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Compressive Creep Behavior of Fruits

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ABSTRACT

Creep tests were performed to determine the nonlinear viscoelastic properties of apples and pears with the creep experiment apparatus designed in this study. Compressive creep characteristics of fruits were tested at two kinds of storage conditions, four periods of storage and three levels of initial stress. Ten replications were made at each treatment combination.

The creep behavior of the fruits could be well described by the nonlinear viscoelastic model as a function of initial stress and time. However, for each level of initial stress applied, the compressive behavior of the samples was satisfactorilly represented by Burger's model. For all sample fruit, the longer the sample was stored, the higher the instantaneous elastic strain was observed, and the creep progressed at a high rate. These phenomena were even more remarkable on the fruit stored at the normal temperature storage rather than at the low temperature storage.

Key Words : Creep, Fruits, Nonlinear Viscoelastic Model

INTRODUCTION

Fruits are affected by various external forces during harvesting and processing operations like sorting, packaging, transporting and storage. Damage of fruit due to such an external force depends on the physical properties of fruits and on the type of load. During transporting and storage the fruit is packaged in boxes, where compressive forces are usually exerted on the fruit. Mechanical injury in this situation is primarily a phenomenon of permanent deformation at the contact points between fruits, and the fruit with the container. If the deformation surpasses the biological yield limit, the tissue will brown within a short time and be spoiled. In these instances such as the browning and bruising of fruits during process operations, it is desirable to minimize resultant deformations. Therefore, the compressive creep characteristics of fruits can be used as criteria in reduction of fruits damage which results in excessive deformations in process operations.

In compressive creep tests, where load is suddenly applied to the material and held constant, the material creeps as a function of time. The creep behavior of the material is generally described by a combination of two basic mechanical elements which are a spring and a dashpot. One combination of elements used to represent creep behavior is the four-element Burger's model which consists of a Kelvin model connected in series to a spring and a dashpot element.

Much research has been conducted to assess the creep behavior of agricultural products (Cenkowski et al., 1991; Clevenger and Hamann, 1968; Nakayama et al., 1978; Purkayastha and Peleg, 1986; Rao et al., 1987; Skinner and Rao, 1986). Those studies were concerned mostly with the linear relationship between stress and strain of the material. But it is generally known that the fruit tissues under a load displays nonlinear rheological behavior.

Chappell and Hamann (1968) tested apple flesh using the uniaxial compressive load method. They used Burger's model to represent the viscoelastic response of the apple flesh. Examining the Burger's model, they reported that it could not be linear viscoelastic because the parameters of the model depended on the initial stress. Sharma and Rafie (1983) also found that apple flesh was nonlinear viscoelastic in nature.

Graham and Bilanski (1984) studied nonlinear viscoelastic behavior during forage wafering and Kim et al (1990) also studied nonlinear viscoelastic behavior of rough rice under a uniaxial compressive load. They reported that compressive creep behavior of biological materials depended not only upon initial stress but also upon the duration of stress application or time, and nonlinear viscoelastic model as a function of initial stress and time was reported.

Fruits are living organism and are perishable. They are in a continual state of deterioration from harvest. During storage, physical properties of fruits are changed by their physiological activities. Therefore it will be very useful to obtain data related to storage and packaging of fruits to investigate effects of storage condition and period on creep behavior of fruits.

The objectives of this study were to develop nonlinear viscoelastic model as a function of initial stress applied and time, to determine the effect of initial stress on the creep characteristics of the fruits flesh, and to determine viscoelastic properties of fruits according to storage condition and period.

MATERIALS AND METHODS

Materials

Sample fruit was selected from each cultivar of apples and pears respectively. Fuji of apple and Niitaka of pear were selected because these fruits are the most popular grown cultivars in Korea. Fruits were obtained from the experimental orchard of Chungnam National University. The agronomic data and physical characteristics of the fruit are shown at Table1.

Selected fruit was divided into two groups right after harvest. One group was stored at a low temperature (3℃, rh 85%) and the other one was stored at a normal temperature (15℃, rh 45%) from harvest to testing, an interval of no more than 10 days.

Fruits were allowed to stabilize at experimental room temperature before tests were performed. Cylindrical specimens of diameter 17.6 mm and height 20 mm were removed from the location perpendicular to the core using a standard cork borer. In order to prevent loss of fluids from the surface, the specimens were covered with thin vinyl film, and the top and the bottom of the specimen were wraped with cellophane tape of 0.3 mm width to reduce local failure when coming in contact with loading plate.

