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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/and 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 interpretated 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, σ_P, (Fig. 1a) that was determined in a previous paper [7]. The real relaxation time, $(t_f - t)_0$, 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

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

TABLE I Main characteristics of the experimental material

Plant	Variety	Dry matter content (w.b.) (%)	Crude fibre content (%)	Type of test[a]
Potatoes	*Resy*	18.4	2.29	R, C
	Karin	18.6	2.37	R, C
	Boubín	22.5	1.21	R, C
Carrot	*Chantenay*	9.7	5.97	R, C
Parsley	*Hanácká*	15.9	9.00	C
Kohlrabi	*Gigant*	7.4	–	R

[a]R denotes usual stress relaxation in a prestrained sample and C denotes the experiment with push changes of strain rate.

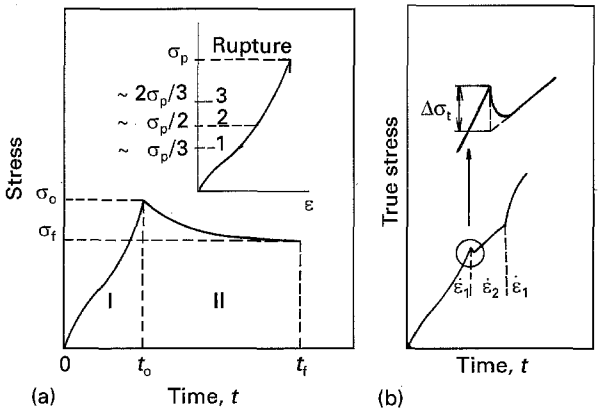

Figure 1 Graphical representation of the obtained results. (a) Stress relaxation test giving the stress–time curve; the first part (I) represents initial loading and the second part (II) is the real relaxation at constant strain. The first part of the stress–time curve also predetermines the shape of the second part. The main parameters of the test are the initial stress, σ_0 (see also the deformation curve in the upper right corner) and the strain rate used in the prestrained part. (b) True stress in relaxation to time in the compression test with push change of strain rate. The stress drop, $\Delta\sigma$, corresponding to the push decreasing of deformation rate is shown, including the method of its direct determination.

where n is the number of points evaluated, σ_i is an experimental value of the relaxed stress and σ_{it} is the corresponding model value at the same point (i.e. at the same time $t_i - t_0$).

Two simple relaxation models were used for detailed approximation of the experiments. The first, so-called logarithmic model [2, 5], is described by

$$\sigma = \sigma_0[1 - \ln(1 + bt')/C] \quad (2)$$

where C and b are model parameters and t' is pure time of stress (σ) relaxation ($t' = t - t_0$, see Fig. 1a). The second model, that will be termed the power model [2], is given by

$$\sigma = \sigma_0(1 + t'/A)^{-n} \quad (3)$$

where A and n are model parameters and t' has the same meaning as in Equation 2. Compression stress is usually understood as the compression force divided by the area of the initial cross section of the corresponding sample. The cross-section of compressed bodies increases with increasing deformation, but it is very difficult to determine the true cross-section of the deformed sample at different stages of the stress relaxation process. One possible way to estimate the true stress, σ_{0t}, in a compressed sample (i.e. the ratio of axial force and real cross-section of the sample) is based on the assumption of its incompressibility

$$\sigma_{0t} = \sigma_0(1 - \varepsilon) \quad (4)$$

where ε is the compression strain.

Ten samples of every inspected product were used for experiments with push change of the compression strain rate. The initial strain rate was $7.6 \times 10^{-4}\,s^{-1}$ in every test. When the bioyield point was reached ($\sigma = 0.2$–0.3 MPa, see [7]) the strain rate was push changed from $7.6 \times 10^{-4}\,s^{-1}$ to $7.6 \times 10^{-3}\,s^{-1}$, then back to $7.6 \times 10^{-4}\,s^{-1}$; these changes were repeated until rupture of the sample occurred. Every change in strain rate causes some change in deformation stress (see $\Delta\sigma$ in Fig. 1b); the decrease in the stress level follows any decrease in strain rate and vice versa. An hypothesis of thermal activation of the process controlling the non-elastic part of the deformation [2, 3], gives the following formula for the activation volume of the process

$$V = kT \ln(\dot{\varepsilon}_1/\dot{\varepsilon}_2)/\Delta\sigma_t \quad (5a)$$

where $\dot{\varepsilon}_i$ are the strain rates used in push-change experiments ($\dot{\varepsilon}_1$ is higher value than $\dot{\varepsilon}_2$), $\Delta\sigma_t$ 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 strain rates used in our experiments, Equation 5a reduces to

$$V = kT \ln 10/\Delta\sigma_t \quad (5b)$$

3. Results

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, where 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. *Boubín*) and carrots, is given in Fig. 2. The values obtained are well approximated by the power relation

$$V = a(\sigma_t/\sigma_{00})^m \quad (6)$$

in which a and m are parameters that could be determined by linear regression analysis of the relation between $\log V$ and $\log \sigma_t$ (see Table III). σ_{00} is a dimensional constant, having the value of 1 MPa in our case (Table III).

