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STRENGTH OF COFFEE BEANS UNDER STATIC AND DYNAMIC LOADING

Šárka Nedomová, Jan Trnka, Pavla Stoklasová, Jaroslav Buchar

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Abstract

NEDOMOVÁ ŠÁRKA, TRNKA JAN, STOKLASOVÁ PAVLA, BUCHAR JAROSLAV: *Strength of coffee beans under static and dynamic loading.* Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, 2013, LXI, No. 3, pp. 743–749

Paper deals with experimental research on the crushing of coffee beans of different kinds under quasi-static and dynamic compression. The process of the crushing is described in details. It has been shown that there is variability in the crushing strength values. A relation between crushing strength and the coffee grain shape is also studied. Roasted Arabica coffee (*Coffea arabica)* beans were used for analyses. Arabica coffees were produced in different countries. All Arabica samples were submitted to a light roast. The detail analysis of the experimental data shows that there is no significant relation between parameters describing the fracture behaviour of the grains and grain geometry. These parameters are also independent on the grain weight. Compression of the coffee grains leads to their crushing. The fracture force is different for the different kinds of the coffee. The same is fact valid also for the strain at the fracture and for the energy absorbed during the grain crushing. Dynamic loading leads to the increase in the fracture force of coffee grains in comparison with the quasi static loading.

coffee beans, compression loading, strength, impact loading

The knowledge of the strength and toughness of the coffee beans is necessary in order to evaluate their brittleness. The reaching of a certain degree of brittleness is very important for the grinding to which coffee beans have to be subjected to before brewing. The uniformity of the product of the grinding process depends on various factors including the brittleness of the roasted coffee bean and it affects the extraction of soluble solids to obtain the coffee brew (Clo and Voilley, 1983; Clarke and Macrae, 1987). Even though the changes in the textural and mechanical characteristics to which the coffee bean undergo during roasting play a relevant role in the quality of the roasted beans, these properties have been scarcely studied until now.

The textural changes of coffee beans during their roasting have been studied e.g. by Pitia *et al.* (2001) using of the static compression of the coffee beans. The same technique has been used for the study of the influence of the moisture content and water activity on the mechanical properties of the coffee beans (Pitia *et al.*, 2007). This technique has been also used for the study of mechanical properties of many others beans, see e.g. (Tran *et al.*, 1981, Borges and Peleg, 1997; Al Salah and Galland, 1985). In our previous paper (Nedomova, 2010) results on the coffee grain compression has been presented. These results have been obtained for the quasi static loading.

The grinding of the coffee represents a loading process which is dynamic rather than static. It means the mechanical properties like crushing strength should be evaluated at the dynamic loading. In the given paper an experimental method for the study of the coffee beans response to the dynamic (impact) loading developed by Nedomová *et al.* (2010). The experimental data have been obtained for 20 different beans of the Arabica coffee. Results are compared with the results of the static loading.

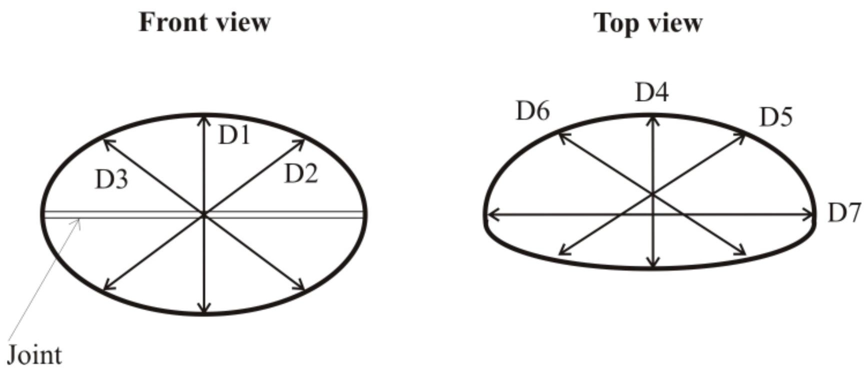
MATERIAL AND EXPERIMENTAL METHODS

Arabica coffee beans (roasted) were used for performed analyses. Coffees were produced in Brazil [B], Colombia [C], Costa Rica [CR], Ethiopia