Experimential apparatus and methods

A schematic and block diagram of the creep apparatus are shown in Fig. 1. This testing apparatus was designed specifically for this study. The apparatus consisted of a main frame, force rod fixed to plate at both ends, and a data acquisition system. The rod was able to slide freely in vertical direction, and was balanced by dead weights hung over the pulley attached to the main frame. The LVDT (0.01 mm, DT-20D) was installed on the frame in the normal direction to the rod, and measured the axial deformation of the specimen. The Load Cell (50 kg_f, CO-50KE) measured the force applied to the specimen which when divided by the cross sectional area of the specimen gave us the initial stress.

Uniaxial creep tests were separately performed on the fruits stored at low temperature and at normal temperature. The tests were conducted at four different of storage periods, an interval of 10 days, and for three stress levels (0.0403, 0.1210, and 0.2017 MPa). These stress values were within the bioyield strength of the fruits as determined by preliminary testing. The dead weight was held constant for approximately 10 min. and the resulting uniaxial deformation was measured through LVDT. Ten replications were made at each treatment combination.

RESULTS AND DISCUSSION

Creep model of fruits

An average creep data was obtained from these tests, and Burger's model was used to predict the behavior of the fruit flesh for each level of stress. For the computer analysis, Burger's model was written as the Eq.(1).

$$\varepsilon(t) = C_1 + C_2 [\, 1 - \exp(-C_3 \cdot t)] + C_4 \cdot t \quad \cdots\cdots\cdots\cdots \quad (1)$$

where, $C_1 = \sigma_o/E_o$, $C_2 = \sigma_o/E_r$, $C_3 = 1/\tau_r$, $C_4 = \sigma_o/\eta_r$

σ_o = initial stress, MPa

E_o = instantaneous modulus, MPa

E_r = retarded modulus, MPa

τ_r = time of retardation, s

η_v = viscosity coefficients of dashpot, MPa·s

Burger's model coefficients were determined by using a nonlinear program developed in the study. Within fruit samples, comparisons were made between coefficients of Burger's model for each storage condition and period, and for initial stress applied. As shown in Table 2, the determination coefficients (r^2) of the equation were better than 0.99 with 10 degree of freedom. Therefore, it was concluded that Burger's model will predict the compressive creep behavior of the fruits flesh. However, the values of E_o, E_r, and η_v given in Table 2 increased with the increasing of initial stress for whole samples. The implication suggested that a nonlinear viscoelastic model to describe the compressive creep behavior of the fruit flesh was needed for a comprehensive understanding of creep characteristics of fruit flesh. To find out the nonlinear viscoelastic model that would give good descriptions of the compressive creep behavior of the fruit flesh, various forms of equations were investigated, and the following Eq. (2) was found to give good results.

$$\varepsilon(\sigma,t) = A\sigma^{B}\,[\,C + D\cdot t - \exp(-F\cdot t)] \quad \cdots\cdots\cdots\cdots (2)$$

where, $\varepsilon(\sigma,t)$ = strain as a function of initial stress and time, mm/mm
σ = initial stress, MPa
A~F = model parameters

Using a nonlinear regression program developed in the study, the model parameters were estimated from the experimental data as shown in Table 3. The response surfaces of creep behavior of apple and pear flesh were shown in Fig. 2 and 3 respectively. The determination coefficients of the model were higher than 0.96, and these indicated that creep behaviors of the fruit flesh predicted from the model agreed well with experimental results.

Effect of initial stress

The results obtained from the analysis of the creep behaviors for apples and pears at different initial stresses reveal that initial stress has an important effect on the fruit property. Fig. 4 and 5 show the creep behaviors of the apple flesh and the pear flesh right after harvest, respectively.

The instantaneous elastic strain (σ_o/E_o) and the degree of viscoelasticity (σ_o/E_r and σ_o/η_v) increased with the increasing of initial stress. This indicated that the higher initial stress caused transient creep to increase its rate in the beginning of creep, and afterward resulted in the higher rate of increase in steady state creep. In a practical sense, the higher initial stress applied to fruit caused the greater permanent deformation and the greater residual deformation remaind with removal of the applied load.

Comparing the creep behavior between fruits, time of retardation which is the time required to deform about 63% of the retarded elastic strain (σ_o/E_r), ranged from 21.15 to 82.14 s for the apple and from 16.27 to 19.37 s for the pear. This indicated that the steady state creep on pear was reached earlier than that on apple. Also the instantaneous elastic strains of pear was higher at the same test conditions than those of apple, this means that pear has softer tissue relative to apple.

