# AN EXPERIMENTAL METHOD FOR DETERMINING THE TIME OF RELAXATION AT STATIC COMPRESSION OF APPLES

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**Abstract:** This paper presents an experimental method to determine the relaxation of „Young's modulus" of elasticity and the relaxation time at static compression of apples, maintaining their integrity. We showed the theoretical basis of the method using the creep test by considering the behavior of linear viscoelastic rheological bodies physical model described by the Burgers model composed of elastic and viscous linear elements. It presents the mathematical model to describe the relaxation modulus of elasticity and experimental results for three varieties of local apples: Idared, Jonathan, Golden Delicious. The data obtained is useful in predicting the time of the storage in certain packages. We present a numerical calculation application for evaluation of storage for the three varieties of apples used in experiments.

**Keyword:** modulus relaxation, relaxation period, apples, creep, storage time.

## 1. INTRODUCTION

Apple production percentage of total fruit production in Romania is 60%, of which 60 – 80% is consumed fresh, large quantities being stored for medium and long periods of time ( 3 – 8 months) [1,2].

Apple culture in Romania includes a rich assortment consisting of traditional varieties, as Jonathan variety, which next to Golden Delicious, Starkrimson and Idared forms the base of apples production.

During processing, after harvesting, in order to maximize the production of fresh fruits, the apples go through an operational chain: packaging - transport (handling)– storage – preservation – sorting. In each operational step injuries of the fruits can appear [3].

The quality of the fruits is affected by the injuries which are produced when the stresses exceed the elastic limit of the fruit flesh, reaching the strength breaking of these. Injuries are highlighted either by contusions (bruises) of the tissue manifested by modification of the color (brown) of the flesh, either by the visible remanent strains.

Damages produced by concussion of the tissue and the permanent visible strains with modification of the geometric shape causes the major loss of quality and leading to the decrease of the commercial value of the apples [1, 4, 5].

Therefore the total losses of fruits after harvest can reach 30% of production, [13] and during storage, the losses can exceed sometimes 10 - 12%, [1, 6].

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Injuries from the apples produced during the storage period are caused by the superficial injuries previously produced under the epicarp which spread through apples pulp and of injuries caused by the application of constant compressive forces determined by the weight of the fruits from the superior layers upon the fruits from the lower layers, creating a force-deformation relationship characterizing the rheological behavior of the creep, [4].

In this case the size of package has an important role (particularly the available storage height) and it must not exceed certain limits. Exciding those limits can produce certain damages to the inferior fruits layers which affects the quality and the class of the apples [4, 5, 7].

Limiting and avoiding the mechanical damages that may affect the fruit`s quality_can be achieved only by knowing the physical and mechanical properties and the behavior of the various types of mechanical forces of the apples. Based on this information the right recommendations can be given in order to choose the appropriate design and packaging method according to the category of fruits, the degree of ripeness, the duration and conditions of storage. Therefore theoretical and experimental research on these properties and about the behavior to different mechanical solicitations, the influence factors and their correlations with the cellular tissue and chemical composition are required.

Appropriate mathematical models have been developed to describe these correlations, as close as possible to the real conditions in order help predict, for certain condition, the mechanical injuries caused by storage in certain packages, or imposing the maximum permitted level of defects or injuries related to deviations from the geometrical shape in order to choose and to design the appropriate packaging methods [4,5,7,8].

The researches were initially based on fundamental theoretical about homogeneous and isotropic bodies with ideal elastic or viscous-elastic behavior [4,5,9,10,11,12], then thoroughly developed accordingly to the parenchymatous structure of the apple tissues in order to correct and adjust the mathematical models to be as close as possible to the real conditions [9,13,14].

From numerous researches developed so far, whose results are synthesized in various papers, we can conclude that the behavior of the apples at different mechanical stress can be represented by the behavior of the linear viscoelastic bodies described by the rheological Burgers model made by elastic and viscoelastic elements, who are generally linear and nonlinear, [6,15,16].