[E], Guatemala [G], Honduras [H], Indonesia [I], Kenya [K], Mexico [M], Panama [P], Papua New Guinea [P-NG], Peru [PE], and Tanzania [T]. The abbreviations in square brackets indicate the coffee type and it is used in the text hereinafter. For the sake of simplicity these abbreviations are also substituted by number. The beans were ordered from a commercial distribution network in the Czech Republic. All analyses were performed for samples of 20 beans randomly selected from each lot.

Dimensions in the main axes (D1, D4, D7 – see Fig. 1) were measured using a digital caliper SOMET (Germany). With regard to measurement accuracy and relevance, one decimal number was considered. According to indication by other authors (Ghosh and Gacanja, 1970) D1, D4, and D7 dimesnsions correspond to *W* (width), *D* (depth) and *L* (length), respectively. Remaining dimensions (D2, D3, D5, D6 – see Fig 1) were determined from digital images using Corel DRAW X3 (Corel Corporation, USA). The detail analysis of the bean's shapes is given in (Severa *et al.*, 2012). In this paper only some main geometric characteristics are used. Their values are given in the Tab. I. Together with the weight of the beans – average from 1000 beans.

A TIRA Universal Testing Machine, equipped with a 200 N load cell was used. For the measurements, 20 beans of each sample were taken at random, and then positioned individually on its longest side and with the flat side up between two metal parallel plates of the dynamometer. Compression force was applied at



1: *Illustration of measuring sides for coffee beans*

I: *Selected physical characteristics of different coffee brands*

Coffee brand	Coffee No	Mean w (g)	Mean width D1 (mm)	Mean depth D4 (mm)	Mean length D7 (mm)
B1	1	0.134 ± 0.026	8.48 ± 0.46	4.56 ± 0.32	11.08 ± 0.91
B2	2	0.130 ± 0.023	8.36 ± 0.54	4.58 ± 0.26	10.85 ± 0.99
C1	3	0.137 ± 0.022	7.98 ± 0.47	4.63 ± 0.24	10.79 ± 0.99
C2	4	0.147 ± 0.023	8.43 ± 0.47	4.79 ± 0.52	11.13 ± 2.24
C3	5	0.135 ± 0.029	8.05 ± 0.58	4.70 ± 0.35	10.83 ± 1.30
CR	6	0.117 ± 0.025	7.94 ± 0.52	4.50 ± 0.30	10.66 ± 0.97
E	7	0.123 ± 0.032	7.56 ± 1.38	4.71 ± 0.37	10.93 ± 1.47
G	8	0.128 ± 0.025	8.20 ± 0.48	4.67 ± 0.34	10.60 ± 0.85
H	9	0.141 ± 0.028	8.26 ± 0.59	4.79 ± 0.26	10.82 ± 2.05
I1	10	0.149 ± 0.026	8.26 ± 0.62	4.64 ± 0.28	11.47 ± 0.84
I2	11	0.146 ± 0.025	8.34 ± 0.57	4.79 ± 0.37	11.90 ± 1.10
I3	12	0.141 ± 0.030	8.09 ± 0.84	4.73 ± 0.58	11.51 ± 1.32
K1	13	0.152 ± 0.022	8.26 ± 1.53	4.91 ± 0.70	10.97 ± 0.92
K2	14	0.163 ± 0.028	8.78 ± 0.42	5.07 ± 0.38	11.60 ± 1.06
K3	15	0.149 ± 0.021	8.71 ± 0.45	4.90 ± 0.31	11.46 ± 0.75
M	16	0.246 ± 0.038	9.76 ± 0.37	5.62 ± 0.36	14.90 ± 1.26
P	17	0.142 ± 0.024	8.20 ± 0.49	4.75 ± 0.30	11.19 ± 2.91
P-NG	18	0.124 ± 0.037	8.02 ± 0.79	4.58 ± 0.49	10.36 ± 2.09
PE	19	0.137 ± 0.031	8.09 ± 1.47	4.78 ± 0.28	10.55 ± 1.85
T	20	0.149 ± 0.021	8.60 ± 0.49	4.78 ± 0.30	11.28 ± 0.65

