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VISCOELASTIC PROPERTIES OF JONAGOLD APPLE FLESH

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ABSTRACT

Linear viscoelasticity of the studied material was assumed in the range of strain up to 0.08 mm/mm. A general Maxwell model was suggested to describe the reaction of apple sample to loading. In stress relaxation experiment two kinds of samples that had been cut from the same fruit were axially compressed. One specimen was free to expand in radial direction, while the other one was constrained in a rigid container.

Compression was carried out at three different rates of deformation: 3.333, 0.833, 0.083 mm/s. On the base of the course of the samples reaction force elastic and viscous time depending modulus, bulk modulus, shear modulus and Poisson's ratio were calculated. The relation between elastic and viscoelastic properties mentioned above and the rate of initial deformation were considered.

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It was stated that an increase of the rate of initial deformation causes an increase of the maximum sample reaction force. On the base of determined viscoelastic coefficients of the model the energy needed to hypothetical compression of the sample model was calculated. A significant difference between energy absorbed by the sample during the experiment and hypothetical value calculated for the model was found. The difference between two kind of energy increases along the increase of the rate of deformation. This phenomenon can confirm the expectation that the amount of micro damage in the tested material increases with the increase of the rate of deformation.

Key words: relaxation test, Poisson's ratio, bulk modulus, shear modulus, energy

INTRODUCTION

The knowledge of fruit and vegetables reaction to different types of mechanical loads constitutes the basis of a description of material properties used to determine agricultural products resistance to damage as well as their consumption and storage quality. Some phenomena that are observed in fruit and vegetables with high water content can be described by means of linear viscoelastic models. A generalized Maxwell model is widely used in research of stress relaxation that is defined as constantly decreasing mechanical stresses in the structure of the investigated material [1, 4, 7].

In the present studies stress relaxation test was used to evaluate the influence of the initial rate of deformation on viscoelastic properties of Jonagold apple.

MATERIALS AND METHOD

Jonagold apples, bought at the Agricultural Institute in Lublin-Felin in October 2000 were studied. The experiment was designed to determine the influence of initial deformation speed on the course of stress relaxation functions of two types of samples cut from the same fruit and axially compressed. One specimen was free to expand in the radial direction, while the other one was constrained [9]. Cylindrical samples 20 mm high and wide were used. The initial deformation was established at the level of 1.7 mm. Tests were carried out with the testing machine Instron 6022 for three different deformation speeds: 3.333, 0.833, 0.083 mm/s. Samples were compressed and constant strain was maintained. The reaction force was recorded every second for the first 12 s and then every 5 s for the rest of the test, which lasted 120 s. 10 repetitions were made for each kind of sample and deformation speed.

RESULTS AND DISCUSSION

The sample reaction force in time was obtained from the compression and stress relaxation tests. The second part of the course of the reaction force was approximated to four parameters exponential curve in the form:

$$F(t) = \sum_{i=1}^{2} A_i \cdot e^{-\alpha_i t} \quad (1)$$

where: A_i, α_i – parameters of the empirical model.

Twenty measurement points were taken to approximate the function: the first twelve every 1 s and the last 8 every 15 s. To describe the behaviour of apple flesh under load, a four-parameter Maxwell model was used. The shape and dimensions of a sample as well as history of deformation were taken into consideration. Chen's equation for the axially compressed cylindrical sample was used [3]:

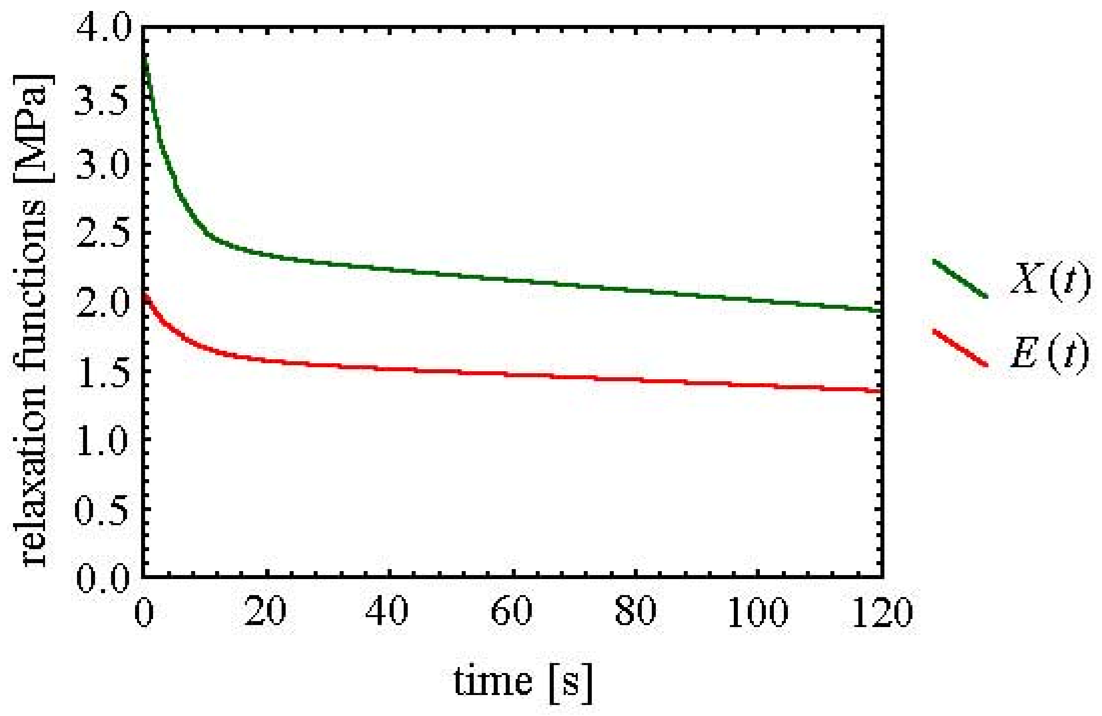
$$F(t) = \sum_{i=1}^{2} \left(\int_0^{t_m} \frac{p}{l} \cdot a \cdot E_i \cdot e^{-\frac{E_i}{\eta_i}(t_m - t)} \cdot dt \right) \cdot e^{-\frac{E_i}{\eta_i}(t - t_m)} \quad (2)$$

where: p – cross-sectional area, a – deformation speed, l – sample height, E_i, η_i – elastic and viscous parameters of the model applied, t_m – time during which a strain developed.

Comparing (1) and (2) force models, the value of E_i, η_i parameters for both kind of samples and different speeds of initial deformation were obtained. The stress relaxation functions for free $E(t)$ and constrained $X(t)$ samples cut from the same fruit [9] were obtained.

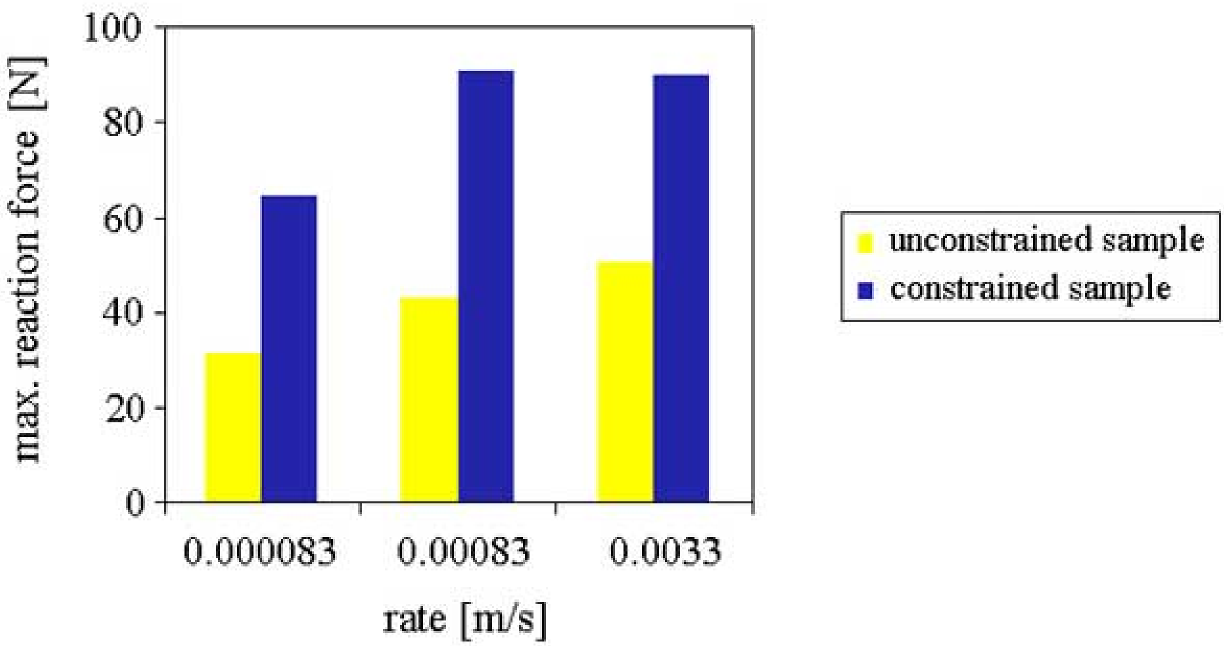
Figure 1 shows typical courses of uniaxial compressed stress relaxation functions for the unconstrained $E(t)$ and constrained $X(t)$ samples. As expected, by constant strain (8.5%) the reaction force value for the constrained sample in comparison with the unconstrained sample were higher and the difference between them decreased in time.

