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Stress relaxation in sugar beet root under various mechanical load conditions

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ABSTRACT

Identification and determination of the mechanical properties of biological materials, especially fruits, vegetables and industrial plants, can be made using commonly applied stress relaxation tests. They are of particular significance because their results make it possible to propose a mechanical model of studied material. The aim of the study was to determine the effects of initial deformation and deformation velocity on the parameters of generalised Maxwell model during stress relaxation in the sugar beet root. The tests were carried out by means of the texture analyser (model TA.HD plus, Stable Micro Systems, Goldaming, UK) at the three deformations: 2.0, 3.5 and 5.0 mm and the four deformation velocities: 1, 2, 10, and 20 mm·s^{-1}. The cut sugar beet samples used in the experiment were cylindrical in shape, with a 9.5 mm diameter and a 20 mm height. They were initially compressed along the vertical axis in a state of uniaxial stress and constant deformation was maintained while recording the force response for 35 seconds. The two-branched generalised Maxwell model with an additional elastic element was used to describe the experimental force response curves. The sample dimensions as well as the initial deformation velocity were taken into consideration in the model formula. Two relaxation times of the model decreased with the increasing deformation velocity and increased with the increasing deformation value. The dependences of the obtained relaxation times on the phenomena inside the tissue such as the flow of fluids and gases under the load were interpreted. Changes of model parameters as a function of deformation velocity could testify the appearance of internal micro damages in the material during deformation. The tendency of increase in the peak force response along with the increase of deformation velocity shows typical viscoelastic behaviour of sugar beet root flesh. The novelty of the paper is the application of the generalized Maxwell model with the stable element for prediction of mechanical response of the sugar beet whose morphological structure is different compared to such soft fruits as apples and pears.

Keywords: sugar beet root, stress relaxation, generalized Maxwell model, mechanical properties, viscoelasticity.

INTRODUCTION

Mechanical damages of sugar beets during harvesting, transport and reloading are a serious problem for both producers and buyers. These losses include both quantitative reduction of root mass and qualitative drop of their production value. This is an essential problem as according to the information provided by Yildiz et al. [1] the share of sugar beets on the Polish market of agricultural and food products was 24%, in the years 2010 and 2020 being the highest of all cultivated plants. In a paper by Bentini et al. [2] the authors found that the sugar beet damages due to the mechanical reaction of harvesting and transport machines diminish the roots productive usability. Defects are made due to impacts during mechanical harvesting, compression during the storage and piles as well as to the action of cyclic loads during the transport. Therefore, the studies on mechanical properties of roots were motivated by the need to diminish losses of sugar beets. That was the reason for the studies undertaken by Gemtos [3] who carried out the tests of compression, stretching, shearing and bending of the tissue.

Another experimental procedure used to determine the properties of biological materials is the test of stress relaxation. There are spaces filled with various amounts of liquids and gases in the cellular structure of plant materials. They relocate under the load which is identified in the viscoelastic centres as the phenomena e. g. of stress relaxation or creep. These processes can be described by means of rheological models. They present a degree of reality simplification. However, they enable elaboration of mathematical description of mechanical plant tissue characteristics.

The course of force response as a function of time based on the stress relaxation test allows determination of the viscoelastic characteristics. The viscoelastic characteristics are closely associated with the texture attributes (e. g. hardness, springiness) as well as the chemical composition (e. g. soluble solids content, acidity) [4]. The literature reports a large number of papers on rheological studies of fruits, vegetables and other materials of biological origin [5–7]. In the case of sugar beet the studies included the experiments consisting e. g. in determination of quality of stored roots [8, 9] as a result of machines work [10] or ways of cultivation and fertilization as well as the production applicability of beets [11]. As the beet root does not have a homogeneous structure and tissue flexibility, the exterior load can change depending on its position related to its surface and the amount of water loss after the storage [12]. Thus the mechanical properties of beets were the object of various investigations on sugar producer's solving problems related to preparation of slices and their treatment inside the extractors in the sugar factory [13–15]. Bzowska-Bakalarz [16] and Alizadeh [17] presented the mechanical properties of sugar beets as obtained from compression and puncture tests. In the paper by Nedomová et al. [18] it was found that it is better to take into account the results of compression than those of puncture and then the roots resistance to damages increases with storage time. In many cases of the analysis of plant material reaction to the mechanical load, the use of simple or generalized rheological models (Bingham, Burgers, Kelvin-Voigt, Maxwell etc.) was the effect not only of development of measuring techniques and research methods but also of their application for description of various processes [19, 20]. This enabled obtaining better knowledge about the phenomena resulting e. g. from transport of gases and liquids in plant tissues during mechanical reactions. The application of viscoelastic models for the analysis of plant tissue reaction to the load is advantageous due to the possibility of determination of relaxation time, elasticity modules and viscosity coefficients based on the courses of experimentally obtained forces e.g. at different deformation velocities [21]. In the paper by Saeidirad et al. [22], Alirezaei et al. [23], it was stated that the generalized Maxwell model is the most advantageous for description of biological materials behavior during stress relaxation. In the papers there was determined the applicability of the generalized Maxwell model for description of (light elastic) viscoelastic behaviour of chosen species of pomegranates and dates. The Maxwell model was found to possess great capability of creating accurate and reliable characteristics of stresses.