Being considered biologic materials, the fruits do not react to tensions (stress) in a purely elastic manner. Their reaction combines an elastic and viscoelastic behavior (purely elastic responses does not depend of time stress action, but the viscoelastic responses are dependent on the time), [17].

Modern research methods regarding the utilization of the finite element method in the analysis of the mechanical contact between apples [11] and regarding the modeling of the apples response to static loads using images technique for reproducing the spatial distribution of the cells mechanically affected by considering the maximum crushing stress level [18,19].

In this paper we present an experimental method for determining the relaxation time at static compression of apples, maintaining their integrity using the creep test, considering the linear viscoelastic behavior of the bodies described with the rheological model of the Burgers model. We also present the mathematical models to describe the relaxation of the Young’s elasticity modulus needed for the evaluation (prediction) of the storage time in certain packaging and the application number on three varieties of apples for which the experiments were performed.

## 2. THEORETICAL CONSIDERATIONS

Being biological materials, apples can be considered, regarding the response to various types of mechanical stress, as materials with a viscoelastic behavior, dependent on time. This fact is directly related to the cellular tissue structure, form, composition and arrangement of cells in tissues and their mechanical properties [17].

Numerous researches made in this domain indicates that the behavior of apples during various types of mechanical stress can be expressed through the Burgers model physical rheological model composed of elastic and viscous elements, generally linear, which gives a linear viscoelastic behavior [6,15,16].

In accordance to [15], the creep test can be an indicator of the fruits visco-elasticity.

We will present the theoretical basis of the creep test performed, not on a special test specimen but on a whole fruit, maintaining its integrity, or on one half of a fruit.

According to theoretical developments upon the impact between convex, isotropic, linear viscoelastic bodies pressed by a constant load force F, on rigid spherical surfaces, the deformation δ(t) is a function of time and the deformation equation corresponding to the creep test is the same with Hertz's solution for the deformation of convex bodies in elastic contact, [6, 16], namely:

$$\delta(t)^{3/2} = 0,531\frac{F(1-\upsilon^2)}{E(t)} \cdot \left(\frac{1}{R_1}+\frac{1}{R_1^{'}}+\frac{4}{d}\right)^{1/2} \tag{1}$$

where:

E(t) - Young's modulus of elasticity of the convex body during the creep test on loading;
$R_1$, $R_1^{'}$ – radius of convex body surface at the point of contact in the normal planes of section;
υ – Poisson's ratio of convex visco-elastic body;
d – diameter of the rigid spherical surface.

If the rigid spherical surface becomes a plane surface (d→∞) then the relationship (1) shall be:

$$\delta(t)^{3/2} = 0,531\frac{F(1-\upsilon^2)}{E(t)} \cdot \left(\frac{1}{R_1}+\frac{1}{R_1^{'}}\right)^{1/2} \tag{2}$$

From Equation (2) is deducted the elasticity modulus E(t), measuring at different times t the deformation δ(t) after applying the constant compressive force F, as suggested in Figure 1 is obtained the equation, [6]:

$$E(t) = 0,531\frac{F(1-\upsilon^2)}{\delta(t)^{3/2}} \cdot \left(\frac{1}{R_1}+\frac{1}{R_1^{'}}\right)^{1/2} \tag{3}$$

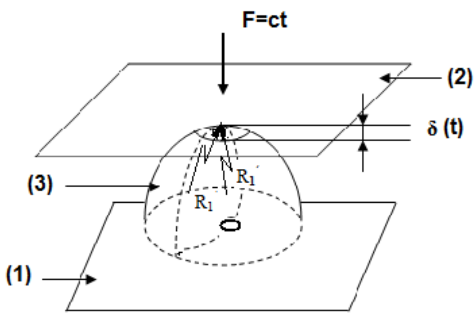



Fig. 1. Load scheme on half an apple through a rigid plane surface:
1 - The fix rigid plane surface; 2 - rigid plane surface parallel to the fix support, loaded with force F=ct; 3- half an apple subjected to the creep test.

