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Anisotropic Relaxation and Creep Properties of Apple (cv. *Shafi Abadi* and *Golab Kohanz*)

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Abstract: Creep and stress relaxation are two important phenomena observed in viscoelastic materials. In this study creep and stress relaxation properties of two Iranian apples varieties (*Shafi Abadi* and *Golab Kohanz*) was investigated. A model based on generalized Maxwell model (contain of a single Maxwell model in parallel with a free spring) was used for determination of relaxation model and a model based on Burger model which is the series combination of the Kelvin and Maxwell models was used to fit the measured creep data. The decay modulus, the equilibrium modulus, time of relaxation, and specific viscosity in the relaxation model and instantaneous elastic modulus retardation time and coefficient of viscosity associated with Newtonian flow in creep model were determined.

Key words: Creep, decay modulus, equilibrium modulus, retardation time, relaxation time

INTRODUCTION

In spite of 2.66 million tons of annual apple production, exportation of that is very low in Iran (FAO, 2009). One of the most important export problems is quality decrease of fruits in postharvest operations such as handling, processing, grading and packaging. Foods, which exhibit characteristics of both liquid and solid, are described as viscoelastic where stress relaxation, creep and strength properties are time dependant (Mohsenin, 1986). Knowledge of viscoelastic properties of foods and agricultural materials are important when considering harvesting, handling, transportation, processing, and storage. Also the data on viscoelastic properties are required as an input for mathematical models, which describe and predict internal stress and cracking during different handling and processing procedures (Waananen and Okos, 1992). Viscoelastic materials become deformed under a load or constant shear stress (Purkayastha *et al.*, 1985). On the basis of relaxation and creep experiments several researchers have shown that fruit and vegetables exhibit viscoelastic behavior; however, it has been demonstrated that creep compliance tests can provide more information than tests involving stress relaxation. The main advantage of creep compliance tests over stress relaxation tests is that analysis can be facilitated by using the Burgers model. With this model, a larger number of rheological parameters can be estimated and elastic, viscoelastic and viscous flow characteristics can be predicted separately (Sherman, 1966). Viscoelastic material exhibit stress relaxation phenomena, which is one of the most important factors in characterizing agricultural materials. The relaxation time measured show how fast the material dissipates stress after receiving a sudden deformation and as well as can be used to characterize the elastic and viscous parts in the behavior of a material. The rheological models obtained from the experimental measurements can be useful in design of food engineering processes if used together with momentum, energy, and mass balances (Sahin and Gülüm Sumnu, 2006).

Several studies have been conducted on stress relaxation and creep of vegetables and fruits. Lewicki and Wolf (1995) studied the relationship between stress relaxation of raisins at different levels of moisture contents. They found that raisins could be classified as brittle body for moisture contents below 25% where the possibility of fracture during compression is high. The Universal Texture Machine was used to determine the viscoelastic properties of solar dried Sultana raisin cultivar (Saravacos and Kostaropoulos, 1995). They found that individual and bulk fruits follow a viscoelastic behavior where the internal portion of the fruit represents the viscous part while the outer skin represents the elastic part. In recent years, the stress relaxation test has been performed to study viscoelastic behavior of sago starch, wheat flour, and sago-wheat flour mixture (Zaidul *et al.*, 2003), potato tuber (Blahovec, 2003), cooked potatoes (Kaur *et al.*, 2002), wheat dough (Li *et al.*, 2003; Safari-Ardi and Phan-Thien, 1998), and osmotically dehydrated apples and bananas (Krokida *et al.*, 2000). Mittal and Mohsenin (1987) used incremental creep and recovery theory to develop a constitutive relationship for apple cortex. They applied

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Table 1: Relaxation and creep Data for *Golab Kohanz* and *Shafi Abadi*