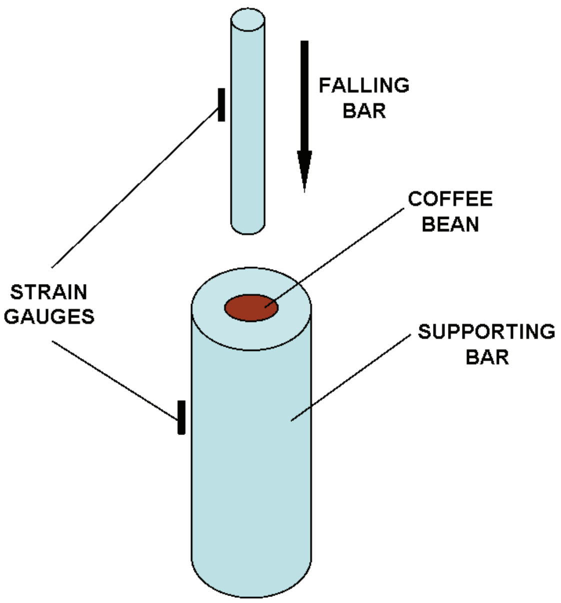
a rate of 20 mm/min until failure occurred; working temperature was 25 °C. Beans were loaded along the D4 axis. Owing to the difficulty to calculate the true stress and strain, the mechanical properties of the coffee beans were characterized with the following empirical measurements carried out in the force-displacement curve (Borges and Peleg, 1997):

- Breaking force (F_s) corresponding to force at the major failure event. It was considered as empirical measure of the crushing strength;
- Strain at fracture (ε_f) corresponding to the deformation at the first breaking point and used as index of the deformability; it was expressed as percentage to keep into account the actual dimensions of the differently heat treated beans;
- Work (W) corresponding to the area under the force – displacement curve until the first breaking event occurred. This parameter has been used as empirical index of toughness. This work represents an absorbed energy during the grain crushing.

Twenty grains have been tested for every coffee type.

Schematic of the experimental device used for the dynamic loading is shown in the Fig.2. Coffee bean is placed on the wood rod and impacted by the falling bar. The bar is made from aluminium alloy. Its length is 200 mm, diameter of the bar is 6 mm. The bar is allowed to fall freely for a pre – selected height. The instrumentation of the bar by the strain gauges (semiconducting, 3 mm in length) enables to record time history of the force at the area of bar – coffee bean contact. The same instrumentation is used for the supporting wood bar. It enables to record a force transmitted by the coffee bean to the bar.

The height of the bar fall can be increased up to value at which the coffee bean damage is observed. The experimental method enables to record the loading force (at the bar and coffee bean) and the force transmitted into the supporting bar. The time histories of both forces can be evaluated in time as well as in the frequency domain. From these histories the breaking force of the coffee beans can be evaluated.