If the rigid plane surface is replaced with another half–apple, considering the contact between two spherical surfaces of the same material ($\upsilon_1 = \upsilon_2 = \upsilon$ and $E_1 = E_2 = E$) but different radius $R_1$, $R_2$ (Figure 2), the equation of the relaxation modulus of elasticity (obtained from the creep test), acting on compression with the force F = ct, is [6]:

$$E(t) = 1,498 \frac{F(1-\upsilon^2)}{\delta(t)^{3/2}} \cdot \left( \frac{1}{R_1} + \frac{1}{R_1^{'}} \right)^{1/2} \tag{4}$$

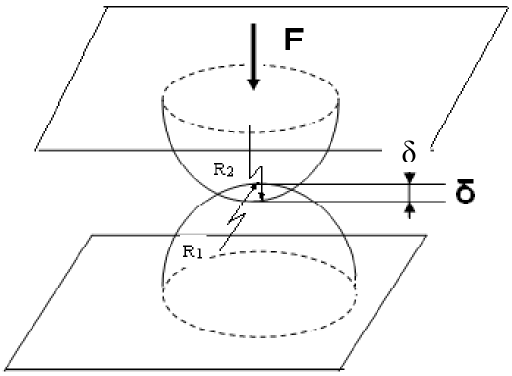



Fig. 2. Apple upon apple loading scheme at force F = ct, for the creep test.

The relaxation E(t) modulus equation for the Maxwell model as part of Burgersmodel, [16] namely:

$$E(t) = E_e + E_d e^{-\frac{t}{T_r}} \tag{5}$$

where:

$E_e$ - the equilibrium module ( E(t) for $t \to \infty$);
$E_d$ - the mitigation module ($E_d$=E(0)-$E_e$);
$T_r$ – relaxation time ($T_r$= η/$E_d$; η is the viscosity of the viscous element from the Maxwell model);
t – time since the beginning of creep test.

From the measuring of the deformation δ(t) at different moments t, E(t) is evaluated from Equation (3) or (4) depending on the measurement scheme used (Figure 1 and Fiure 2) and the ($t_i$, E($t_i$)) points are obtained, which will be used for testing the function given by equation (5) for the nonlinear regression module of relaxation, resulting the values $E_e$, $E_d$ şi $T_r$.

The initial modulus $E_0 = E_e + E_d$ can be taken as Young's modulus of elasticity for the elastic behavior of the apple at small deformations. Relaxation time $T_r$ is useful in predicting the storage time of apples in various packaging so that the modification (distortion) of the geometric shape of the fruit on the bottom of the packaging (boxes) do not exceed the allowed size to cause loss of quality of their marketing.

In a previous paper, [20] authors have proposed the evaluation equation of this parameter ($t_l$) namely:

$$t_1 = \beta \frac{KT_r}{GH} d^2 \sin\theta \tag{6}$$

where:

β is the distortion coefficient of the geometric shape of the apple (β = 0.015);
K is the local rigidity at deformation of the apple [6] ($K = 0.943 \frac{E}{1-\upsilon^2} d^{1/2}$);
$T_r$ – relaxation time; G – the average weight of apples in the package (box);
H – height of the box;
d – the average diameter of the apples from the box;

θ – the contact angle between the direction of apple, supposed spherical with the diameter d, to the bottom of the boxes.

Based on these theoretical considerations an experimental measurements program was developed for three local apples varieties: Jonathan, Golden Delicious and Idared, which will be presented below.

## 3. MATERIAL, METHOD AND EQUIPMENTS

### 3.1. Materials

For experimental calculation of the relaxation time at static compression there were used Jonathan, Golden Delicious and Idared apples, the most representative varieties, suitable for long storage and preferred by customers.

