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Mechanical properties of sugar beet root during storage**

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Abstract. This paper is an investigation *via* two experimental methods, of the textural properties of sugar beet roots during the storage period. In the work, sugar beet roots mechanical properties were evaluated during the post-harvest period – 1, 8, 22, 43, and 71 days after crop. Both experimental methods, *i.e.* compression test and puncture test, suggest that the failure strength of the sugar beet root increases with the storage time. The parameters obtained using the puncture test, are more sensitive to the storage duration than those obtained by way of the compression test. We also found that such mechanical properties served as a reliable tool for monitoring the progress of sugar beet roots storage. The described methods could also be used to highlight important information on sugar beet evolution during storage.

Keywords: sugar beet root, texture, compression, puncture, storage

INTRODUCTION

Sugar beet (*Beta vulgaris* L.) is the world's most cultivaed crop after sugarcane (*Saccharum officinarum* L.) or the production of sucrose for human consumption. The mechanical properties of the beet, together with sucrose, soluble solids and moisture content, are important parameters in evaluating the sucrose yield and the cost of sugar beet production, and also for assessing new sugar beet germplasms and/or cultivars (Cheng *et al.*, 2011; Kabas and Ozmerzi, 2008; Kertész *et al.*, 2015; Kumbár *et al.*, 2015). Most of these properties are evaluated through compression, rheological and puncture testing (Sirisomboon *et al.*, 2012; Szymanek, 2009; Trávníček *et al.*, 2016; Trnka *et al.*, 2016). The compression test is effective in evaluating the mechanical response of the whole agricultural product, while the puncture test is useful in indicating the approximate strength of the peel and the flesh at the puncture point (Nedomová *et al.*, 2016). These two tests are also effective in testing for most of the categories of damage to fruit and vegetables (Sirisomboon and Pornchaloempong, 2011). In addition, such tests provide useful data for engineers which can be utilized in the design of postharvest handling machines and equipment for fruit and vegetables, such as that for sorting, grading, packing and conveying, as well as for designing storage systems (Božiková and Hlaváč, 2016; García-Ramos *et al.*, 2003).

The aim of this paper is to investigate the textural properties of sugar beet root during the storage period. Herein, both of the aforementioned methods are utilized.

MATERIAL AND METHODS

The sugar beets used in this study were collected from a field near Jiříkovice (region South Moravia) during the 2015 harvest season. The sugar beet variety was Gellert, which is a species-tolerant diploid variety, NC type, suitable for early harvesting. The variety is resistant to flowering, but less resistant to leaf spot complexes (Hakaufová, 2013). Exactly 100 sugar beet roots samples were placed in refrigerated storage at 4°C and 85% relative humidity prior to the experiment.

Cylindrical samples with a diameter of 10 mm were cut from the central region of each beet using a cork borer, then were trimmed to the height of 12 mm. The specimens were compressed between two steel plates. The crosshead velocity was 20 mm min^{-1}. The mechanical properties assessment was conducted using TIRATEST 27025 (TIRA Maschinenbau GmbH, Germany). This equipment enables both compression, as well as puncture testing (Nedomová *et al.*, 2016).

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Mechanical testing of material by means of the uniaxial compression test is basically very simple (Atluri and Kobayashi, 1993). A cylindrical sample of height l_o and cross section A_o is compressed between two parallel metal plates at a fixed crosshead speed. The force F and the deformation Δl are measured during this compression, and both quantities are recorded. The generated force-deformation data may be easily transformed into normalized quantities such as stress and strain. The Cauchy or engineering strain and Hencky's natural or 'true' strain are commonly used in representing compression curves (Peleg, 1984). The Cauchy's strain measure ε_C gives the relative deformation with respect to the initial sample height l_o (Liu and Krempl, 1979):

$$\varepsilon_C = \frac{\Delta l}{l_0}. \tag{1}$$

Hencky's strain ε_H (often denoted as 'true' strain) derives from the integration of the infinitesimal strain $-\frac{dl}{l}$ and reads (Plešek and Kruisová, 2006):

$$\varepsilon_{\mathrm{H}} = -\ln\left(\frac{l_0 - \Delta l}{l_0}\right) = -\ln(1 - \varepsilon_{\mathrm{C}}). \tag{2}$$