4. Discussion

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

TABLE II Parameters from Equations 2 and 3. Strain rate (SR) and initial stress, σ_{0r}, see Equation 4; standard error is given in parentheses

Plant variety	SR	Initial stress (MPa)	Logarithmic model		Power model	
			C	b (s^{-1})	n	A (s)
Potatoes						
Resy	2	0.358	18.2 (0.5)	1.64 (0.17)	0.073 (0.003)	1.15 (0.13)
	2	0.610	13.4 (0.5)	1.31 (0.10)	0.111 (0.005)	1.73 (0.17)
	2	0.792	10.5 (0.6)	0.87 (0.13)	0.153 (0.011)	2.75 (0.42)
	1	0.593	14.2 (0.7)	0.77 (0.07)	0.100 (0.008)	1.65 (0.21)
	3	0.634	17.0 (0.2)	9.91 (0.64)	0.086 (0.002)	0.25 (0.02)
Karin	2	0.311	20.6 (2.1)	2.77 (0.47)	0.074 (0.003)	0.86 (0.16)
	2	0.551	15.4 (0.2)	2.30 (0.07)	0.093 (0.002)	0.87 (0.03)
	2	0.703	13.0 (0.5)	1.61 (0.15)	0.116 (0.005)	1.39 (0.11)
	1	0.541	17.0 (0.4)	1.57 (0.06)	0.079 (0.003)	1.12 (0.05)
	3	0.564	18.6 (0.6)	41.80 (6.90)	0.084 (0.003)	0.11 (0.02)
Boubín	2	0.344	18.8 (0.4)	1.64 (0.15)	0.069 (0.002)	1.11 (0.12)
	2	0.633	16.8 (0.3)	2.09 (0.08)	0.081 (0.002)	0.86 (0.04)
	2	0.808	14.5 (0.3)	1.85 (0.16)	0.097 (0.003)	1.07 (0.08)
	1	0.621	15.9 (0.7)	1.10 (0.14)	0.085 (0.004)	1.84 (0.30)
	3	0.670	17.5 (0.3)	7.62 (0.68)	0.082 (0.002)	0.33 (0.04)
Carrot						
Chantenay	2	0.651	17.5 (0.9)	2.37 (0.37)	0.080 (0.005)	0.98 (0.13)
	2	1.156	15.9 (0.6)	2.63 (0.31)	0.091 (0.003)	0.93 (0.07)
	2	1.374	13.9 (0.9)	1.55 (0.06)	0.107 (0.028)	1.28 (0.08)
	1	1.146	15.7 (0.3)	1.09 (0.11)	0.086 (0.002)	1.73 (0.18)
	3	1.162	16.0 (0.4)	10.70 (1.00)	0.098 (0.007)	0.27 (0.03)
Kohlrabi						
Gigant	2	0.637	23.4 (0.8)	2.89 (0.36)	0.054 (0.002)	0.64 (0.08)
	2	1.068	29.1 (1.0)	28.70 (4.20)	0.045 (0.002)	0.09 (0.02)
	2	1.340	21.8 (2.7)	26.90 (9.60)	0.070 (0.008)	0.30 (0.07)
	1	1.049	25.0 (1.0)	3.12 (0.49)	0.050 (0.002)	0.62 (0.08)
	3	1.172	26.4 (1.3)	232.90 (73.8)	0.055 (0.005)	0.05 (0.01)