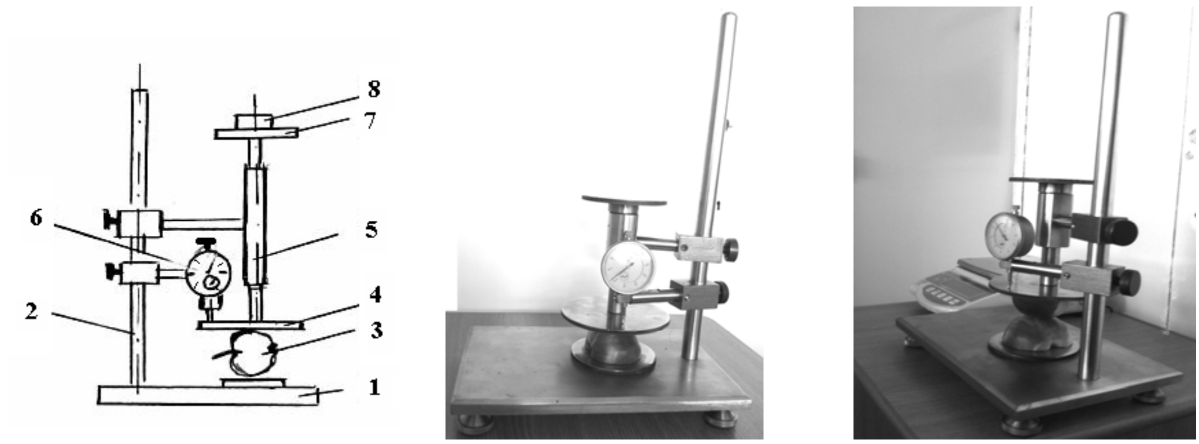
As the geometric shape, these three apples can be classified as sphero-conical and approximately spherical form.

The apples used in experiments were cultivated at ISCP Voinesti, Dâmboviţa County and they have been harvested at the end of August 2010, stored in cells refrigerators at a temperature of 3 – 4 $^0$C and a relative humidity of 80 - 85%.

We chose fruits as close as possible to a spherical shape and with medium sizes. Before experiments, the apples were brought out of their containers and kept in the lab for 4 -5 hours for acclimatization.

### 3.2. Description of the apparatus

In order to conduct the creep tests and determine the relaxation of the elasticity modulus and the time of relaxation at static compression of apples, a simple creep apparatus was designed and made (Figure 3.a). In Figure 3.b and 3.c are presented the views of the device ready to make measurements. In accordance with the testing, the apple is subjected to static compression by pressing, with a constant load, or a rigid plane surface Figure 3.c, or another half–apple Figure 3.b and the deformation is measured on a dial gauge, at different moments in time.




**a)** **b)** **c)**

Fig. 3. Creep apparatus:
1 - device frame; 2 - support; 3 - apple; 4 - compression rigid surface; 5 - guide; 6 - dial gauge; 7 - plane; 8 - constant load.

### 3.3. Experimental procedure

With the help of sphero-meter the radiuses $R_1$ and $R_2$ are determined in two perpendicular planes, in the contact point of the apple with the rigid plane surface.

Before each test the geometric dimensions of apples were measured with a digital caliper, with an accuracy of 0.02 mm.

The experiments were performed in two variants according to Figure 1 and Figure 2.

Apple is cut off in an axial plane using a sharp knife with rigid blade and one half was placed on the fixed flat surface of the device. The superior turntable was loaded with the loading mass corresponding to a constant pressure force F = 15 N. The rigid board was brought into contact with the apple surface and was released the turntable rod to achieve compression application.

Deformation δ(t) was measured at different moments of time, measured in seconds, at the beginning of the application at first every 15 seconds for 10 readings, every 30 seconds for 5 readings, every minute for 5 readings, every 5 minutes for 5 readings, every 10 minutes for 5 readings and every 15 minutes for 5 readings, which necessitated a total period of 2.5 hours for each experiment consisting in 35 readings.

In each point the elastic modulus E was calculated using the Equation (3) or (4) and with the values obtained the Equation (5) of the relaxation modulus was researched and tested.

## 4. RESULTS AND DISCUSSION

Compressive creep experiments were performed with three varieties of apples: Idared, Golden Delicious and Jonathan at a pressure–load of 15 N and for the two application schemes Figure 1 and Figure 2. Deformations δ(t) were measured for different moments of time and the values of Young's elasticity modulus were calculated with Equation (3) and (4). The data what was obtained are presented in Table 1 and Table 2.