	Variety			
	Golab Kohanz		*Shafi Abadi*	
Time (min)	Strain Mean±SD	Stress (KPa) Mean±SD	Strain Mean±SD	Stress (KPa) Mean±SD
0.00	0.00009±0.000047	136.05±25.12	0.0002±0.00008	222.27±2.50
0.06	0.0022±0.0001	112.78±23.32	0.0023±0.00018	196.55±47.54
0.10	0.004±0.0002	107.57±22.62	0.0041±0.00021	188.91±45.74
0.20	0.0053±0.00078	100.25±21.64	0.0058±0.0002	178.09±43.02
0.30	0.0063±0.00068	95.91±21.03	0.0071±0.00091	171.77±41.40
0.50	0.0078±0.0006	90.54±20.27	0.0087±0.00097	164.27±39.62
0.70	0.0094±0.00057	86.99±19.77	0.0097±0.0012	159.42±38.46
1.00	0.01±0.0009	83.19±19.19	0.011±0.001	154.34±37.35
1.50	0.012±0.00093	79.08±18.57	0.012±0.001	148.51±36.00
2.00	0.013±0.0012	76.03±17.77	0.013±0.0012	144.38±35.03
3.00	0.015±0.0016	71.54±16.41	0.015±0.0011	137.88±34.02
4.00	0.017±0.0011	67.52±15.64	0.017±0.0012	132.64±33.02
5.00	0.019±0.0018	64.85±14.90	0.018±0.0011	128.13±32.24

successive loading and unloading cycles of increasing duration to cylindrical specimens, showing that elastic, viscoelastic and plastic strains of the tissue resulting from creep and recovery tests can be separately predicted. The objectives of the current study were: (1) measure the stress relaxation and creep properties, i.e. the equilibrium modulus, the decay modulus, time of relaxation and retardation and the specific viscosity of two Iranian apples varieties and (2) find the best model to description of the stress relaxation and creep data.

MATERIALS AND METHODS

Material: Two Iranian apple varieties (*Golab Kohanz* and *Shafi Abadi*) were prepared in 2009 summer season from an orchard located at the Horticultural Research Center, Agricultural Faculty, University of Tehran, Karaj, Iran. The fruits were cleaned to remove all foreign matters such as dust, dirt and chaff as well as immature and damaged fruits. After removing from the cool store apples were kept during 24 h at 23ºC before testing. The analysis was carried out at a room temperature of 23ºC. The initial moisture content of fruit was determined by using dry oven method at 77ºC for 10 days (Kheiralipour *et al*., 2008). This study was conducted in August 2009, in laboratory of agricultural machinery engineering department, University of Tehran, Iran.

Methods: The stress relaxation and creep tests were performed by Universal Testing Machine (Santam, MRT-5). This machine was equipped with a load cell of 20 N and two parallel plates that one is fixed and the other is versatile and moves at a compressive rate of 25.4 mm.min^{-1}. Cylindrical specimens were cut in vertical orientation with 10 mm in diameter and 24 mm in height (Fig. 1). All tests were performed in 10 replicate and 5 minute and data were saved in computer which results were shown in Table 1. The data were analyzed using Excel software (2007).Stress relaxation:

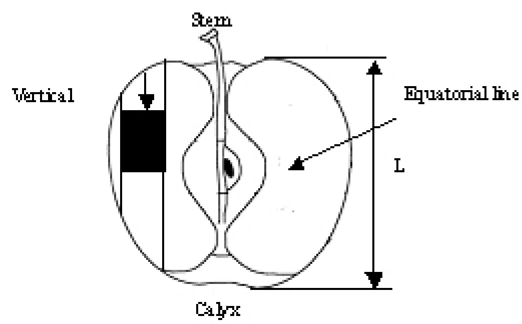


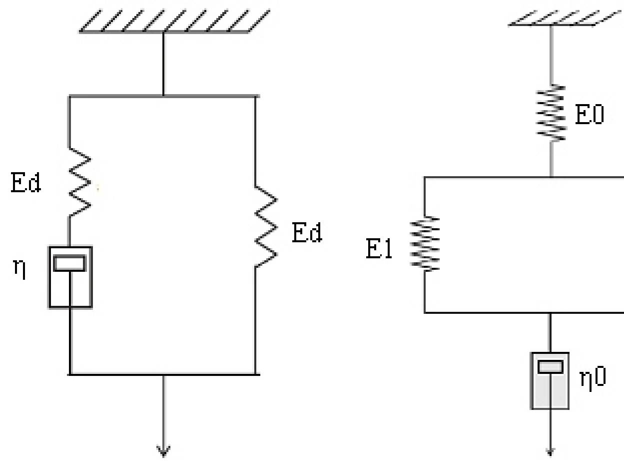
Fig. 1: Sample orientation in direction of vertical L is length of apple

In stress relaxation tests, samples are subjected to stress or compression up to a constant strain; maximum force attained and relaxation are then measured as functions of time. A generalized Maxwell model has frequently been used to interpret stress relaxation data of a linear viscoelastic material. The model contains n Maxwell elements and a spring in parallel; each element of Maxwell model consisting of a dashpot and a spring in series (Watts and Bilanski, 1991). The generalized Maxwell model can be written as follows:

$$\sigma(t) = \sigma_e + \sum_{i=1}^{n} \sigma_{di}\left(e^{-t/T_i}\right) \quad (1)$$

According to researches of Mohsenin (1986), the model (1) was simplified and a model with three elements (Fig. 2a) was fitted to the curves. The model was expressed as:

$$\sigma(t) = \sigma_e + \sigma_d\left(e^{-t/T_{rel}}\right) \quad (2)$$



(a) (b)

Fig. 2: Generalized Maxwell model with 3 elements for stress relaxation test (a) and Burger model with 4 elements for creep test (b)

where: $\sigma_e = \epsilon_0 E_e$, $\sigma_d = \epsilon_0 E_d$, $T_{rel} = \eta / E_d$ and ϵ_0 is initial strain and 3 mm was assumed. The stress in fifth minute was assumed as equilibrium stress. With substituting $(\sigma_0 - \sigma_e)$ instead σ_d in Eq. (1):

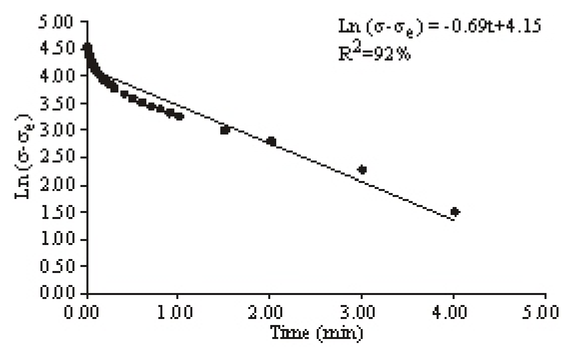
$$\sigma(t) = \sigma_e + (\sigma_0 - \sigma_e)\left(e^{-t/T_{rel}}\right) \qquad (3)$$

With modifying the Eq. (3) and taking the natural logarithm of both sides:

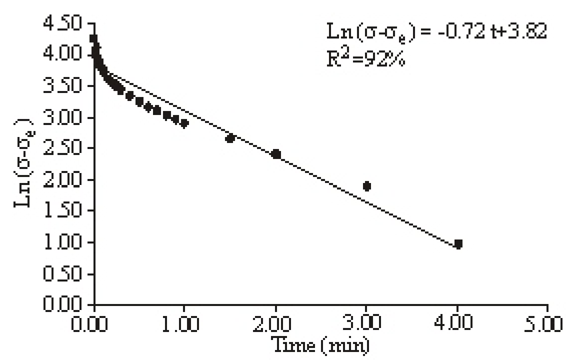
$$Ln(\sigma(t) - \sigma_e) = Ln(\sigma_0 - \sigma_e) - \frac{t}{T_{rel}} \qquad (4)$$

$Ln(\sigma_0 - \sigma_e)$ versus time is plotted as shown in Fig. 3. From the linear regression, the slope, which is equal to $(-1/T_{rel})$, relaxation time is determined and from the intercept, which is $Ln(\sigma_0 - \sigma_e)$, $(\sigma_0 - \sigma_e)$ is found. Then, other stress relaxation model parameters such as initial stress, decay stress and specific viscosity were determined.

