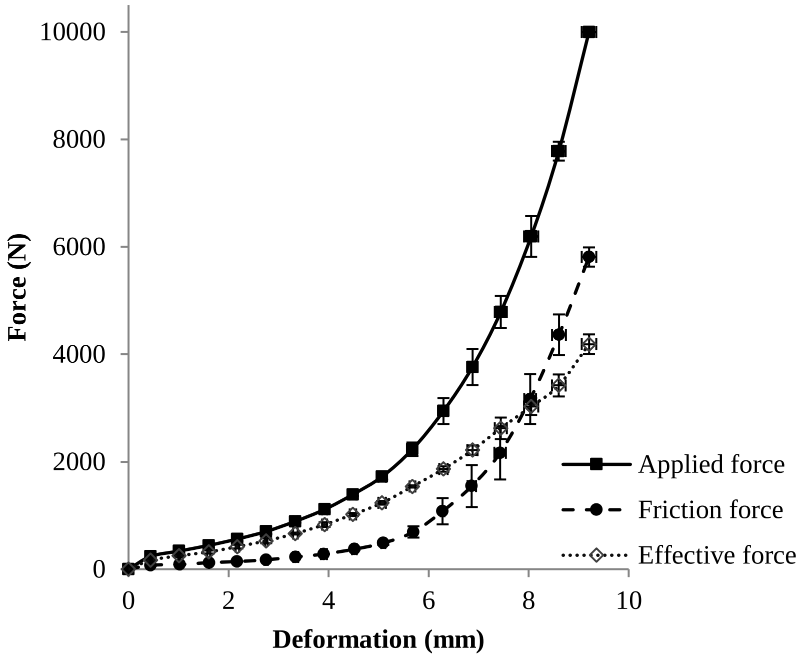


**Fig. 2** Force profiles during the compression of dry carob powder

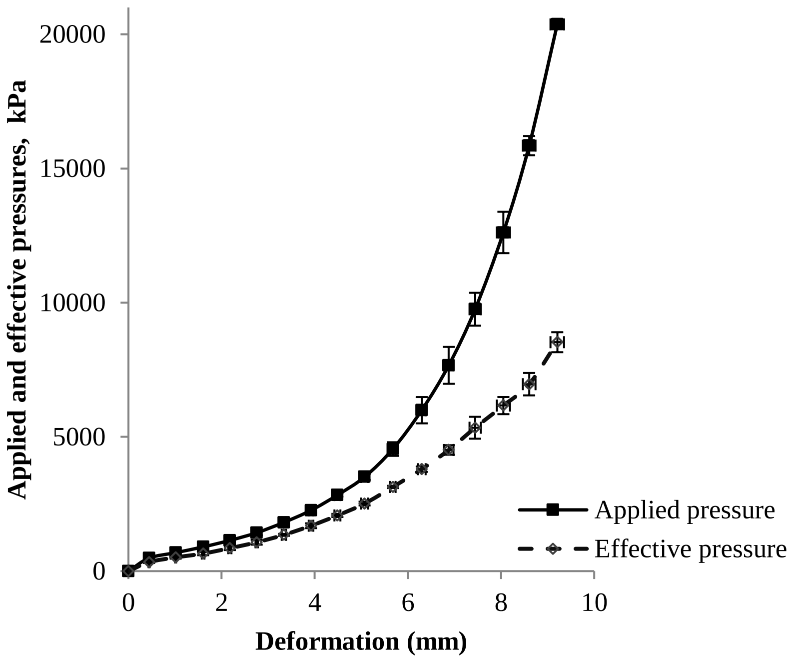


**Fig. 3** Applied and effective pressure profiles during the course of product deformation

was responsible for a significant loss (1.12 kJ.kg$^{-1}$) of the input energy, which represented 43.4% of the total energy supplied. The final bulk density of the compressed carob powder was 1154.55 kg.m$^{-3}$. At the applied pressure, gain in bulk density of 58.3% occurred in the material, its porosity having been lowered from 50.2% – 24.4%. The time rate of the expenditure of energy by the material for this gain in density was 26.25 kW.kg$^{-1}$. This was energy use following losses to friction. The attendant modulus of deformation given friction loss (64.9 kPa) was also less compared to what may obtain at the full magnitude of the applied pressure of 20 MPa, which is 187 kPa.

## DISCUSSION

Wall friction has a limiting effect on the force acting on the compressed material *(Briscoe & Rough, 1998)*; it significantly reduces the effective compression force and grows with the applied force *(Tien, Wu, Huang, Kuo, & Chu, 2007)*. Contributory effects of the, so called, stick-slip phenomenon *(Stasiak & Molenda, 2004)* translate to significant reductions in transmissibility of applied pressure *(Michrafy, Ringenbacher, & Tchoreloff, 2002)*. Along the material-wall interface, modifications of the layer of the compressed material in contact with the wall occurs. This is associated with friction coefficient, magnitude of radially transmitted force and the comencement and degree of thermal excitations *(Li, Liu, & Rockabrand, 1996; Persson, 1999)*. The onset of such activity is indicated by the occurrence of stick and slip. High fibre content of carob powder *(Yousif & Alghzawi, 2000)* is, in part, responsible for the high frictional resistance, consequent thermal excitation and modification of the material in contact with the wall of the die. *Stasiak, Molenda, Horabik, Mueller, & Opaliński (2014)* report lessening or near elimination of this effect through the use of some lubricating media, although under low compressive pressures. Density attained by the bulk material is therefore attributable, essentially, to the effective compressive pressure. There are important implications of these in respect of achievable product densification and densification energy requirement.

## CONCLUSIONS

A method for direct acquisition of data on frictional drag along material-wall interface of product compression dies is presented. Wall friction was satisfactorily related to output voltage and the effect of friction on product densification was found to be pronounced and limiting to effective compression force beyond some critical point for the reported test conditions. Understanding the effects of friction along the interface between compressed products and the wall of compression dies is vital to product densification and food handling and storage schemes.

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