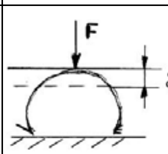
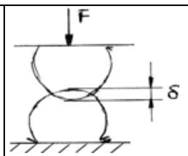
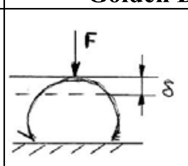
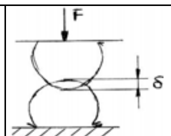
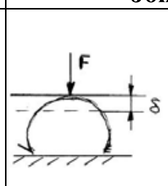
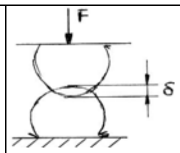
Table 1. Experimental data for the creep test at compressive application at constant force F = 15 N, for three varieties of apples, properly to the stress scheme in Figure 1 (deformation δ(t) at various time intervals t and the longitudinal Young's modulus of elasticity evaluated with Equation (5)) – sample data.

| Time [s] | Idared | | Golden Delicious | | Jonathan | |
|---|---|---|---|---|---|---|
| | δ [m] | E [Pa] | δ [m] | E [Pa] | δ [m] | E [Pa] |
| 15 | 0.000668 | 4990696 | 0.000308 | 14048046 | 0.000335 | 12276428 |
| 45 | 0.000699 | 4662406 | 0.00034 | 12112216 | 0.00035 | 11495746 |
| 75 | 0.000718 | 4478568 | 0.00035 | 11596847 | 0.000359 | 11066175 |
| 105 | 0.00073 | 4368593 | 0.00036 | 11117016 | 0.000361 | 10974340 |
| 135 | 0.000741 | 4271678 | 0.000369 | 10712786 | 0.000368 | 10662708 |
| 180 | 0.000752 | 4178295 | 0.000377 | 10373611 | 0.00037 | 10576370 |
| 240 | 0.000769 | 4040511 | 0.000384 | 10091255 | 0.000378 | 10242395 |
| 300 | 0.000775 | 3993680 | 0.00039 | 9859277 | 0.00038 | 10161641 |
| 420 | 0.00079 | 3880478 | 0.000404 | 9351256 | 0.0003885 | 9829981 |
| 540 | 0.0008 | 3807947 | 0.000416 | 8949567 | 0.0003905 | 9754560 |
| 900 | 0.000815 | 3703305 | 0.00044 | 8227407 | 0.0004 | 9409125 |
| 1500 | 0.00082 | 3669485 | 0.000469 | 7476231 | 0.000404 | 9269732 |
| 2100 | 0.000832 | 3590384 | 0.000489 | 7022289 | 0.00041 | 9066996 |
| 3300 | 0.00087 | 3357739 | 0.000515 | 6497274 | 0.000419 | 8776436 |
| 4500 | 0.00089 | 3245195 | 0.000543 | 6001257 | 0.000428 | 8501070 |
| 6000 | 0.00091 | 3138801 | 0.000575 | 5507319 | 0.0004345 | 8311024 |
| 7800 | 0.0009285 | 3045461 | 0.00061 | 5040194 | 0.000446 | 7991659 |
| 9600 | 0.00095 | 2942662 | 0.00064 | 4689991 | 0.00045 | 7885341 |

Table 2. Idem Table 1 for the stress scheme in Figure 2 (E(t) with Equation (4))