The force F can be converted to the ultimate or engineering stress σ_u or to the true stress σ_c. The ultimate stress is simply given as:

$$\sigma_u = \frac{F}{A_0}. \tag{3}$$

The true stress is evaluated using the instantaneous cross section A. Its value is mostly obtained through assuming a constant volume of the specimen (Casiraghi *et al.*, 1985):

$$V = V_0 \Leftrightarrow Al = A_0 l_0 \;\; A = A_0 \frac{l_0}{l - \Delta l}, \tag{4}$$

The true stress is then expressed as (Čadek *et al.*, 2004):

$$\sigma_C = \frac{F}{A} = \frac{F}{A_0}\frac{l_0 - \Delta l}{l_0} => \sigma_C = \sigma_u(1 - \varepsilon_C). \tag{5}$$

The puncture test is the most common method for assessing fruit and vegetables texture characteristics (Juxia *et al.*, 2015; Nannyonga *et al.*, 2016; Rodriguez-Arcos *et al.*, 2002). It measures firmness (Duprat *et al.*, 1995). A typical penetration curve is shown in Fig. 1 (Camps *et al.,* 2005).

The maximal force F_s represents the force required to puncture the fruit skin. Herein, F_s is the skin strength. If the dependence force-displacement is linear, the slope of the penetration curve defines the stiffness $S_{stiff} = \frac{F_S}{D_p}$ (Okamura *et al.*, 2004). Work W_1 is the mechanical work needed to reach the rupture point. The flesh firmness F_f is the average values of the forces measured after the skin rupture (Altuntas and Karaosman, 2015; Ozturk *et al.*, 2009). In a similar way, work W_2 is the work measured after the skin rupture.

Analysis of variance (ANOVA) was applied to all variables studied. Mean values obtained in the different measurements were compared by one-way analysis of variance (ANOVA). Statistical analysis was performed with the statistical toolbox of software Matlab version 7.12.0.635 (R 2011a) (The MathWorks, Inc., Nattick, MA).

RESULTS AND DISCUSSION

In the compression testing, an example of the experimental record force-displacement is displayed in Fig. 2. This record $F(\Delta l)$ can be converted to the stress strain dependence as described in Eqs (1) – (5). Stress increases with the strain up to some maximum. This maximum corresponds to the tissue damage. Owing to this fact, this stress is denoted as the failure stress. The same qualitative features exhibit the stress-strain curves during the whole period of the storage (Fig. 3).

Four parameters were identified so as to characterise the compression stress-strain curves (Canet *et al.*, 2005; Luginbühl, 1996; Smith and Kobayashi, 1993). These are:

- the failure stress;
- the Cauchy strain at stress maximum ε_C;
- the Hencky strain at stress maximum ε_H;
- the apparent energy density at the failure. This is defined as the total work of deformation divided by the original sample volume $W = \int_0^{\varepsilon_C} \sigma_u d\varepsilon$ (J m^{-3}) (Náhlík *et al.*, 2016).

All these parameters are given in Table 1. The data are presented as mean value from 5 measurements ± standard deviation.

The maximum of the stress increases with the duration of the storage as in Molenda *et al.* (2002). The same can be observed for the corresponding strain. The changes in the energy W with the storage duration are not too significant (Fig. 4).

In the puncture testing, we obtained a force-penetration depth dependence which is denoted as the penetration curve (Marshall *et al.*, 2008; Oraguzie *et al.*, 2007; Wen *et al.*, 2006). This method has been used for the evaluation of fruit quality (de Escalada Pla *et al.*, 2006; Forney, 2008; Harker *et al.,* 2002; Ruiz *et al.*, 2005; Wu and Abott, 2002). With this test, the maximal penetration force is measured that is required to let a cylindrical probe penetrate, *e.g.* in the apple, flesh up to a predetermined depth (Bianchi *et al.*, 2016; Mehinagic *et al.,* 2003; Valdez-Fragoso *et al.*, 2009).