The aim of the study was to determine the effects of the initial deformation, deformation velocity and storage time on the parameters of the generalized Maxwell model during the stress relaxation in sugar beet root tissue. The novelty of the paper is the comparison of the obtained relaxation times of the Maxwell model with the phenomena of liquids and gases flow inside the sugar beet tissues as well as the conclusions about the changes of the amount of interior deformations in the samples after their loading. Moreover, the novelty concerns the application of the generalized Maxwell model with the stable element for prediction of mechanical response of the sugar beet whose morphological structure is different compared to such soft fruits as apples and pears.

MATERIALS AND METHODS

The tests were carried out with the texture analyser (model TA.HD plus, Stable Micro Systems, Goldaming, UK) equipped with a load cell of 300 N capacity at the three deformations: 2.0 mm, 3.5 mm and 5.0 mm and the four deformation velocities: 1, 2, 10 and 20 mm·s^{-1} (Figure 1). The sampling frequency during the tests was 200 Hz. The measurement was triggered when the force response exceeded 0.5 N (Figure 2). The sugar beet roots of Zorian variety obtained from the region of Lublin, Poland, were subjected to the studies. The beets were stored in the inspected atmosphere of 15 ºC and humidity 50% for 3 and 5 days. The density and water content of the samples are presented in Table 1. The sugar beet samples used for the experiment were cylindrical in shape, with 9.5 mm diameter and 20 mm height. The samples were cut out from the central part of the root up to the 25 mm depth from its exterior surface. The tests were carried out in 9 repetitions for each value of deformation and velocity of deformation.

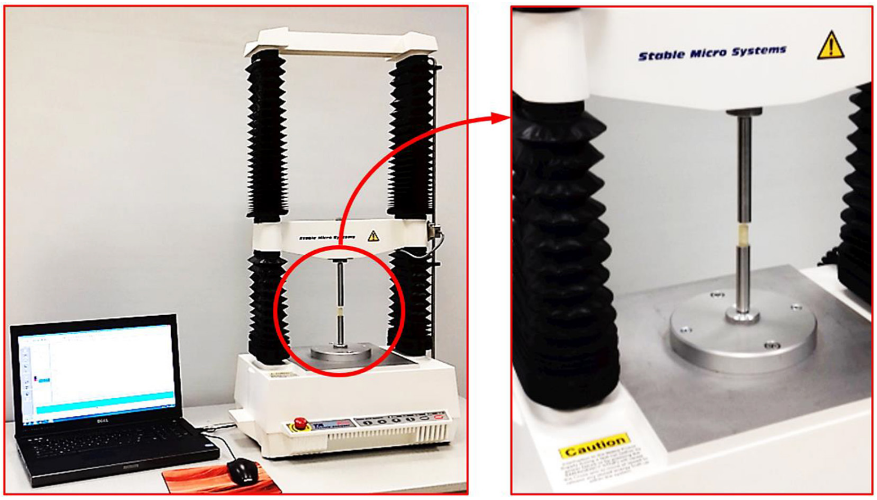

Figure 1. Measuring stand – texture analyser (model TA.HD plus, Stable Micro Systems, Goldaming, United Kingdom) with a computer