| **Time [s]** | **Idared** | | **Golden Delicious** | | **Jonathan** | |
|---|---|---|---|---|---|---|
| | **δ [m]** | **E [Pa]** | **δ [m]** | **E [Pa]** | **δ [m]** | **E [Pa]** |
| 15 | 0.00092 | 2782478 | 0.000823 | 3116449 | 0.00089 | 2806647 |
| 45 | 0.000968 | 2578104 | 0.000881 | 2813817 | 0.000945 | 2565223 |
| 75 | 0.000988 | 2500219 | 0.000912 | 2671576 | 0.000972 | 2459084 |
| 105 | 0.000999 | 2459038 | 0.000923 | 2623960 | 0.00099 | 2392324 |
| 135 | 0.00101 | 2418975 | 0.000938 | 2561271 | 0.00101 | 2321618 |
| 180 | 0.001023 | 2373013 | 0.00095 | 2512895 | 0.00102 | 2287560 |
| 240 | 0.001039 | 2318410 | 0.000962 | 2466023 | 0.00103 | 2254328 |
| 300 | 0.00105 | 2282073 | 0.000979 | 2402070 | 0.001041 | 2218691 |
| 420 | 0.001069 | 2221503 | 0.000991 | 2358573 | 0.001061 | 2156253 |
| 540 | 0.00108 | 2187650 | 0.001006 | 2306019 | 0.00108 | 2099603 |
| 900 | 0.0011 | 2128259 | 0.00104 | 2193864 | 0.00111 | 2015062 |
| 1500 | 0.001115 | 2085457 | 0.001076 | 2084689 | 0.00114 | 1936046 |
| 2100 | 0.001134 | 2033265 | 0.001105 | 2003163 | 0.00117 | 1862062 |
| 3300 | 0.001168 | 1945133 | 0.001148 | 1891677 | 0.001211 | 1768303 |
| 4500 | 0.0012 | 1867848 | 0.001179 | 1817561 | 0.001248 | 1690250 |
| 6000 | 0.001254 | 1748506 | 0.001229 | 1707780 | 0.001283 | 1621559 |
| 7800 | 0.0013 | 1656527 | 0.001253 | 1658950 | 0.001311 | 1569889 |
| 9600 | 0.00131 | 1637595 | 0.001271 | 1623833 | 0.00133 | 1536368 |

Table 3. The values of equilibrium modulus of elasticity ($E_e$), mitigation ($E_d$) and relaxation time ($T_r$) obtained from testing Equation (5) of the relaxation modulus with the experimental data and the corresponding values of the correlation coefficient $R^2$

| | **Idared** | | **Golden Delicious** | | **Jonathan** | |
|---|---|---|---|---|---|---|
| |  |  |  |  |  |  |
| $E_e$ (Pa) | 3.26 x10$^6$ | 3.46 x10$^6$ | 5.68 x10$^6$ | 3.51 x10$^6$ | 8.52 x10$^6$ | 3.32 x10$^6$ |
| $E_d$ (Pa) | 1.39 x10$^6$ | 1.54 x10$^6$ | 6.33 x10$^6$ | 1.99 x10$^6$ | 3.07 x10$^6$ | 1.73 x10$^6$ |
| $T_r$ (sec.) | 578.0 | 1724.1 | 909.1 | 1052.6 | 555.55 | 934.58 |
| $R^2$ | 0.904 | 0.908 | 0.944 | 0.931 | 0.918 | 0.928 |

Based on the data obtained from experiments the elasticity modules E function of time t were represented by points in Figure 4 – Figure 6 for the stress scheme with rigid board (see Figure 1) and in Figure7 – Figure 9 for the apple / apple stress scheme (Figure 2).

With the Microcal Origin program the data obtained from the experiments was processed , testing the Equation (5) for nonlinear regression of relaxation modulus with the experimental data and there were represented the corresponding curves, compared with the experimental data on the same graphics – Figure 4 – Figure 9.

The values of the equilibrium modulus of elasticity ($E_e$), mitigation ($E_d$) and relaxation time ($T_r$) obtained at testing Equation (5) of the relaxation modulus with the experimental data and the corresponding values of the correlation coefficient $R^2$ are presented in Table 3.

It appears that the values of the correlation coefficient $R^2$ are acceptable, $R^2 \geq 0.904$, which proves a good representation of the relaxation modulus through Equation (5).

Also, the module baseline values ($E(0) = E_d + E_e$) varies within 4.65 x $10^6$ – 12.01 x $10^6$ Pa for the stress scheme in Figure 1 and 5.0 x $10^6$ and 5.5 x $10^6$ Pa for the stress scheme in Figure 2, values known in the specialty literature, [6].

The relaxation periods are included in a large wide 555 – 1.724 s.

In [6], from the creep experiments made on the samples from the apple pulp it was obtained a relaxation time, $T_r$ = 3.150 s, a value which differs significantly from the values obtained from the experiments.