Creep: In creep compliance tests, samples are subjected to constant stress and deformation is measured as a function of time. The compliance is defined ratio of strain to stress. The creep behavior can be explained by the burgers model (Fig. 2b). By connecting a Maxwell unit and a kelvin unit in series, the burgers model divides the creep strain of fruits into three parts: (1) the instantaneous deformation (Maxwell spring), (2) viscoelastic deformation (Kelvin unit), and (3) the viscous deformation (Maxwell dash-pot). These can be represented by:



(a)

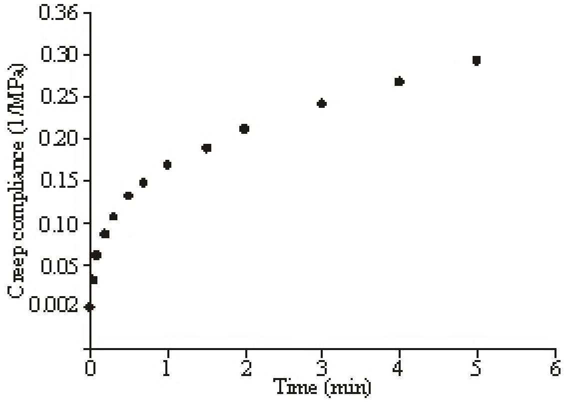


(b)

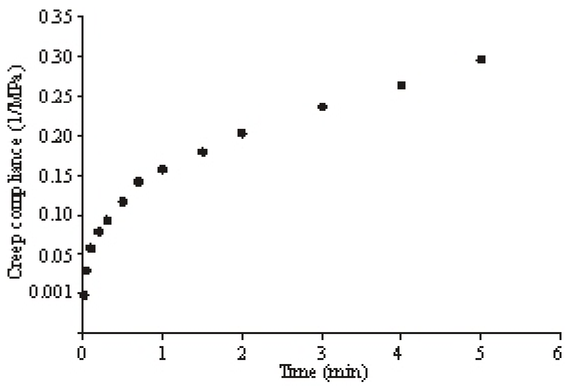
Fig. 3: Stress relaxation curves related to *Shafi Abadi* variety (a) and *Golab Kohanz* variety (b)

$$\varepsilon(t) = \frac{\sigma}{E_0} + \frac{\sigma}{E_1}\left[1 - \exp\left(-\frac{t}{T_{ret}}\right)\right] + \frac{\sigma t}{\eta_0} \qquad (5)$$

where T_{ret} is usually denoted as η_1/E_1, the retardation time required to generate 63.2% deformation in the Kelvin unit

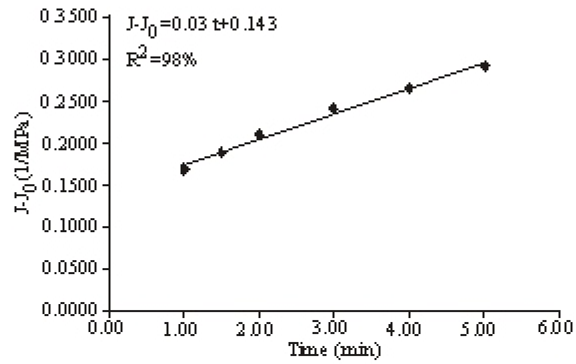


(a)

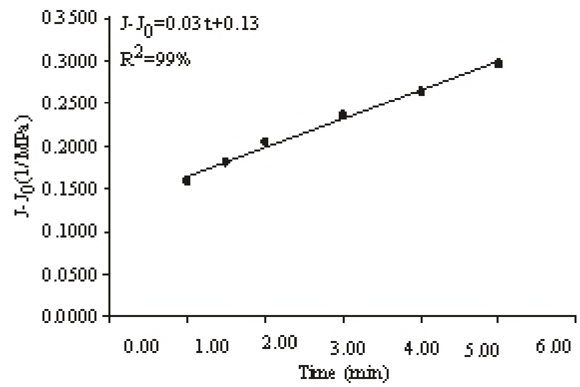


(b)