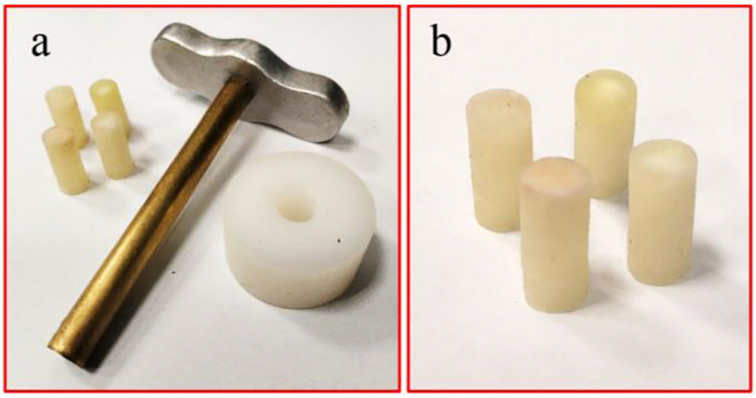

Figure 2. a) Samples as well as a chisel and liner for length trimming, b) the samples prepared for the relaxation tests

The samples were initially compressed along the vertical axis in a state of uniaxial stress and constant deformation was maintained while recording the force response for 35 seconds. The 5-parameter generalized Maxwell model was used to describe the behaviour of sugar beet root tissue under load. The following formula was developed for the cylindrical sample compressed along the axis [19]:

$$F(t) = \left(\frac{S \cdot v}{l}\int_0^{t_m}\left(E_3 + \sum_{i=1}^{2} E_i \cdot e^{-\frac{E_i}{\eta_i}(t_m - t)}\right)\cdot dt\right)\cdot e^{-\frac{E_i}{\eta_i}(t - t_m)} \quad (1)$$

where: $F(t)$ – the force in time (N), S – the cross sectional area of the sample (m^2), v – the deformation velocity (m·s^{-1}), l – the sample length (m), t_m – the increasing deformation time (s), t – the time counted from the beginning of sample deformation (s), E_3 – the equilibrium modulus (MPa), E_i – the elasticity modulus (MPa), η_i – the viscosity coefficient (MPa·s).

The formula $F(t)$ was applied for the second stage of the test in which the constant deformation was maintained ($t > t_m$). Therefore the formula $F(t)$ includes the v and t_m parameters of the model in order to take into account the stress relaxation process which takes place during the first stage of the test when the sample deformation increased. The nonlinear minimization Quasi-Newton method was applied to determine parameters (Statistica ver. 13.0). Thirty three measuring points were used to approximate the experimental curves: the first 10 points every 0.01s, the next 10 points every 0.1s, the successive 9 every 1s and the last 4 every 5s. The obtained approximations of the experimental strength of samples reaction were compared with formula (1) determining the parameters of the generalized Maxwell model (E_i, η_i).

Table 1. Average values of density and water content of the tested samples subjected to stress relaxation tests obtained from fresh roots and stored for 1-day, continuation for roots stored 3-days and 5-days