The values of the relaxation times $T_r$ are useful in evaluating the duration of storage time for apples in packages so that the geometric shape distortion factor would not exceed a certain value suggested by us, β= 0,05. For this, we use equation (6) and the following data: K=0.835 x$10^6$ (N/$m^{2/3}$); G=0.85N; d=62.5 x$10^{-3}$ m; θ=60.2$^0$; [5]; H=0.47 m and $T_r$ =1724 s (from our measurements). Replacing the data in equation (6), after performing the calculations, we obtain $t_l$= 609491 s = 169.3 hours ≈ 7 days. A relatively low value for the duration of storage was obtained, which is explained by the fact that the experiments were performed with apples stored in refrigerated cells for approx. 5 months after harvest, fact leading to the decrease in the rigidity of the pulp.

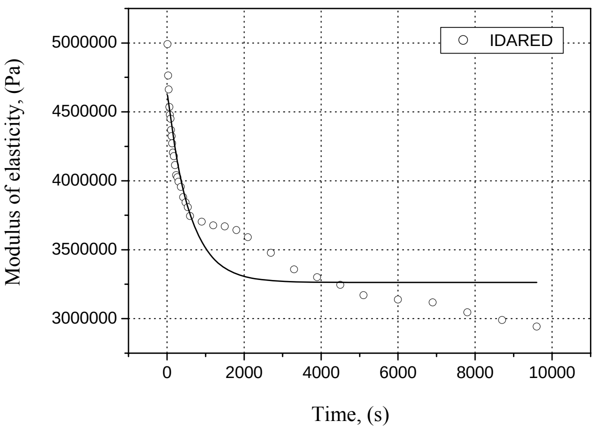



Fig. 4. Experimental points and the relaxation modulus curve E(t) versus time (t) for the stress of the Figure 1, for Idared variety.

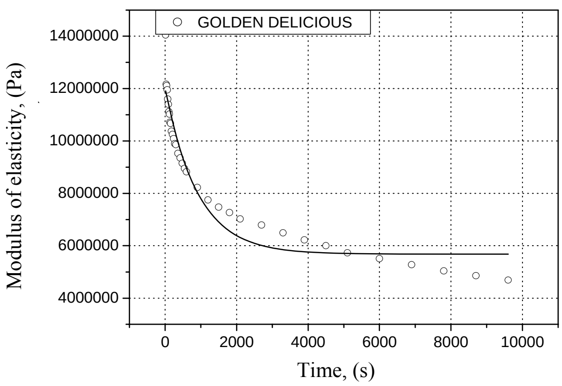



Fig. 5. Experimental points and the relaxation modulus curve E(t) versus time (t) for the stress of the Figure 1, for Golden Delicious variety

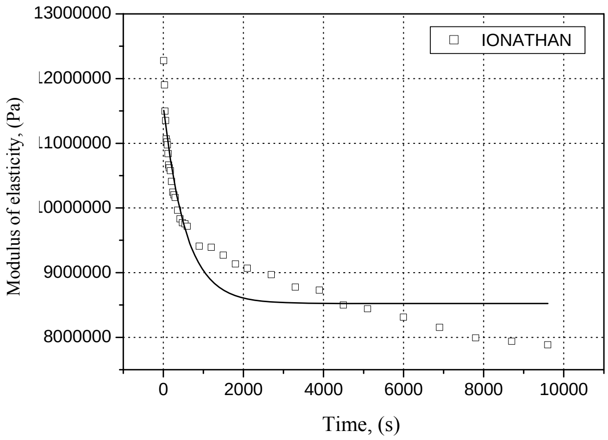



Fig. 6. Experimental points and the relaxation modulus curve E(t) versus time (t) for the stress of the scheme in Figure 1, for Jonathan variety.