Puncture tests were performed on the samples using the same testing device, *i.e.* the TIRATEST 27025. A stainless steel plunger with a flat end diameter of 6 mm was

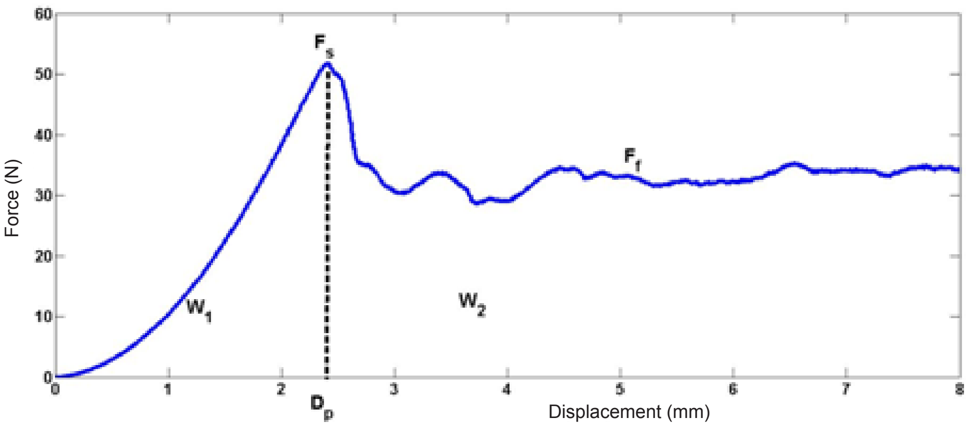

Fig. 1. Typical course of the force-displacement curve during the puncture test.

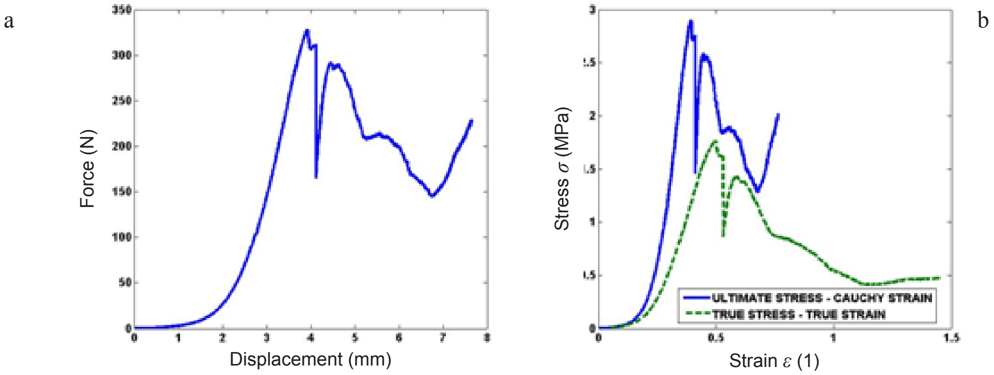

Fig. 2. Example of the experimental record: a – force-displacement and b – stress-strain dependence.

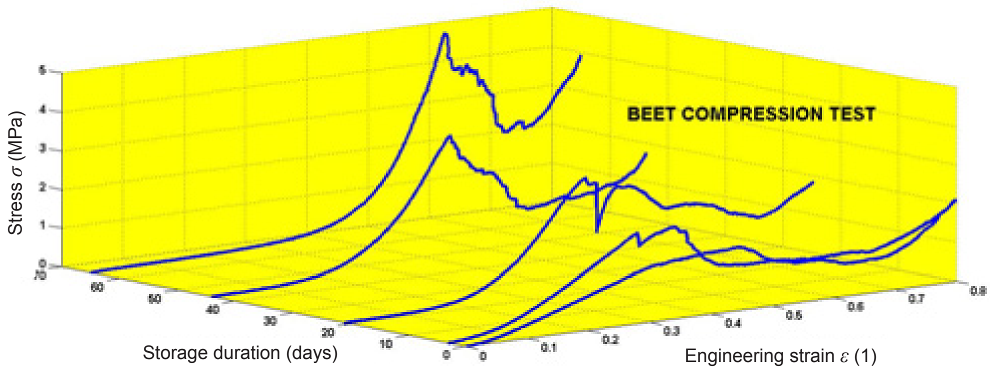

Fig. 3. Stress-strain curves during the storage period.

Table 1. Main parameters of the compression stress-strain curves

Storage (days)	σ_{max} (MPa)	ε_C	ε_H	W (MJ m^{-3})
1	2.08 ±0.388a	0.316 ±0.0554a	0.372 ±0.0754a	1.035 ±0.1930a
8	2.34 ±0.496ab	0.276 ±0.0229a	0.318 ±0.0312a	1.141 ±0.0897ab
22	2.48 ±0.352b	0.312 ±0.0030a	0.366 ±0.0041a	0.950 ±0.1638a
43	2.81 ±0.394a	0.308 ±0.0210a	0.360 ±0.0287a	0.803 ±0.0573ac
71	3.69 ±0.206c	0.349 ±0.0165b	0.417 ±0.0234b	1.090 ±0.2407a

*Different letters in the same column for each source indicate significant differences in means, N = 5, $p \leq 0.01$.