Deformation (mm)	Deformation velocity (mm·s^{-1})	Fresh roots				Roots stored the 1-day			
		Density (g·cm^{-3})	St. Dev. Denisity	Humidity (%)	St. Dev. Humidity	Density (g·cm^{-3})	St. Dev. Denisity	Humidity (%)	St. Dev. Humidity
2.0	1.0	1.125	0.0195	77.561	0.5395	1.126	0.0038	76.661	0.4250
	2.0	1.133	0.0051	77.957	0.2901	1.138	0.0070	77.205	0.5312
	10.0	1.125	0.0056	77.530	0.3050	1.148	0.0087	76.519	0.5455
	20.0	1.126	0.0053	77.793	0.2502	1.145	0.0121	76.903	0.0121
3.5	1.0	1.138	0.0070	77.754	0.3187	1.116	0.0052	76.830	0.2606
	2.0	1.126	0.0077	78.179	0.2394	1.124	0.0045	77.232	0.3619
	10.0	1.137	0.0067	77.619	0.3040	1.125	0.0034	76.701	0.3169
	20.0	1.124	0.0054	77.903	0.2332	1.121	0.0045	77.191	0.3673
5.0	1.0	1.132	0.0065	77.882	0.3597	1.116	0.0055	77.165	0.2905
	2.0	1.137	0.0054	78.147	0.2413	1.120	0.0103	77.227	0.3513
	10.0	1.134	0.0074	78.134	0.4665	1.126	0.0087	77.215	0.3402
	20.0	1.134	0.0071	78.426	0.2488	1.129	0.0128	77.278	0.5422
Deformation (mm)	Deformation velocity (mm·s^{-1})	Roots stored for the 3-days				Roots stored for the 5-days			
		Density (g·cm^{-3})	St. Dev. Denisity	Humidity (%)	St. Dev. Humidity	Density (g·cm^{-3})	St. Dev. Denisity	Humidity (%)	St. Dev. Humidity
2.0	1.0	1.155	0.0086	75.574	0.4738	1.157	0.0119	74.181	0.6761
	2.0	1.144	0.0100	75.875	0.4166	1.151	0.0075	73.155	0.4282
	10.0	1.150	0.0045	75.785	0.1885	1.165	0.0072	73.925	0.3371
	20.0	1.133	0.0051	75.793	0.3553	1.164	0.0178	74.489	0.4375
3.5	1.0	1.142	0.0092	75.857	0.4672	1.159	0.0100	73.401	0.3895
	2.0	1.149	0.0077	75.828	0.2914	1.161	0.0096	73.904	0.5387
	10.0	1.134	0.0049	75.792	0.4745	1.157	0.0120	74.290	0.2362
	20.0	1.153	0.0056	75.358	0.5388	1.154	0.0096	74.504	0.3495
5.0	1.0	1.149	0.0057	75.869	0.1642	1.170	0.0057	73.641	0.3386
	2.0	1.156	0.0077	75.518	0.3937	1.149	0.0075	73.064	0.405
	10.0	1.131	0.0062	75.608	0.5385	1.154	0.0057	74.083	0.3599
	20.0	1.150	0.0121	75.444	0.3238	1.146	0.0091	73.785	0.5289

RESULTS

The typical courses of stress relaxation for fresh roots at the deformation velocity V_d = 10 mm·s^{-1} are presented in Figure 3. The parameters: elasticity modulus – E_1, E_2 (MPa), equilibrium modulus E_3 (MPa) and viscosity coefficients (MPa·s) – η_1, η_2 determined for the four velocities and three deformations describe the physical conditions of sugar beet root tissue during the relaxation test. Two parameters T_1 and T_2 being the quotient of $T_1 = \eta_1 \cdot E_1^{-1}$ and $T_2 = \eta_2 \cdot E_2^{-1}$ were introduced in order to interpret properly the sugar beet root tissue behaviour under load.

Figure 4 presents the dependences of the relaxation time T_1 on the deformation velocity V_d for the fresh roots and those stored for 3 or 5 days. The decrease of T_1 with the increasing V_d was statistically significant and the coefficients R^2 for simple regressions were in the range from 0.51 to 0.64 for the fresh roots and from 0.80 to 0.86 for the 5-day old ones. Moreover, much larger values of relaxation times T_1 were found for the velocities of 1.0 and 2.0 mm·s^{-1} for the fresh roots. However, no significant differences were observed in the case of dependences of relaxation time T_1 on V_d for the 3-day old roots and d_q = 3.5 mm. Furthermore, T_1 decreased for d_q = 3.5 mm depending on the deformation velocity V_d for the fresh roots and the 5-day old ones (R^2 = 0.64 and 0.80, respectively).

Figure 5 presents the dependences of the relaxation time T_2 on the deformation velocity V_d which show a statistically significant decrease of T_2 with the increasing V_d for all values of deformation and groups of roots. For the fresh roots the range of determination coefficients (R^2) for the simple regressions

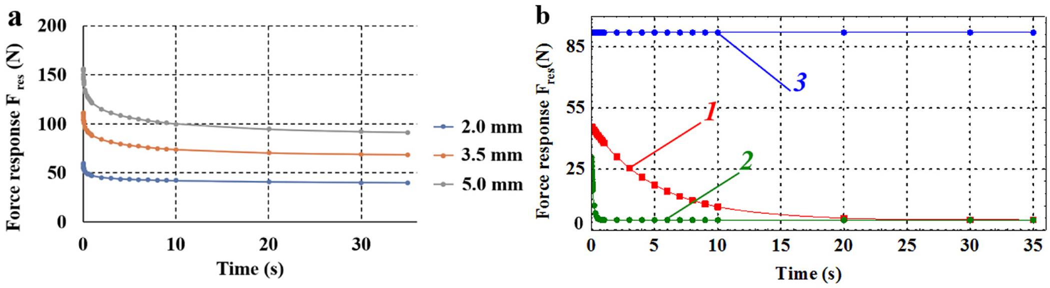

Figure 3. Typical courses of force response in time: a) for three various deformation values, b) components of the typical force response curve: *1* – the component of force response for the calculation of modulus E_1 and η_1, *2* – the component of force response for calculation of modulus E_2 and η_2, *3* – the component of force response of modulus E_3.