Effect of storage condition and period of time

Fig. 6 and 7 show compressive creep curves obtained for the apple and the pear according to storage condition and period. For all sample fruit, the longer sample was stored, the higher instantaneous elastic strain was observed, and creep progressed at a higher rate. Such an effect of storage life on the creep behavior of the fruit was more significant for the fruit stored at normal temperature than those stored at low temperature. Comparing the effect of storage conditions and period on fruit property, it was observed that the pear was more sensitive to storage temperature and period than the apple.

CONCLUSIONS

1. The compressive creep behavior of the sample could be well described by Burger's model for each level of stress applied, but the creep behavior was found to be highly stress-dependent, and it was satisfactorily modelled by an equation of the following form :

$$\varepsilon(\sigma,t) = A\ \sigma^B\ [\ C + D\cdot t - \exp(-F\cdot t)]$$

2. The effect of initial stress applied was significant on the creep behavior of the all samples. The instantaneous elastic strain increased with the increasing of initial stress, and the creep progressed at a relatively high rate on higher levels of initial stress.

3. Trends for time of retardation showed inconsistent response to initial

stress, and time of retardation for the pear was of a little greater value than that for the apple. The implication was that the transient creep for the pear was complete earlier than the apple.

4. For all sample fruit, it was found that the instantaneous elastic strain varied with length of storage life, and also creep progressed at a high rate along with it. These trends appeared to be more obvious in the samples stored at normal temperature than those stored at low temperature.

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Table 1. Agronomic data and physical characteristics of the fruits used in compressive creep test

Kind of fruit	Cultivar	Date of		Volume ($10^{-4}m^3$)	Weight (kg_f)	D_T (kg/m^3)	Grade
		full bloom	harvest				
Apple	Fuji	1991.5. 1	1991.11.7	3.129	0.2625	838.93	56
Pear	Niitaka	1991.4.23	1991.10.1	3.830	0.3801	992.43	38

Note ; Volume : water displacement method by Archemedes theory, D_T : true density, Grade : number of fruits per 15 kg_f(with standard corrugated fiberboard box and cushioning material)(1990)

Table 2. Parameters of the Burger's model for the fruit flesh

Fruits	S.P. days	S.C.	Initial stress MPa	$\varepsilon(t)=\sigma_0/E_0+\sigma_0/E_r[1-\exp(-t/\tau_r)]+\sigma_0 t/\eta_v$				r^2
				E_0, MPa	E_r, MPa	τ_r, s	η_v, MPa·s	
Apple	0	—	0.0403	5.3862	13.9747	21.3761	5127.4673	0.9998
			0.1210	6.2700	16.5144	21.8459	6067.0952	0.9999
			0.2017	6.7723	17.6264	21.5832	6517.8662	0.9999
	10	NT	0.0403	3.4124	11.3308	22.1359	4242.6890	0.9998
			0.1210	4.5684	15.2838	21.8827	5677.9150	0.9999
			0.2017	5.2400	17.4718	21.6665	6480.8252	0.9999
		LT	0.0403	4.0325	12.6863	21.8849	4718.8516	0.9999
			0.1210	4.9635	15.8232	21.8525	5828.4019	0.9999
			0.2017	5.4781	17.3528	21.7618	6419.7783	0.9999
	20	NT	0.0403	2.4115	9.8680	21.5382	3658.4707	0.9999
			0.1210	3.4097	13.8376	21.8143	5177.1211	0.9999
			0.2017	4.0024	16.3125	21.6484	6046.7217	0.9999
		LT	0.0403	3.1210	11.7174	21.1554	4339.4399	0.9999
			0.1210	3.9790	14.9522	21.7122	5579.6074	0.9999
			0.2017	4.4538	16.8491	21.8370	6233.8691	0.9999
	30	NT	0.0403	1.8485	8.0647	21.5266	3019.8606	0.9999
			0.1210	2.9001	12.8043	21.7765	4772.6685	0.9999
			0.2017	3.5823	15.8404	21.5655	5852.8359	0.9999
		LT	0.0403	2.5670	10.3115	21.5168	3802.0349	0.9999
			0.1210	3.6092	14.4986	21.3744	5333.4766	0.9999
			0.2017	4.2290	16.8914	21.4531	6254.0459	0.9999
Pear	0	—	0.0403	3.6903	8.8653	16.3490	4182.6816	0.9999
			0.1210	4.7015	11.2651	16.4655	5336.8384	0.9999
			0.2017	5.2657	12.5636	16.3862	5991.9009	0.9999
	10	NT	0.0403	2.9165	7.3747	16.8203	3712.5015	0.9999
			0.1210	4.1315	10.4189	16.6004	5212.5610	0.9999
			0.2017	4.8490	12.2287	16.8563	6129.8047	0.9999
		LT	0.0403	3.1713	7.9093	19.2754	4361.6514	0.9999
			0.1210	4.3404	10.7976	19.3726	6009.9126	0.9999
			0.2017	5.0317	12.4686	19.3011	6936.3057	0.9999
	20	NT	0.0403	2.4139	6.3424	16.7016	3167.4656	0.9999
			0.1210	3.6872	9.6611	16.7619	4856.9150	0.9999
			0.2017	4.4833	11.8412	16.8044	5879.1196	0.9999
		LT	0.0403	2.7994	7.6839	16.5540	3626.2227	0.9999
			0.1210	4.0351	11.0428	16.6071	5248.0781	0.9999
			0.2017	4.7905	13.0646	16.4662	6210.1162	0.9999
	30	NT	0.0403	1.9741	5.5253	16.8603	2778.4053	0.9999
			0.1210	3.1764	8.9191	16.7575	4471.8740	0.9999
			0.2017	3.9617	11.1219	16.7436	5584.1572	0.9999
		LT	0.0403	2.3994	7.0079	16.9182	3347.4910	0.9999
			0.1210	3.6446	10.6095	16.4890	5069.0479	0.9999
			0.2017	4.4217	12.8903	16.4132	6131.0479	0.9999