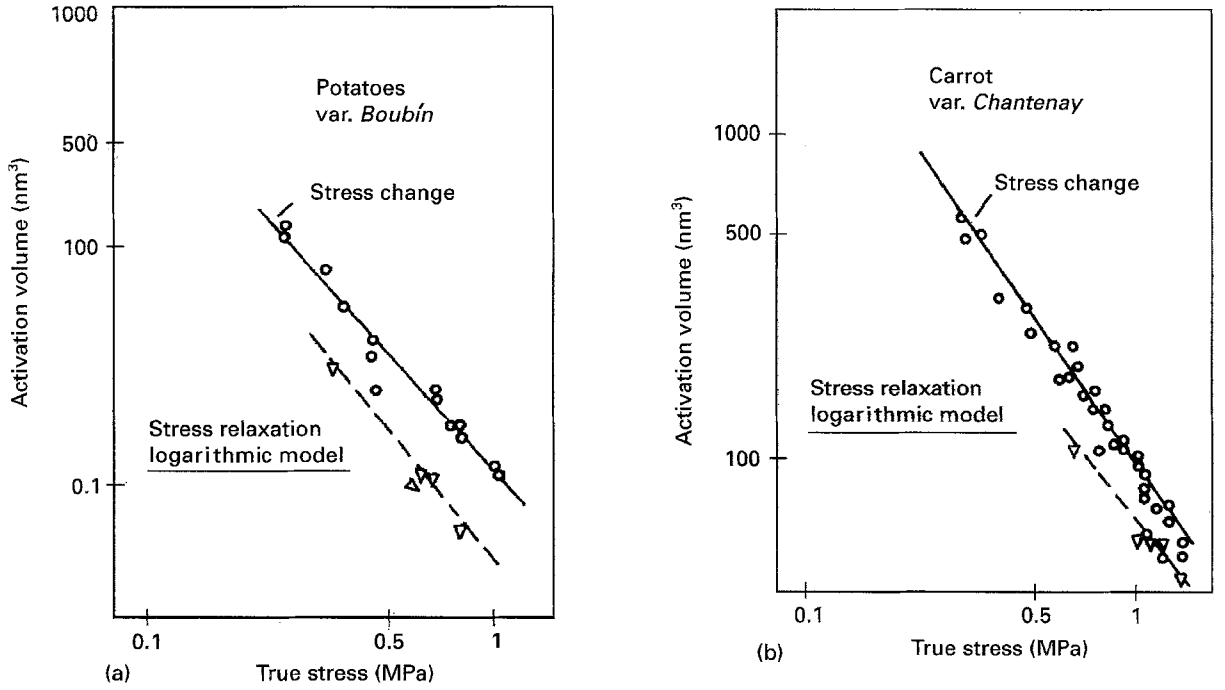

Figure 2 Activation volumes determined by push change strain rate and by stress relaxation plotted against true stress–strain (for stress relaxation, the initial true stress is used). Parameters of the linear equations used for approximation of the experimental results are collected in Table III. (a) Potatoes var. *Boubín*. (b) Carrot var. *Chantenay*.

expressed by Equations 2 and 3. The minimal values of the chi-squared function for both models are approximately the same and are usualiy less than the maximal accuracy of the experimental apparatus. The models can also be expressed by new parameters that are similarly defined for both models. Equation 2 can be rewritten in the following form

$$\sigma = \sigma_0[1 + t_x s_0 \ln(1 + t'/t_x)] \quad (7a)$$

TABLE III Parameters of Equation 6; r is the correlation coefficent of the linearized form of this equation

Plant variety	Push change stress rate			Stress relaxation logarithmic equation		
	$a(nm^3)$	m	r	$a(nm^3)$	m	r
Potatoes						
Resy	93.7	1.46	0.962	42.3	1.58	0.963
Karin	78.6	1.63	0.970	53.2	1.33	0.963
Boubín	110.4	1.13	0.976	59.0	1.25	0.991
Carrot						
Chantenay	96.1	1.46	0.981	64.4	1.26	0.993
Parsley						
Hanácká	87.5	1.15	0.942			
Kohlrabi						
Gigant				101.2	0.97	0.925
All*	92.4	1.38	0.951	71.3	0.92	0.854

*The regression parameters of all the obtained data (for all plants and/or varieties).

where s_0 and t_x are the initial slope of the relaxation curve, expressed as a ratio σ/σ_0, and time factor, respectively. The initial slope of the relaxation curve ($t' = 0$) equals $-b/C$ and the time factor equals $1/b$. For the second model, similar parameters can be defined: the initial slope, s'_0, and the time factor, t'_x. Then Equation 3 can be written as

$$\sigma = \sigma_0(1 + t'/t'_x)^{s'_0 t'_x} \quad (7b)$$

where $s'_0 = -n/A$ and $t'_x = A$. The analysis of the results obtained shows that s'_0 is always lower than s_0, and on the other hand, t'_x is always higher than t_x.