2: *Schematic of the experimental device for the impact testing*

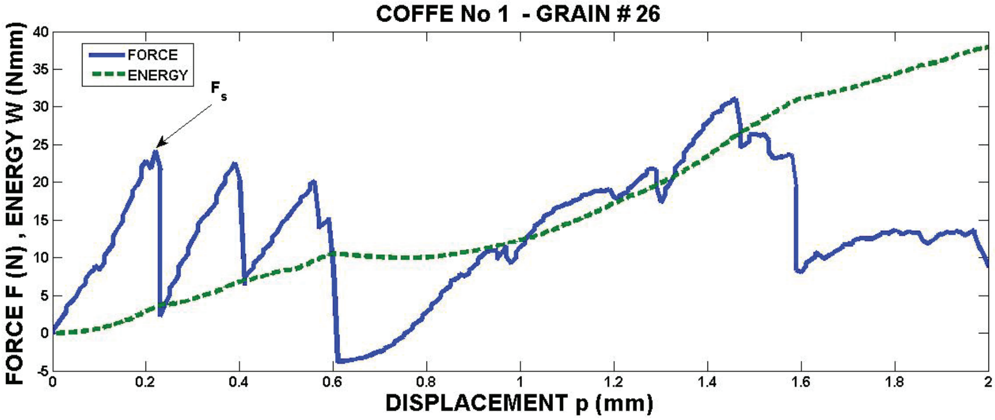
EXPERIMENTAL RESULTS

In the Fig. 3. an example of the experimental record of the force F *vs* displacement p obtained at the quasi static compression is shown. This record exhibits several peaks of the force. The peak corresponds to the specimen fracture. The first peak is taken as the breaking force of the coffee grain. The following peaks of the loading forces correspond to the process of the repeated grain crushing into several fragments.

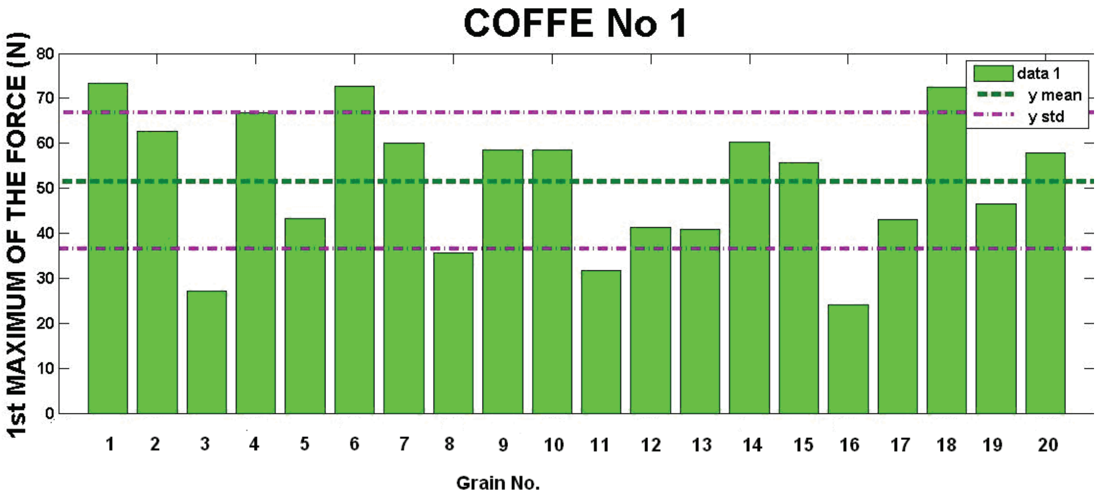
The values of breaking force exhibit a significant scatter as shown in the Fig. 4.

Average values of the coffee beans strength are displayed in the Fig. 5.

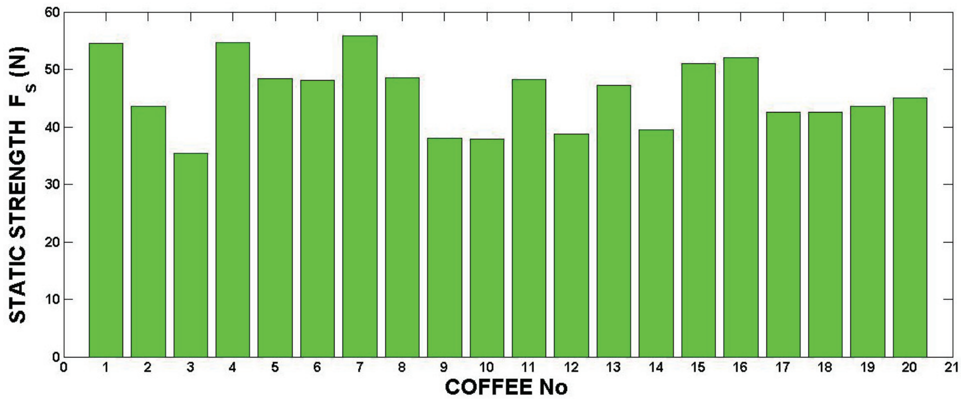
Strength of different branch of coffee changes between about 30 and 60 N. These values are