Note ; S.P.: storage period, S.C.: storage conditions, —: initial state, NT : normal temperature, LT : low temperature

Table 3. Parameters of nonlinear viscoelastic model for creep of the fruit flesh according to the storage period and conditions

Fruits	S.P. days	S.C.	$\varepsilon(\sigma, t) = A\sigma^{B}[C + D\cdot t - \exp(-F\cdot t)]$					r^2
			A	B	C	D	F	
Apple	0	—	0.0451	0.8568	3.6091	0.0027	0.0458	0.9633
	10	NT	0.0374	0.7343	4.3378	0.0027	0.0460	0.9633
		LT	0.0425	0.8100	4.1724	0.0027	0.0459	0.9633
	20	NT	0.0371	0.6868	5.0838	0.0027	0.0461	0.9633
		LT	0.0417	0.7780	4.7741	0.0027	0.0462	0.9633
	30	NT	0.0327	0.5884	5.4207	0.0027	0.0463	0.9633
		LT	0.0361	0.6911	4.9989	0.0027	0.0463	0.9634
Pear	0	—	0.0559	0.7799	3.3920	0.0021	0.0606	0.9633
	10	NT	0.0495	0.6859	3.5192	0.0020	0.0600	0.9633
		LT	0.0507	0.7143	3.4852	0.0018	0.0516	0.9633
	20	NT	0.0458	0.6152	3.6296	0.0020	0.0596	0.9633
		LT	0.0450	0.6676	3.7275	0.0021	0.0607	0.9633
	30	NT	0.0449	0.5674	3.8151	0.0020	0.0596	0.9633
		LT	0.0424	0.6221	3.9147	0.0021	0.0608	0.9633

Note ; S.P.: storage period, —: initial state, NT : normal temperature, LT : low temperature

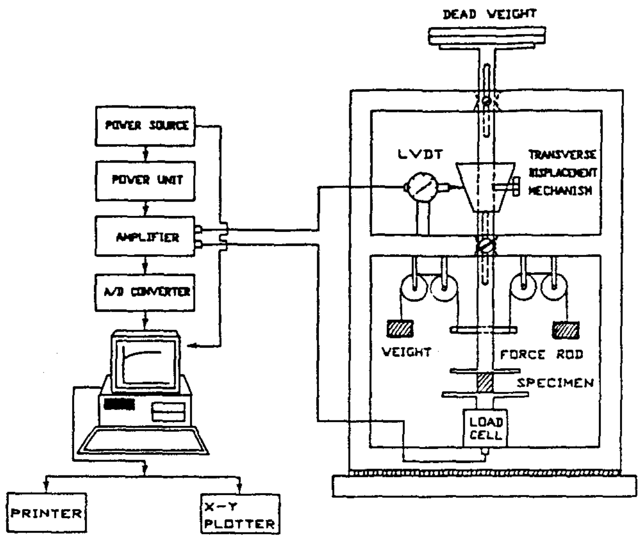

Fig. 1. Schematic and block diagram of the compressive creep test apparatus.

