Stress relaxation phenomena in vegetable tissue
Part I Experimental results

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The stress relaxation in some compressed vegetable fleshes, i.e. potato and kohlrabi tubers, and carrot and parsley roots, has been investigated. The relaxation curves obtained with different prestrain parts (different stress level and different prestrain rate) are approximated in the second part by simple equations, i.e. logarithmic and power equations. The similarity of these equations is demonstrated using similarly defined parameters: the initial slope of the relaxation curve and the time factor. The influence of prestrain on the strain relaxation is shown by the probability density of the decay processes. The activation volume was determined by two different methods: analysis of relaxation curves or by push change of the deformation rate. The second method gives systematically higher values than the first one. The activation volume strongly decreases with increasing stress, but only small differences in activation volumes were observed for different vegetable fleshes. The activation volumes between 50 and 110 nm$^{-3}$ are in a good agreement with the pore volume in the cell walls. The results obtained agree with the hypothesis of the controlling role of squeezing out of the cellular sap for stress relaxation in vegetable flesh.

1. Introduction
Stress relaxation in solids is understood as a successive decrease of the mechanical stresses in their structure. Relaxation properties of different solids can be investigated by a special relaxation test that has two relatively independent parts: the first is the loading of a solid body and the second is characterized by keeping the deformation at the stage that was reached in the first step. This type of test has a long history, even in the sphere of agromaterials [1], for which the methods and theories developed originally for crystal solids [2, 3], have been usually used. The Maxwell rheological model in an exponential form is the most frequent model used for mathematical description of the decreasing stress in the second part of the test. Unfortunately, more complex multi-parameters models of this type are necessary for a good description of stress relaxation in fruit and vegetable flesh [1, 4]. But even in this case, the parameters of the model can serve as a source of information on the susceptibility of agricultural flesh products to mechanical damage.

Stress relaxation can also mathematically be described by other relatively simple functions, suitable for special materials. For vegetable flesh, Giessmann and co-workers [5, 6] were successful with a logarithmic function. One advantage of this function consists, among others, in the direct relation of its parameters to thermally activated processes controlling the stress relaxation. In this work, some experiments on stress relaxation in various types of vegetable flesh were performed, and the results were interpreted using a simple mathematical function. The values of activation volume obtained are broadly discussed.

2. Experimental procedure
Tests were made on the fleshy parts of several fresh vegetables at the time of their harvesting. Potatoes were supplied by the Potatoes Research Institute, Havlíčkův Brod, and other vegetables were obtained from the University garden at Prague-Troja. The characteristics of the products tested are given in Table I.

Compression tests were carried out on cylindrical specimens, 15 mm diameter and 23 mm long, cut from the central parts of fleshy products by a cork borer in such a manner that the specimen axis was approximately parallel to the axis of the corresponding product. All tests were performed in an Instron deformation machine, type 1122.

Thirty samples were used for the usual stress relaxation test (see Fig. 1a); 20 at a prestrain rate of 0.0076 s$^{-1}$ (5 at level 1, 10 at level 2, and 5 at level 3 – see upper right corner of Fig. 1a), and 10 samples at level 2 (5 each for prestrain rates 0.0038 and 0.038 s$^{-1}$). The different stress levels used in this work are related to the compression strength of the sample, $\sigma_P$ (Fig. 1a) that was determined in a previous paper [7]. The real relaxation time, $(t_T - t_0)$, was about 180 s for every test. For the second part of every stress–time curve (Fig. 1a) about 10 points were evaluated for approximation by simple relaxation models. The approximation consists in minimization of the chi-squared function, defined by

$$F = 100 \left[ \sum_{i=1}^{n} \frac{(\sigma_i/\sigma_0 - 1)^2}{\sigma_0} \right]^{1/2}$$

(1)
The parameters of the simple relaxation models that were obtained by evaluation of the relaxation tests under Equations 2 and 3, are given in Table II. Minimal values of the chi-squared function, see Equation 1, are not incorporated into the table because of their very low values; they are usually less than 1%, i.e. less than the accuracy of the Instron machine. Higher values of 1%–2% were only observed in some sporadic cases with strong stress relaxations at higher stress levels and/or at the highest prestrain rates, whereas the correctness of the force recording could be limited by the maximum velocity of the force recorder.

The dependence of activation volumes on stress level, determined by push change of the deformation rate for potatoes (var. Boubin) and carrots, is given in Fig. 2. The values obtained are well approximated by the power relation

\[ V = a(\sigma_l/\sigma_{0l})^m \]

where \( \sigma_l \) are the stress rates used in push-change experiments (\( \dot{\varepsilon}_l \) is higher value than \( \dot{\varepsilon}_2 \)), \( \Delta \sigma \) is the corresponding change in true stress (see Fig. 1b), \( k \) is the Boltzmann constant and \( T \) is the sample temperature in the absolute scale. For the stress rates used in our experiments, Equation 5a reduces to

\[ V = kT \ln(\dot{\varepsilon}_1/\dot{\varepsilon}_2)/\Delta \sigma_t \]  

where \( \dot{\varepsilon}_i \) are the strain rates used in the experiments, and \( \Delta \sigma \) is the stress drop corresponding to the push decreasing of deformation rate.

3. Results

Stress relaxation in vegetable flesh can be well described by both of the simple relaxation models