Figs 3 and 4 demonstrate the relationships which are valid between the parameters s_0 and s'_0 (Fig. 3) and/or t_x and t'_x (Fig. 4). They are relatively tight and of power-type. It is clear, on the contrary, to the good approximation of the experimental results by both models, that the logarithmic model gives lower values of stress for initial parts of the stress relaxation curves than is given by the power model. The initial slope of a relaxation curve increases with increasing stress level as well as with increasing prestrain rate. The same changes in stress level and prestrain rate cause a decrease of both the time factors. The initial slope of the relaxation curve, s_0, is plotted against the prestrain deformation rate in Fig. 5. This dependence for one product and one stress level is approximately of the power type. For most products (only kohlrabi can be understood as an exception) and different stress levels, the exponents of the relationship are about 0.9 and the main differences between the different cases have their origin in different proportionality constants. No change in this trend was observed over the whole range of the prestrain rates studied (up to 0.1 s^{-1}). Thus, strain rates up to 0.1 s^{-1} are not high enough to exclude the stress relaxation processes taking part in the prestrain period. The analysis of the time factors leads to a similar conclusion, even if time factors of a few tens of microseconds were observed for the highest stress levels and strain rates.

Stress relaxation can also be expressed as a decay process given by

$$\sigma = \sigma_0 \int_0^\infty p(\gamma) \exp(-\gamma t') \, d\gamma \quad (8)$$

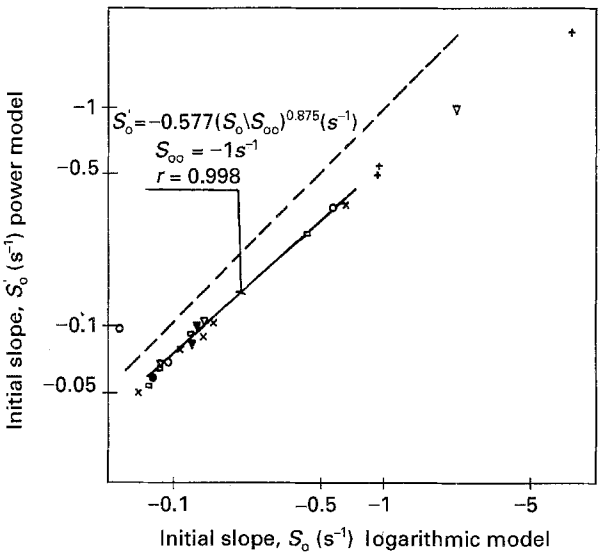

Figure 3 Initial slope of the relaxation curve described by the power model plotted against the same quantity in the logarithmic model. (– – –) Given by $s'_0 = s_0$. (——) Obtained by regression analysis of the experimental results for s_0 higher than $-1\ s^{-1}$. Potatoes: (○) *Resy*, (□) *Boubín*, (▽) *Karin*. Carrot: (×) *Chantenay*. Kohlrabi: (+) *Gigant*.

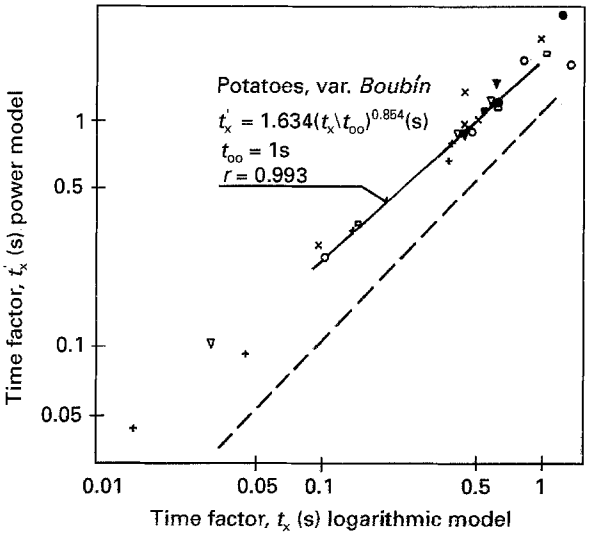

Figure 4 The time factor of the relaxation curve described by the power model plotted against the same quantity in the logarithmic model. (– – –) Given by $t'_x = t_x$. (——) Obtained by regression analysis of the experimental results for potatoes, var. *Boubín*. Some modifications of regression parameters can be expected for the other varieties. For Key, see Fig. 3.