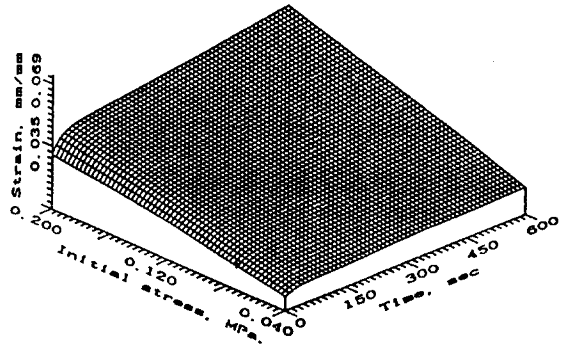

Fig. 2. Response surface of creep for the apple flesh as a function of time and initial stress.

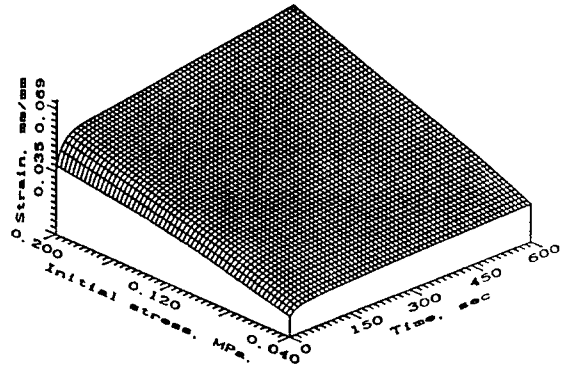

Fig. 3. Response surface of creep for the pear flesh as a function of time and initial stress.

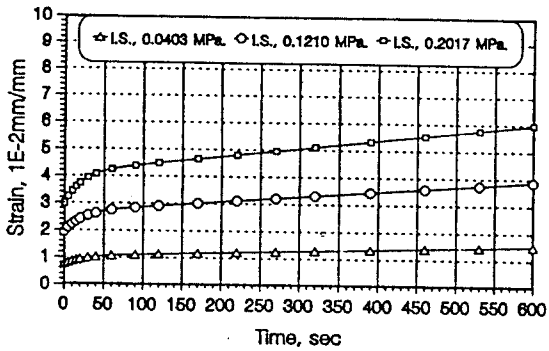

Fig. 4. Effect of the initial stress on the creep behavior of the apple flesh.

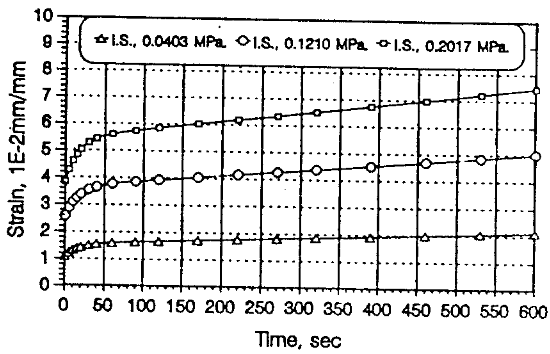

Fig. 5. Effect of the initial stress on the creep behavior of the pear flesh.

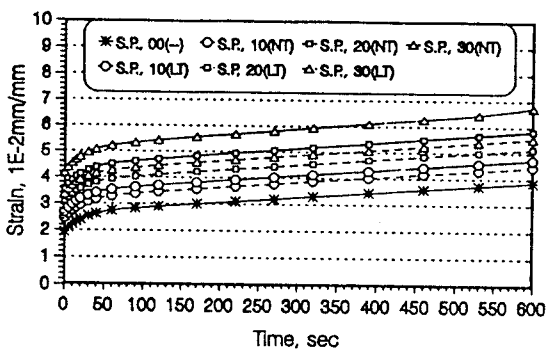

Fig. 6. Effect of the storage condition and the storage period on the creep behavior of the apple flesh at the initial stress of 0.1202 MPa.

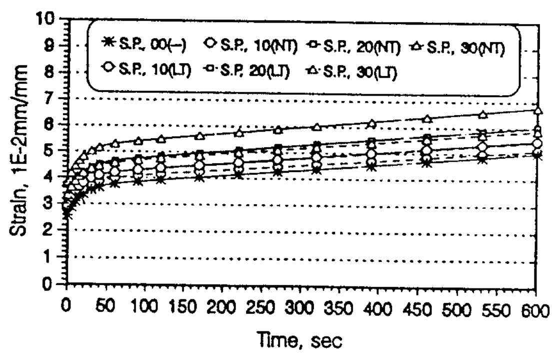

Fig. 7. Effect of the storage condition and the storage period on the creep behavior of the pear flesh at the initial stress of 0.1202 MPa.