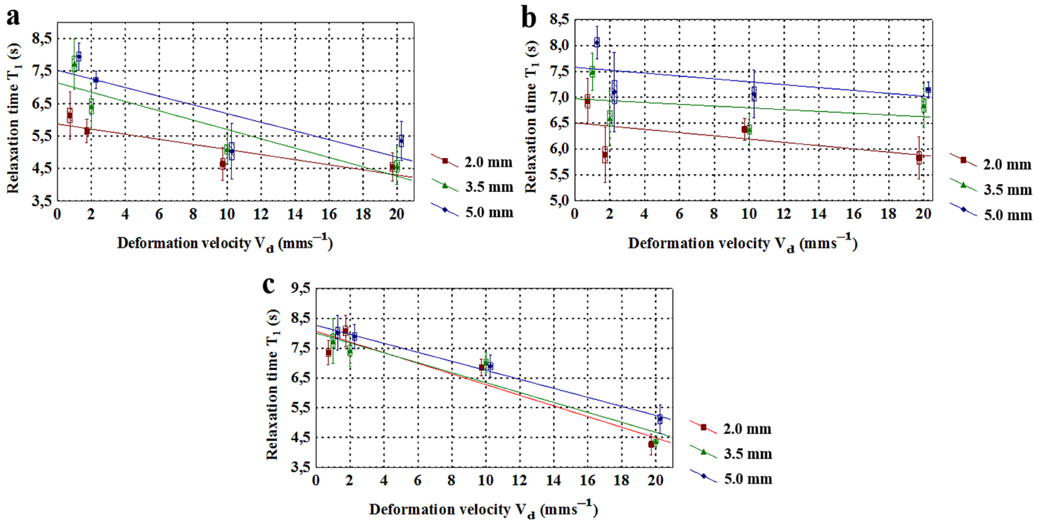

Figure 4. Relationship between the relaxation time T_1 and the deformation velocity at different values of deformation for: a) fresh roots, b) roots stored for 3 days, c) roots stored for 5 days

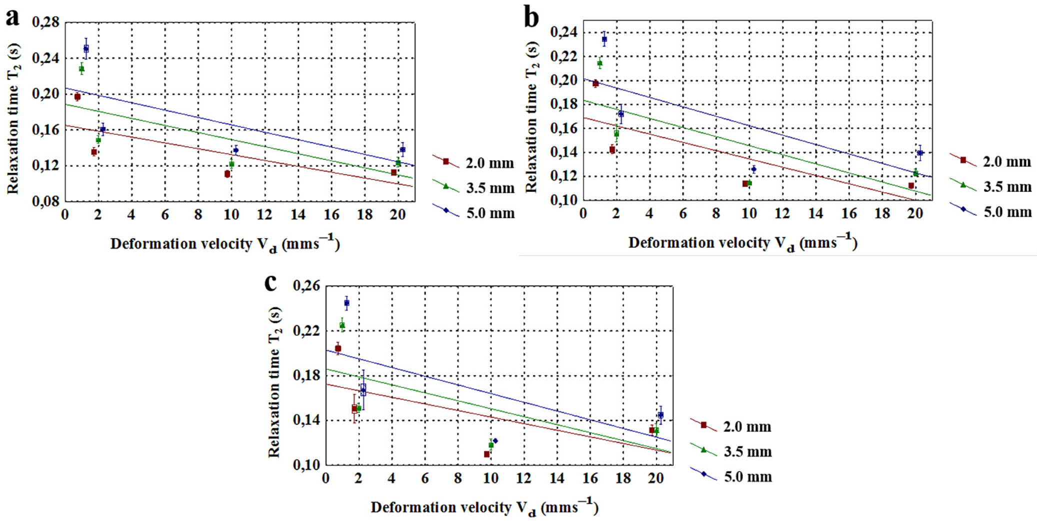

Figure 5. Relationship between the relaxation time T_2 and the deformation velocity at different values of deformation for: a) fresh roots, b) roots stored for 3 days, c) roots stored for 5 days

was 0.44–0.50, for the 3-day old ones $R^2 = 0.50–0.58$ and for the 5-day old ones $R^2 = 0.38–0.41$. Moreover, much longer times of relaxation T_2 were observed for the small values of deformation velocities.