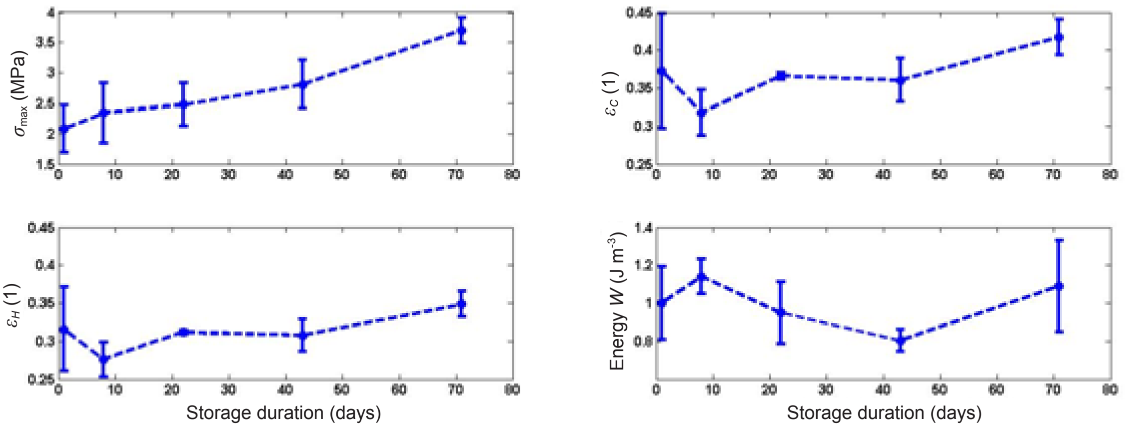

Fig. 4. Effect of the storage duration on the main parameters of the compression stress-strain curve.

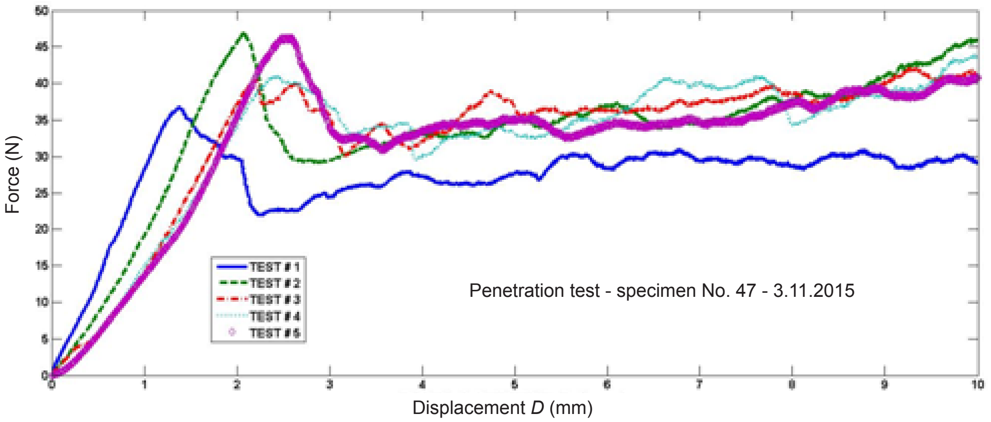

Fig. 5. Experimental records force – displacement (1st day of the storage).

Table 2. Parameters of the puncture test

Storage (days)	D_p (mm)	F_s (N)	W_1 (Nmm)
1	2.087 ±0.5752a	35.16 ±5.443a	133.00 ±9.491a
8	2.455 ±0.3904a	47.56 ±3.975b	142.89 ±29.082a
22	3.812 ±0.6106b	45.07 ±7.165b	154.27 ±46.705a
43	4.524 ±0.8521b	50.16 ±6.445bc	197.74 ±32.215b
71	6.833 ±0.9741c	56.16 ±10.2c	349.13 ±47.892c

Explanations as in Table 1.

attached to the load cell and used to penetrate the fruit at a deformation speed of 20 mm min^{-1}. An example of the obtained experimental data (the penetration curves and force-displacements) is shown in Fig. 5.