Fig. 4: Stress relaxation curves related to *Shafi Abadi* variety (a) and *Golab Kohanz* variety (b)



(a)



(b)

Fig. 5: Creep compliance curves, *Shafi Abadi* variety(a) and *Golab Kohanz* variety (b)

(Yang *et al.*, 2006) . This model shows an initial elastic response due to the free spring, retarded elastic behavior related to the parallel spring-dashpot combination and Newtonian type of flow after long periods of time due to a free dashpot. The creep analysis results were obtained for apple (*Golab Kohanz* and *Shafi Abadi*) by applying a constant stress of 0.065 MPa for 5 min on the samples. The data are given in Table 1. The parameters E_0, E_1, η_0 and η_1 can be obtained by fitting the equation to the experimental data and can be used to describe the creep behavior.

With division of the two sides of Eq. (5) to constant stress (σ), the Burger model in terms of creep compliance is:

$$J(t) = J_0 + J_1\left[1 - \exp\left(-\frac{t}{T_{ret}}\right)\right] + \frac{t}{\eta_0} \qquad (6)$$

where $J_0 = 1/E_0$ and $J_1 = 1/E_1$

First, the strain data (Table 1) are converted into compliance data using the constant stress of 0.065 MPa. Then, creep compliance versus time graph is plotted to determine the model parameters (Fig. 4). The instantaneous compliance, J_0 is determined from the raw data as 0.0002 and 0.0009 MPa^{-1} for *Shafi Abadi* and *Golab Kohanz* varieties respectively and E_0 was determined. Then, using the straight line portion of the ($J - J_0$) versus time curve (the last six data points) (Fig. 5), linear regression analysis yields retardation compliance, J_1 and η_0, from the intercept and slope, respectively:

$$J - J_0 = J_1 + t/\eta_0 \qquad (7)$$

It should be noted that J_1 reflects the fully equilibrated Kelvin element, making the exponential term of the Eq. (6) equal to zero. The slope of the straight-line portion of the graph (Fig. 5) is $1/\eta_0$, and the Newtonian viscosity of the free dashpot (η_0) is determined and from the intercept of the straight portion of the graph (Fig. 5), J_1 is found and E_1 can be calculated from J_1.

Using the exponential portion of the data (initial period), the retardation time is determined from the linear regression analysis over $J < J_1 + J_0$:

Table 2: Stress relaxation model parameters for *Shafi Abadi* and *Golab Kohanz* varieties

	Variety	
Relaxation properties	*Golab Kohanz*	*Shafi Abadi*
σ_d (Kpa)	45.6	63.43
σ_e (Kpa)	64.85	128.13
T_{rel} (min)	1.3	1.5
η (MPa.s)	3756.2	5449.1

Table 3: Creep model parameters for *Shafi Abadi* and *Golab Kohanz* varieties

	Variety	
Creep properties	*Golab Kohanz*	*Shafi Abadi*
E_0 (MPa)	714.28	400
E_1 (MPa)	7.7	7
η_0 (MPas)	2000	2000
η_1 (MPas)	92.4	126
T_{ret} (min)	0.2	0.25

$$Ln\left(1-\frac{J-J_0}{J_1}\right)=-\frac{t}{T_{ret}} \quad (8)$$

and since $T_{ret} = \eta_1/E_1$ thus, η_1 is calculated. Then substituting the model parameters into Eq. (5), the Burger model is calculated.

RESULTS AND DISCUSSION

The stress relaxation and creep tests were performed in 86% and 84% moisture contents for *Golab Kohanz* and *Shafi Abadi* varieties, respectively. The Stress relaxation and creep model parameters were shown in Table 2 and 3, respectively.