No statistically significant dependences of the equilibrium modulus E_3 on the initial deformation velocity were found for the fresh and stored roots (Fig. 6). Figure 7 presents the dependences of the equilibrium modulus E_3 on the deformation value d_q for the fresh and stored roots. The diagrams show the decrease of the equilibrium modulus E_3 for all deformation values d_q and the greatest changes were observed for the deformation 3.5 mm.

Figure 8 presents the dependence of the peak force response F_{res} on deformation velocity V_d for the fresh roots. The statistical significance was observed for both fresh roots in the case of all deformations and the 5-day old ones for the deformations 2.0 mm and 5.0 mm. The coefficients R^2 were in the range 0.32–0.38 for the fresh beets and 0.27–0.43 for the 5-day old ones.

DISCUSSION

Location of sites on the beet surface which were the most susceptible to mechanical damage was defined by Nasirahmadi et al [26]. They were in the area to a depth of 25 mm from the root outside surface at a distance of 0.25–0.60 of the length measured from the trimmed crown of the beet. This is consistent with the information included in the papers by Bzowska-Bakalarz [17], Kołodziej et al. [25] and Kleuker et al. [26] concerning the places of obtaining samples.

The constitutive equations are generally applied for description of plant materials behaviour under

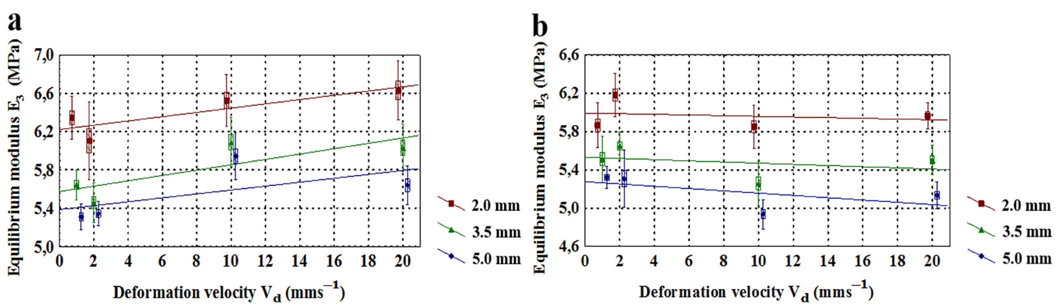

Figure 6. Relationship between the equilibrium modulus E_3 and the deformation velocity V_d at different values of deformation: a) for fresh roots, b) for roots stored for 3 days

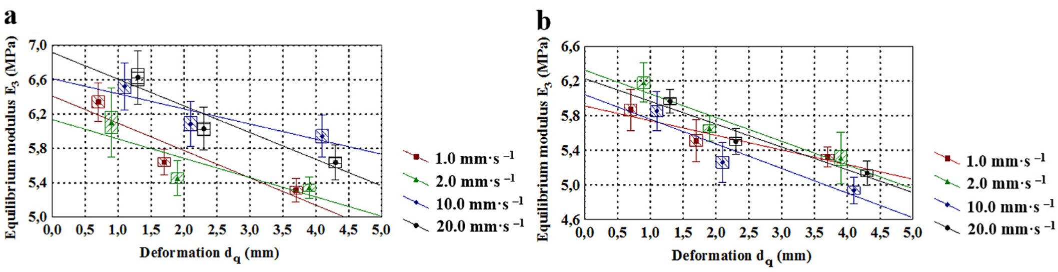

Figure 7. Relationship between the equilibrium modulus E_3 and the value of deformation d_q at different velocity of deformation for: a) fresh roots, b) roots stored for 3 days