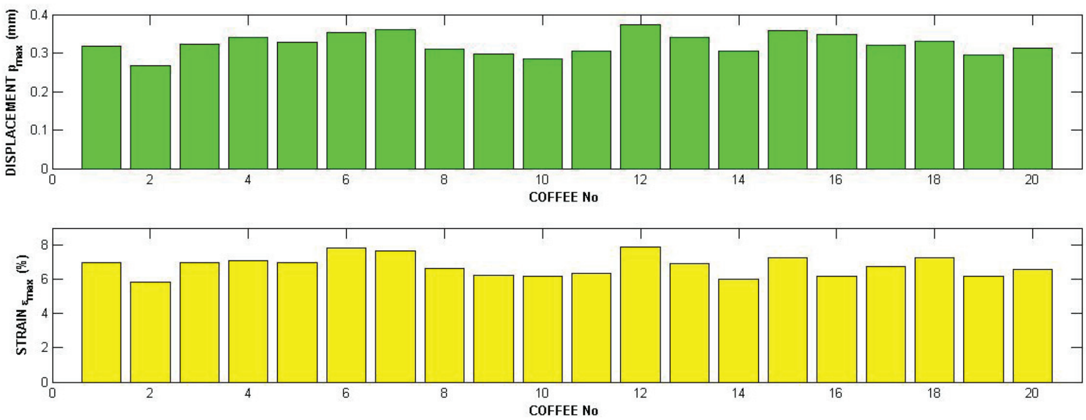
3: *Experimental record of the force during static compression of the coffee bean*