where γ is the rate constant of the stress relaxation and the probability density function, $p(\gamma)$, represents the probability density of the decay processes characterized by the lifetime $\tau = \gamma^{-1}$. The power model function (see Equations 3 and 7b) is the Laplace transformation of the function [8]

$$p(\gamma) = \frac{t'^n_x}{\Gamma(n)} \gamma^{(n-1)} \exp(-t'_x \gamma) \quad (9a)$$

that could be understood as a spectral function of a generalized Maxwell model of stress relaxation [4, 9]. Substitution of $p = \tau^{-1}$ in Equation 8 leads to

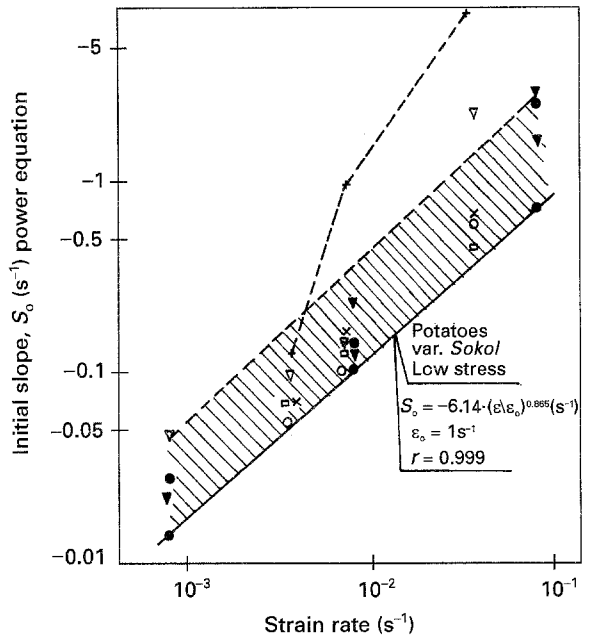

Figure 5 Initial slope of the relaxation curve in the logarithmic model plotted against the prestrain rate. The marked area between the two lines (power relations with exponents of approximately $0.9\ s^{-1}$) contain nearly all the experimental results obtained for different plant varieties (kohlrabi is an exception), different stress levels, and different prestrain rates. Potatoes: (○) *Resy*, (▽) *Karin*, (□) *Boubín*, (●) (*Sokol*, (▼) *Andretta* [5].) Carrot: (×) *Chantenay*. Kohlrabi: (+) *Gigant*.

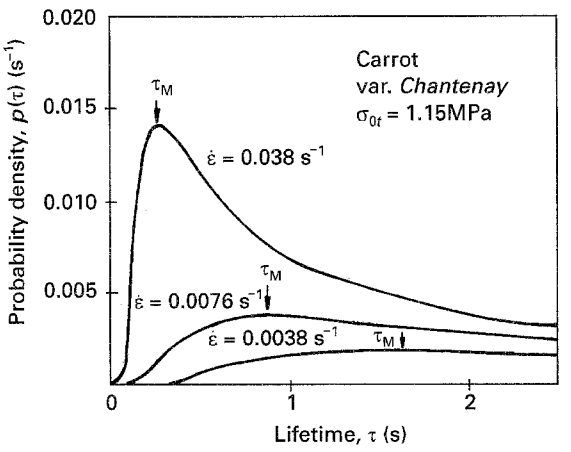

Figure 6 The probability density of decay processes (see $p(\tau)$ in Equation (9b) that control stress relaxation in carrot plotted against lifetime for different prestrain rates, $\dot{\varepsilon}$. τ_M denotes lifetimes that correspond to the maximal values of probability density. σ_{0t} denotes the initial stress.

a new probability density function $p(\tau)$

$$p(\tau) = \frac{t_x'^n}{\Gamma(n)} \gamma^{-(n+1)} \exp[-t_x'/\tau] \qquad (9b)$$

Examples of probability density functions of this type are shown for our results in Fig. 6. They have maxima at lifetimes $\tau_M = t_x'/(n+1)$, i.e. at only slightly lower time values than the time factor t_x' usually reaches. Lifetimes with maximum probability are about 0.1 s for the highest prestrain rates and reach values of about 1 s for the lowest prestrain rates. Kohlrabi is the flesh product with very quick stress relaxation; the lifetimes corresponding to the maxima of the probability, $p(\tau)$, are much lower than the similar lifetimes determined for the other tested materials. Fig. 6 demonstrates the strong influence that the prestrain part of a relaxation curve has on the corresponding probability density function; for lower prestrain rates (higher prestrain times) the important part of the probability function is missing in comparison to the same functions for higher prestrain rates. This process is caused by the decay processes or, in other words, by stress relaxations acting during the prestrain part of the relaxation experiment. The longer the prestrain part of the stress relaxation experiment, the smaller is the part of the original spectral function remaining for analysis.