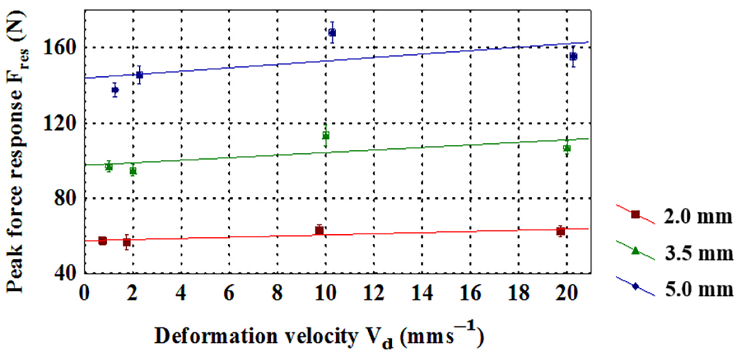

Figure 8. Relationship between the peak force response F_{res} and the deformation velocity V_d at different values of deformation for fresh roots

loading. In this paper there were applied the five parameters of the generalized Maxwell model for description of the stress relaxation phenomena in the sugar beet sample. Better developed phenomenological models possessing a larger number of parameters allow better fitting of the assumed regression equations to the experimental results. However, as pointed out by Wang et al. [27] in the case of applying the five and seven-parameter generalized Maxwell model to investigate the Korla pear samples the regression coefficient increased only by 0.005. The applied models are not structural ones whose parameters are directly connected with the phenomena taking place during the tissue material loading. However, the literature confirms the relationships of phenomenological models (viscoelastic properties) with many utilizable features such as: content of liquid fraction, acidity, turgor level, ripeness etc. [4, 22, 30]. A large number of model parameters makes interpretation of their significance difficult referring to real phenomena taking place in the studied material. In this paper only three parameters (i. e. relaxation times T_1 and T_2, equilibrium modulus E_3) were taken for the model description. Referring to the results of Chen's [19] investigations the relaxation times T_1 and T_2 characterize the flow of liquids and gases in the intercellular spaces under mechanical loading. Assuming that beet is a linearly viscoelastic body, using different initial deformation velocities should not affect the obtained values of parameters. However, in practice the values of both relaxation times decreased with the increasing deformation velocity. This has been also confirmed in other studies for different materials of biological origin [21, 28, 29]. The observed deviations from the rules of linear viscoelasticity may be due to different times of obtaining the established value of deformation at different deformation velocities that is to different times of liquids flow in the intercellular spaces. A short period of time to obtain the assigned deformation results mainly in elastic distortion, which can cause a local excess of critical stresses and damage of fragments of tissue structures.

This phenomenon confirms the growing tendency of the maximal force of sample reaction with the increasing deformation velocity. The model applied in the studies takes into consideration the phenomenon of stress relaxation during the initial deformation assuming a linear viscoelasticity of the sample. The decrease of both relaxation times indicates easier flow of fluids in the material after deformation with higher velocities which can be attributed to an increase of a number of internal damages. Figure 1b presents an exemplary contribution of model components to creation of material reaction force to the assigned loading. The exponential component of the model described by relaxation time T_1 has many times greater contribution than the component described by the relaxation time T_2. This is due to the very quick flow of gas and thus the times T_2 are short. Moreover the beet root includes small amounts of gases compared with other vegetables or fruits. The model component described by the time T_1 characterizing the liquid flow under loading is tens times larger than T_2 and makes an essential part of the total reaction force.

The module E_3, being the fifth parameter characterizes the physical condition of the material after the test. A small value of the module E_3 confirms a smaller value of the sample reaction which is associated with a larger number of intratissue damages. This experiment did not show significant essential dependences of the equilibrium modulus E_3 on the velocity of assigned initial deformation. However, a decrease in the value E_3 with the increasing deformation can be observed.

CONCLUSIONS

1. Both relaxation times T_1 and T_2 of the generalized Maxwell model decreased with the increase of the deformation velocity, indicating easier flow of gases and liquids in the intercellular spaces by greater internal damages of the cellular structure after the deformation at higher velocities.
2. Both relaxation times T_1 and T_2 increased with the increase of the value of deformation.
3. Equilibrium modulus E_3 was not affected by deformation velocity but decreased along with the increase of deformation value which could be due to the increase of the amount of damaged tissue structures.
4. Peak force showed the tendency of increase with the increasing deformation velocity. This phenomenon can confirm the viscoelastic nature of sugar beet root tissue.
5. The values of the Maxwell model parameters can be used to assess the susceptibility of sugar beet root to damage under the mechanical loading conditions.

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