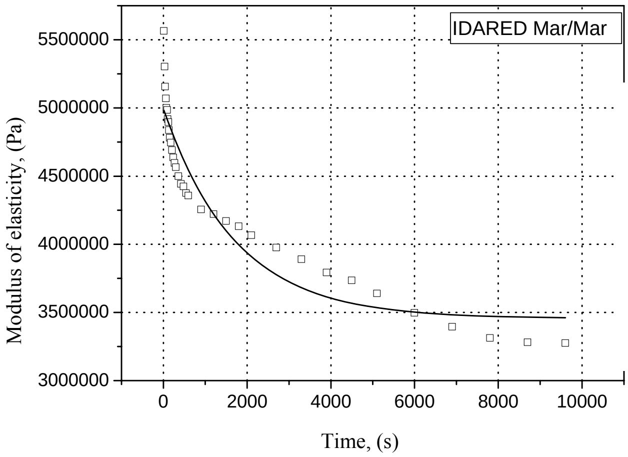



Fig. 7. Experimental points and the relaxation modulus curve E(t) versus time (t) for the stress of the scheme in Figure 2, the Idared variety.

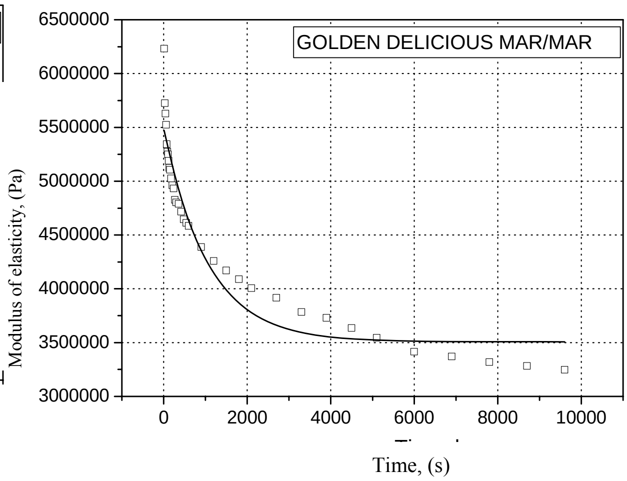



Fig. 8. Experimental points and the relaxation modulus curve E(t) versus time (t) for the stress of the scheme in Figure 2, the Golden Delicious variety.

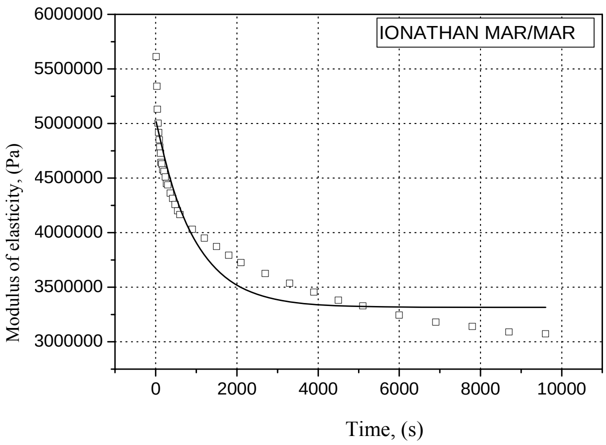



Fig. 9. Experimental points and the relaxation modulus curve E(t) versus time (t) for the stress of the scheme in Figure 2, the Jonathan variety.

## 4. CONCLUSIONS

In this paper we put the base for an experimental method to determine the time of relaxation at static compression of apples, considering the behavior of linear viscoelastic bodies described by the Burgers physical rheological model, using the creep test while maintaining the integrity of the fruit, presented the mathematical models for description of the elasticity Young's modulus needed for the evaluation (prediction) of the storage time in certain packages. Experimental creep tests are carried out for three varieties of apples: Jonathan, Idared and Golden Delicious and the known equation of the relaxation modulus of elasticity is tested with the experimental data, giving satisfaction, achieving a correlation coefficient $R^2$ = 0,904. From this data were obtained the relaxation times for each of the three varieties of apples tested.

At the end of the paper we presented a numerical calculation application for three varieties of apples (Jonathan, Idared and Golden Delicious) of storage time based on the values of the relaxation times so that the geometric shape distortion factor would not exceed a certain value imposed, specified in the paper.

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