Figure 1. Example of the course of relaxation functions for unconstrained *E*(*t*) and constrained *X*(*t*) sample cut from the same fruit



The maximum of the sample reaction force, registered at the moment of final strain, obtained for the constrained sample about twice as high values than for the unconstrained one. A significant growth of average values of this force, for both higher deformation rates, was noticed (figure 2). Similarly for the unconstrained sample, average values of the maximum force became constantly higher as the speed was increasing. The same relations are observed in the case of ideal Maxwell body.

Figure 2. Influence of deformation speed on the maximum reaction force of unconstrained and constrained samples



As a result of a double experiment for the same fruit, uniaxial $E(t)$ and $X(t)$ stress relaxation functions were determined. It made it possible to calculate viscoelastic Poisson's ratio. Baerdemaeker [4] gave formula on the Laplace transformation of viscoelastic Poisson's ratio using the elastic-vicoelastic correspondence principle and Hughes and Segerlind method [9].

$$\nu(s) = \frac{1}{4 \cdot s} \cdot \left[\frac{E(s)}{X(s)} - 1 + \left[\left(\frac{E(s)}{X(s)} - 1 \right)^2 - 8 \cdot \left(\frac{E(s)}{X(s)} - 1 \right) \right]^{\frac{1}{2}} \right] \quad (3)$$

where: s – complex variable.

In order to find the inverse Laplace transform, the method worked out by Stankiewicz [10] was applied. It uses Bessel's functions of the first kind, zero and first rank. On this basis, using the Baerdemaeker's equation [4], viscoelastic Poisson's ratio was calculated. Figure 3 shows a typical course of viscoelastic Poisson's ratio, which changes during the experiment. In the case of apple flesh it had decreasing exponential course and its value for all specimens vary within the range of 0.3 to 0.4. No influence of initial deformation speed on viscoelastic Poisson's ratio was observed.