4: *Values of breaking strength of the single coffee beans*



5: *Static strength of the coffee beans*

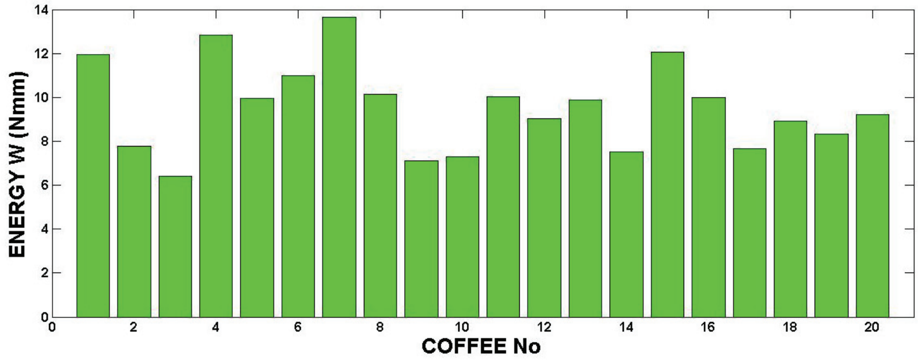


6: *Strain at fracture for different coffee branch.*

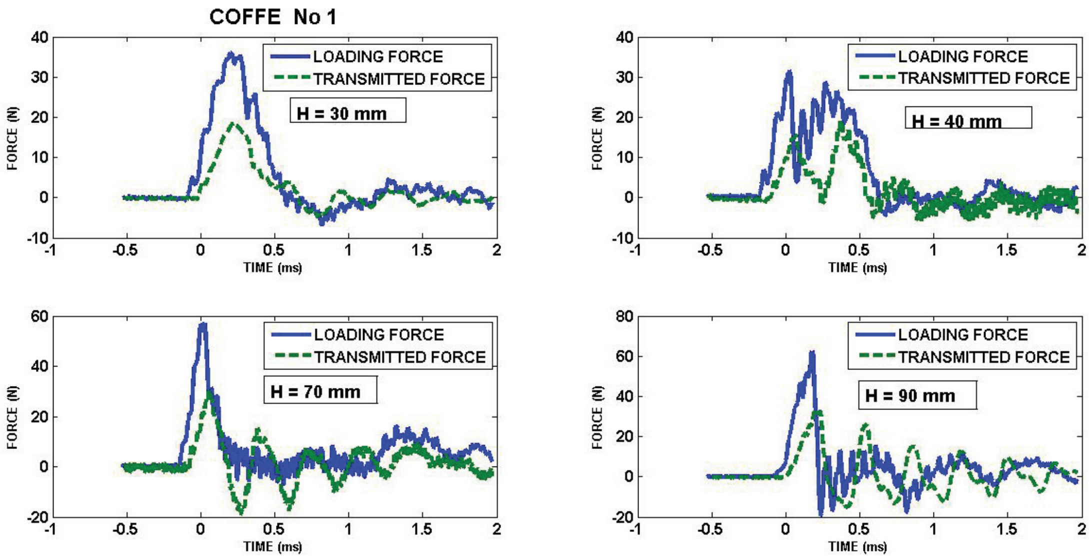
comparable with those reported by Pitia (2001) for well roasted beans. The remaining textural characteristics mentioned in the section 2.3 are shown in the Figs. 6 and 7.

The values of absorbed energy correspond with those reported by Pitia *et al.* (2001) for high yield coffee. At the same time the values of fracture strain achieved in this paper are significantly lower than those given in (Pitia *et al.*, 2001). The values of these mechanical characteristics are dependent on the loading orientation. The orientation used in this paper leads to the maximum of the breaking force, F_s.

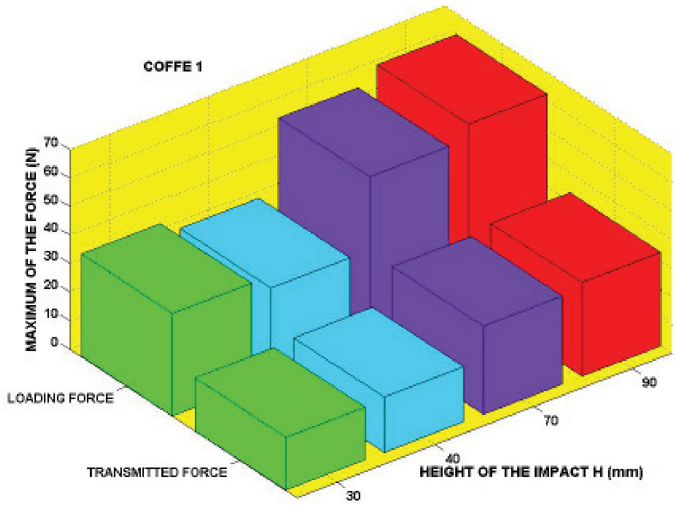
Example of the time histories both impact force and the force transmitted into the wood bar is displayed in the Fig. 8. With the increasing height,



7: *Absorbed energy during the bean crushing*

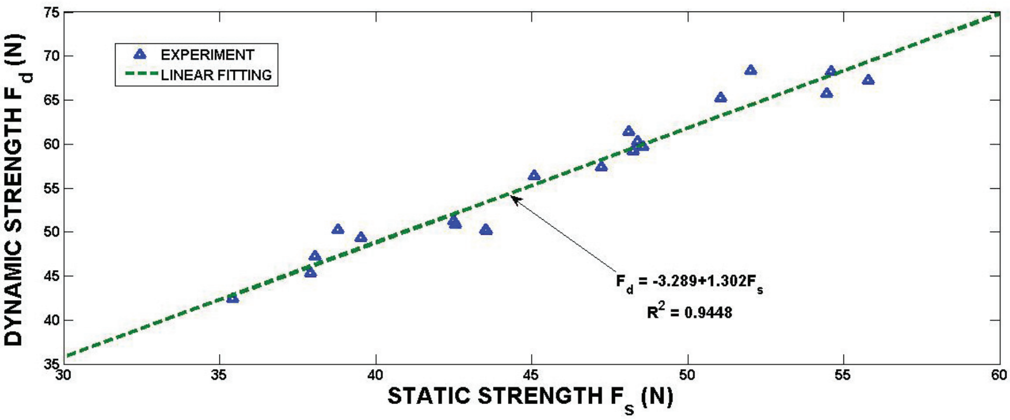


8: *Time history of the forces during the coffee bean loading (Coffee grains produced in Brazil)*