Stress relaxation model: According to results of Table 2, decay stress, equilibrium stress, relaxation time and specific viscosity were obtained 63.43, 128.13 (KPa), 1.5 (min) and 5449.1 (MPa.s) for *Shafi Abadi* variety and corresponding values for *Golab Kohanz* were 45.06, 64.85 (KPa), 1.3 (min) and 3756.2 (MPa.s), respectively. Between these parameters, the relaxation time is the most important factor in industrial food, for example, juice industry. Since relaxation time of *Shafi Abadi* variety is bigger than *Golab Kohanz* variety, thus it is resulted that the exerted force to machine components is smaller when *Golab Kohanz* variety is relaxed than the other variety and components were merged in more long time. In research of Wang (2003), the relaxation time was 30.33 s for pear and this may be to reason texture of pear is softer than the apple texture. According to obtained results, the stress relaxation models for these two varieties were shown in Table 4.

Creep model: According to results of Table 3, the elastic modules of the Maxwell and the Kelvin springs, the viscosities of the Maxwell and the Kelvin dashpots and retardation time were obtained 400 and 7 (MPa), 2000 and 126 (MP.s) and 0.25 (min) for *Shafi Abadi* variety and corresponding values for Golab Kohanz were 714.28 and 7.7 (MPa), 2000 and 92.4 (MPa.s) and 0.2 (min), respectively. Between these parameters, the retardation time is a important factor in storage time, for instance. Since retardation time of *Shafi Abadi* variety is bigger than *Golab Kohanz* variety, thus the texture of *Shafi Abadi* variety is stiffer than *Golab Kohanz* variety versus the time. Thus the time of storage for *Shafi Abadi* variety is longer than the other variety. Alvarez *et al.* (1998), investigated viscoelastic characterization of solid foods from creep compliance data for potato tissues (fresh and Cooked). They determined retardation time 136.58 and 54.89 (s) for fresh and cooked texture respectively. These results shown that potato have longer storage time than apple in status of fresh tissue. According to obtained results, the creep models for these two varieties were shown in Table 4.

CONCLUSION

The stress relaxation and creep tests were carried out with two Iranian apples varieties. The relaxation and retardation time for *Shafi Abadi* variety were obtained more than *Golab Kohanz* variety. This study has provided data on the fundamental relaxation and creep properties of apple. The results may have some important implications in developing computer simulation model to study rheological behavior of fruit, to sort intact fruit, and store and transport fruit with better positions.

Table 4:Stress relaxation and creep models for *Shafi Abadi* and *Golab Kohanz* varieties

Variety	Stress relaxation model	Creep model	R^2 (%)
Shafi Abadi	$\sigma(t)=63.43+128.13\left(e^{-t/1.5}\right)$	$\varepsilon(t)=1.6\times10^{-4}+0.009\left(1-e^{-t/0.25}\right)+3.2\times10^{-5}$	0.92
Golab Kohanz	$\sigma(t)=45.6+64.85\left(e^{-t/1.3}\right)$	$\varepsilon(t)=9.1\times10^{-5}+0.008\left(1-e^{-t/0.2}\right)+3.2\times10^{-5}$	0.92

ABBREVIATIONS

Ed : Decay modulus (MPa)
E_e : Equilibrium modulus (MPa)
E_1 : Elastic modulus of the Maxwell spring in creep test (MPa)
E_2 : Elastic modulus of the Kelvin spring in creep test (MPa)
J_0 : Instantaneous compliance (1/MPa)
J_1 : Retarded compliance (MPa.s)
T_{rel} : Relaxation time (min)
T_{ert} : Retardation time (min)
ϵ_0 : Initial strain in stress relaxation test
η : Specific viscosity in stress relaxation test (MPa.s)
η_1 : Viscosity of the Maxwell dashpot in creep test (MPa.s)
η_2 : Viscosity of the Kelvin dashpot in creep test (MPa.s)
σ : Constant stress in creep test (MPa)
σ_e : Equilibrium stress (KPa)
σ_d : Decay stress (KPa)
R^2 : Determining coefficient

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