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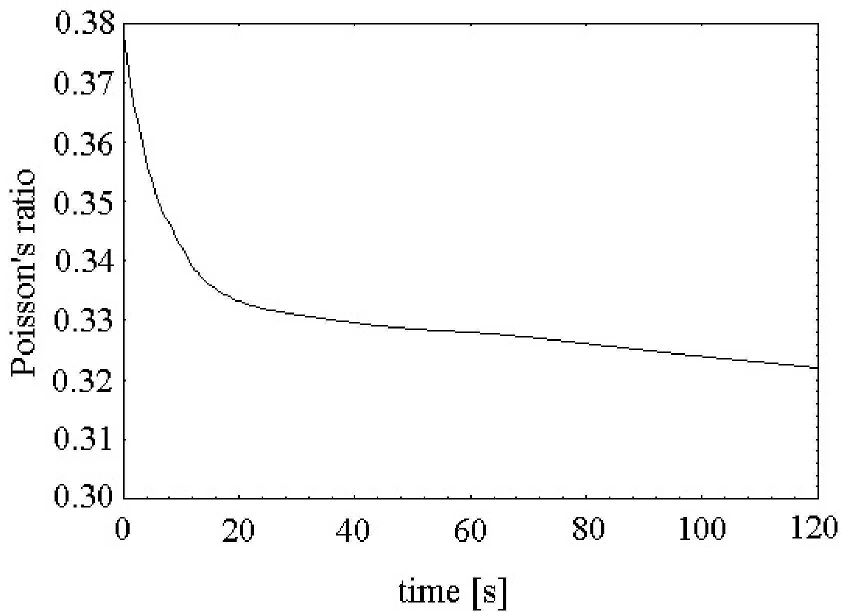
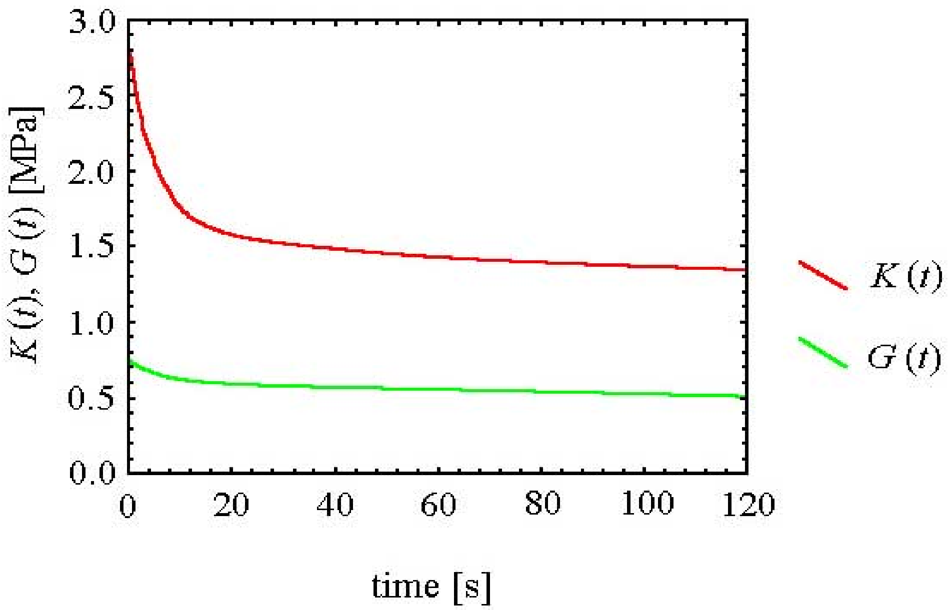
Figure 3. Typical course of viscoelastic Poisson's ratio in time for Jonagold apple flesh at deformation rate 0.833 mm/s



The properly determined stress relaxation functions $E(t)$ i $X(t)$ and viscoelastic Poisson's ratio can be used to develop analytical formulae for Laplace transforms of viscoelastic bulk modulus $K(s)$ and shear modulus $G(s)$. However, these formulae are so complicated that the procedures available by the author are not sufficient to determine them. That is why it was decided to base the calculation of value of $K(t)$ and $G(t)$ modulus on principles of elasticity theory instead of on analytical formulae. Figure 4 shows typical courses of $K(t)$ and $G(t)$ corresponding to $\nu(t)$ course in figure 3.

Figure 4. Typical courses of the bulk *K*(*t*) and shear *G*(*t*) modulus in time



It turned out that relaxation times for $K(t)$ and $\nu(t)$ are short and their values are very similar (they differ only by several seconds). Much longer relaxation time was observed for $G(t)$ modulus. Chen [2] suggests that long relaxation time represents water flow in intercellular

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spaces that can be the main reason for the slow drop of shear stress value in the tested material. Moreover, it seems that the slight fall of shear stresses level can show that the building tissue of frame cellular walls structure was maintained during the second part of the test (constant strain). Sudden drop of $K(t)$ modulus and $\nu(t)$ Poisson's ratio, just after the strain was set, can be caused by gases displacement and change of cells in the tissue as a result of destruction of some cellular walls during the first part of the test (increase of strain). A study of viscoelastic behaviour of apple flesh in connection with parameters, which determine the state of water as water potential or moisture content, could confirm these suggestions.