9: *Effect of the height of the bar fall on the force maxima (Coffee grains produced in Brazil)*

h, of the bar impact, i.e. with the impact velocity, the shape of this time history changes. The qualitative features of the changes are nearly the same as in the case of the eggshells dynamically loaded by the impact (Nedomová *et al.*, 2009).



10: *The dependence of the dynamic strength on the static one*

For the value of h = 90 mm the coffee bean has been completely broken. The dependence of the maximum of the forces on the height, h, is shown in the Fig. 9.

The dependence of the maximum of the loading (impact) force on the height h enables to evaluate the force at which the bean is fractured. The procedure has been outlined e.g. in (Nedomová *et al.*, 2009). The values of this dynamic breaking force (strength) are plotted in the Fig. 10 as function of the breaking force (strength) obtained at the static compression. One can see that the coffee beans resistivity against to fracture is higher at the dynamic (impact) loading.

The experimental points can be fitted by a linear function with a relatively good correlation.

The increase the strength at transition from static to dynamic loading is very often observed for many technical materials including metals and their alloys, polymers etc. This increase can be explained in terms of material structure. It means the explanation of this phenomenon in coffee beans must be based on the detail study of the microstructure of this material.

CONCLUSSIONS

In the given paper a new experimental method for the testing of impact behaviour of coffee beans has been used. This procedure enables to evaluate the dynamic strength of these beans. Results obtained for 20 coffee brands showed the higher values of the dynamic strength than strengths evaluated at the static compression. The dependence of the dynamic strength is linear function of the static strength. The dynamic forces recorded at the impact loading show different features from those obtained at the static compression. At the same time the dynamic force time histories are very similar to those obtained for other brittle biological materials (eggshells).

SUMMARY

The deformation and fracture behaviour of the twenty types of the *Arabica* coffee grains have been studied. In the first step the tested coffee beans have been loaded in compression using of TIRATEST testing machine. Cross – head velocity was 20 mm.min^{-1}. This velocity is generally accepted as static loading. From the given test the following quantities have been evaluated:

- Breaking force (N) corresponding to force at the major failure event. It was considered as empirical measure of the crushing strength;
- Strain at fracture (%) corresponding to the deformation at the first breaking point and used as index of the deformability; it was expressed as percentage to keep into account the actual dimensions of the differently heat treated beans;
- Work (J) corresponding to the area under the force - displacement curve until the first breaking event occurred. This parameter has been used as empirical index of toughness. This work represents an absorbed energy during the grain crushing.

In the next step a new method of impact loading of coffee beans has been used. The procedure of the bean fracture evaluation under dynamic loading has been applied. It has been shown that the dynamic strength is higher than the static one. The dynamic strength seems be linear function of the static one.

The experimental data exhibit large scatter. For the evaluation of some bean property at least 20 coffee beans are needed. The obtained results suggest that there is significant dependence of the parameter mentioned above on the type of the coffee beans. At the same time no dependence on the bean size, weight and shape have been observed. Main source of the difference in the coffee beans properties is thus probably given by the roasting conditions.

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Address

doc. Ing. Šárka Nedomová, PhD., Department of Food Technology, prof. Ing. Jaroslav Buchar, DrSc., Department of Technology and Automobile Transport, Mendel University in Brno, Zemědělská 1, 613 00 Brno, Czech Republic, Ing. Jan Trnka, CSc., Ing. Pavla Stoklasová, PhD., Czech Academy of Sciences, Dolejskova 5, 182 00 Praha, Czech Republic, e-mail: snedomov@mendelu.cz, buchar@mendelu.cz, trnka@it.cas.cz, pavla.stoklasova@gmail.cz