The activation volume can also be estimated from relaxation experiments [2, 5]. Parameters of the logarithmic model can be used for this purpose [5]

$$V = kTC/\sigma_{0t} \qquad (10)$$

The activation volumes that were obtained by evaluation of the stress relaxation results in Table II, decrease with increasing stress level, σ_{0t}, similarly, the values obtained by push change of deformation rate. Some results are given in Fig. 2a and b but the full information is given in Table III in a similar form to the information on the activation volumes obtained by push change deformation rate. The activation volumes obtained from relaxation experiments are lower than the corresponding values given by the other method. The exponent m of the power Equation 6 is about 1.5 for results obtained by push change deformation rate. Lower values were observed for potatoes, var. *Boubín* and for parsley (but with lower correlation coefficients in these cases). The lower values of correlation coefficients were observed for the relaxation experiments.

For stresses of about 1 MPa the activation volume takes values between 50 and 110 nm^3 as is shown in Table III. This very small volume can be explained by different real processes. One of them is squeezing out of cellular sap from the compressed flesh. This process can easily be observed with the naked eye during the course of every deformation experiment. It causes a decrease of the sample volume and, therefore, it has to be a very important source of stress relaxation. The values obtained of activation volume correspond approximately to the volume of a typical cell wall pore: wall thickness about 1 μm and pore diameter about 0.5 nm [10] giving a pore volume of about 200 nm^3. The activation of the pores for transport of cellular sap through cell walls can control the entire relaxation process. Small differences between the activation volumes obtained for different vegetable fleshes (Table III) yield information about small differences in cellular pore dimensions and structure. Only kohlrabi is an exception in this observation.

5. Conclusions

1. Stress relaxation in vegetable flesh can be described by very simple equations (based on logarith-

mic or power functions) in such a manner that the standard chi-squared function gives values that are lower than the accuracy of the experimental method. Even in this case, both equations give different values of the relaxed force. The similar structure of both the equations mentioned above is expressed by similar parameters (initial slope of relaxation curve and time factor).

2. The fundamental influence of the prestrain part of the relaxation experiments was demonstrated for all cases studied in this paper. The spectral analysis of the decay processes controlling stress relaxation in vegetable flesh gives important information on stress relaxation that is usually hidden in the prestrain part of the experiment.

3. The activation volumes obtained in stress relaxation experiments are lower than the corresponding values obtained by push change of deformation rate. In both cases the values are very similar for all the materials tested (kohlrabi excepted). Similarly, as for crystal solids, the activation volume for vegetable flesh depends on stress and decreases with increasing stress value under a power equation, approximately (with exponent 1–1.5). The activation volumes are in the range 50–110 nm^{-3} for a stress level of about 1 MPa. This value is approximately equal to the cellular pore volume.

4. The results of this work support the hypothesis that stress relaxation in vegetable flesh originates in the squeezing out of the cellular sap.

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References

1. N. N. MOHSENIN, "Physical Properties of Plant and Animal Materials", Vol. I (Gordon and Breach, New York, 1970).
2. V. I. DOTSENKO, *Phys. Status. Solidi. (b)* **93** (1979) 11.
3. J. C. M. LI, in "Dislocation Dynamics", edited by A. R. Rosenfield, G. T. Hahn, A. L. Bement Jr and R. I. Jaffee (McGraw-Hill, New York, 1968) p. 87.
4. P. CHEN and R. B. FRIDLEY, *Trans. ASAE* **15** (1972) 1103.
5. E.-J. GIESSMANN and B. SZOT, *Tag.-Ber. Akad. Landwirtsch. Wiss. DDR* **208** (1982) 53.
6. E.-J. GIESSMANN and D. SAGER, *ibid.* **208** (1982) 63.
7. J. BLAHOVEC, K. PATOČKA and B. MÍČA, *Zemed. Techn.* **30** (1984) 335 (in Czech).
8. F. MUSUMECI, A. TRIGLIA, F. GRASSO, A. SCORDINO and D. SITKO, *Nuovo Cimento* **16D** (1994) 65.
9. S. FUJIHARA, R. YAMAMOTO and Y. MASUDA, *Biorheol.* **15** (1978) 63.
10. U. LÜTTGE and N. HIGINBOTHAN, "Transport in Plants" (Springer, New York, 1979).

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