The second aim of the research was to determine the energy absorbed by the material during the first part of relaxation test. The total amount of energy absorbed during the first part of the test consists of elastic deformation energy, viscous flow energy, water flow energy across cellular walls and intercellular spaces and destruction tissue energy [5]. The rheological model (equation 2) presents the second part of stress relaxation test, thus, it determines material state after initial deformation. The maximum sample reaction force, obtained from experimental curves, and calculated parameters of Maxwell model create the basis for determination of values of two types of strain energy: empirical e_a and hypothetical e_m. The first one is that actually absorbed and calculated as the area under the experimental curve. The second one was calculated from the parameters of the model according to formula:

$$e_m = p \cdot \frac{a}{l} \cdot \int_0^{t_m} \sum_{i=1}^{2} \eta_i \cdot \left(1 - e^{-\frac{E_i}{\eta_i} \cdot t}\right) \cdot dt \quad (4)$$

assuming that the hypothetical loading conditions of the model are the same as in real test. A comparison of these two values of energy may constitute the basis for determination of damage and other plastic deformation occurring in a material as a result of different mechanical loads. Moreover, it can be used to determine the scope of model application taking into account the rate and value of deformation of the tested sample [6].

Figure 5. Value of the energy, for constrained (*c*) and unconstrained (*u*) sample, absorbed by specimen e_a and calculated on the basis of parameters model e_m depending on deformation rate

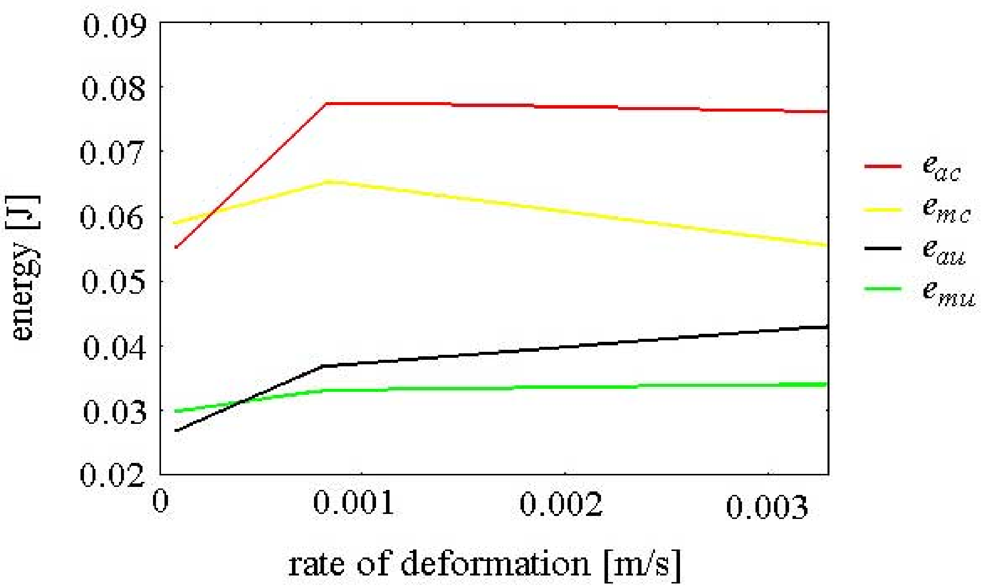

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Figure 5 shows how these two kinds of energy change depending on deformation rate. It can be seen that as the deformation speed increases the difference between the values of these two kinds of energy also increase. Higher values are those for constrained samples. The presented results are analogous to those obtained for carrot root [9] and confirm expectations that an increase of deformation rate causes increase of the amount of micro damage in the tested material.

CONCLUSIONS

1. Research revealed an increase of the maximum sample reaction force along with an increase of the rate of deformation.
2. It was stated that the difference between energy absorbed by a sample and calculated on the basis of two-elements Maxwell's model increases with rate of deformation.
3. Poisson's ratio decreasing with time, bulk modulus and shear modulus were observed and determined.

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