It is evident that the results of our experimental work exhibit the main features displayed in Fig. 1. The main parameters of this dependence, *i.e.* skin strength F_s corresponding displacement D_p and energy $W_1 = \int_0^{D_p} FdD$ are given in Table 2. The dependence of these parameters is displayed in Figs 6-8.

Our work indicates that all the described parameters increase with the duration of the storage (Miraei Ashtiani *et al.*, 2016; Nedomová *et al.*, 2016, 2017).

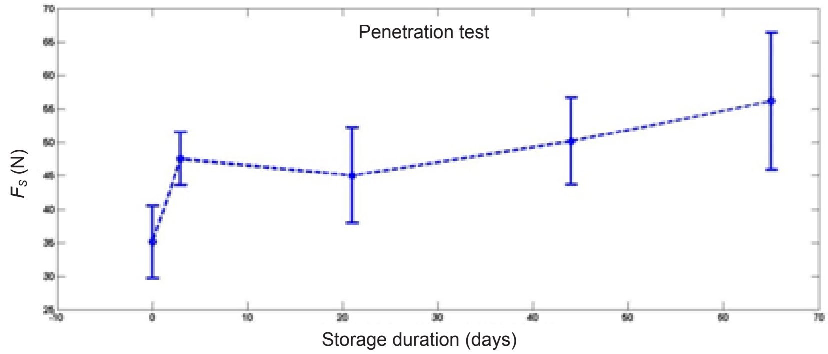

Fig. 6. Effect of the storage duration on the skin strength.

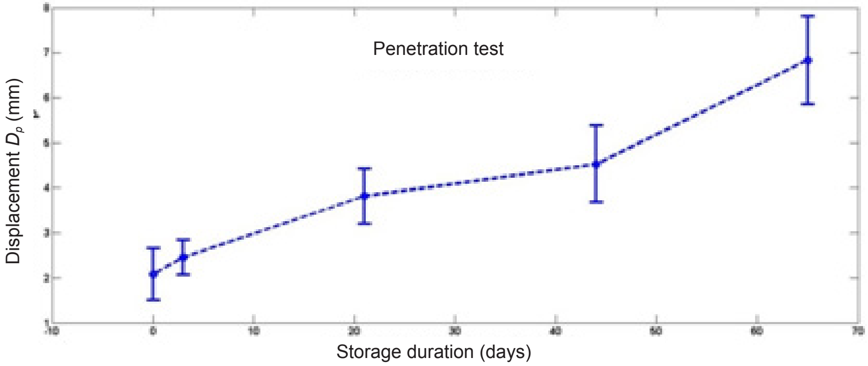

Fig. 7. Effect of the storage duration on the penetration depth at the rupture point.

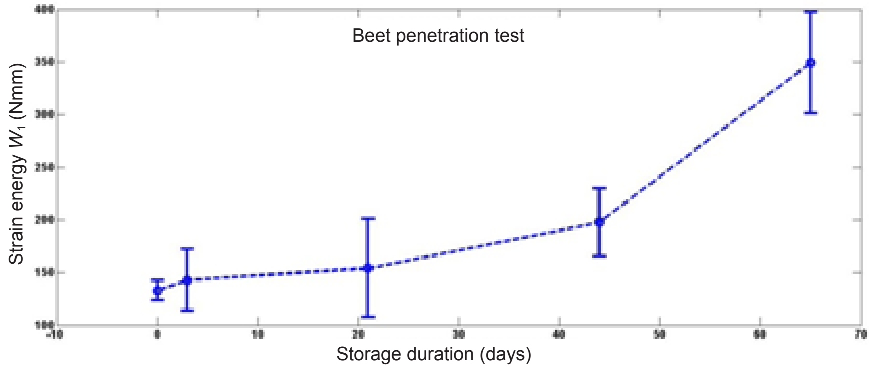

Fig. 8. Effect of the storage duration on the work up to the rupture point.

CONCLUSIONS

1. Sugar beet failure strength increases with the storage time.

2. The changes in mechanical parameters of sugar beet roots during storage time can be described better through the compression test than by way of the puncture test.

3. The described methods can be used for determination mechanical properties during sugar beet processing (*e.g.* crop, transport, root wash, mechanical strip slicing).

Conflict of interest: The Authors do not declare conflict of interest.

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