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Research paper

Hysteresis characteristics and relationships with the viscoelastic parameters of apples

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ABSTRACT

The hysteresis test was performed to measure the hysteresis properties of Fuji, Golden and Red Delicious apples. Loading speed of the texture analyzer was 2.5 mm/min and loading deformation set 1.0 mm. Hysteresis parameters were compared with the viscoelastic parameters presented by the oscillatory test. Correlation coefficients between viscoelastic parameters and hysteresis parameters was significantly high for Golden Delicious apple, but low for Fuji and Red Delicious apples. For Golden Delicious apple, correlation coefficients were −0.85, −0.81 and −0.80 for hysteresis loss and 0.84, 0.85 and 0.86 for degree of elasticity, with phase lag, loss modulus and dissipated energy, respectively. Multiple linear regression analysis results for three apple varieties that phase angle, loss modulus, complex modulus and dissipated energy had the adjusted R-square values of 0.532–0.687 for calibration model with statistical significances at $p < 0.001$ and the validation correlation coefficients of 0.704–0.780, when independent variables measured by the oscillatory test were energy loss, hysteresis loss or hysteresis modulus. It should be noted that the hysteresis and the oscillatory tests take quite different approaches to characterize hysteresis phenomenon of apples.

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1. Introduction

As fruits have viscoelastic attributes, it is important to analyze their elastic components and viscous components. Force-deformation curves for fruits show some residual deformation remaining because none of the biological materials shows perfect elasticity. This means some energy is obtained by taking the difference between the loading work and the unloading work. This energy loss is referred to as specific damping capacity of fruits (Mohsenin, 1986).

Hysteresis tests used force–deformation curves obtained by unloading after loading up to the predefined deformation or force using universal testing machines (Kim et al., 1992, 1999). Hysteresis losses in loading–unloading test correlate well with directly observed volume of fruits (Blahovec et al., 2002). Characteristic values of hysteresis losses and degree of elasticity were used to determine the bruise index, that was suitable for classifying the pear varieties as to tissue susceptibility to low-level bruising (Blahovec and Mareš, 2003). They attempted to apply the hysteresis loss concept to dynamical impact tests (Blahovec et al., 2004).

The viscoelastic behavior is evaluated using methods such as stress-relaxation, quasi-static and dynamic tests. Except for the dynamic test, these tests can only provide partial information about the materials (Zhang, 2005). In the previous study (Lee et al., 2012), the oscillatory test, one of dynamic tests, was performed to identify viscoelastic parameters of apples such as phase angle, storage modulus, loss modulus, and dissipated energy. Phase angle or tan δ is a measure of damping or internal friction in a linear material (Lakes, 2004). It is reasonable that more firm apple have lower phase angle and lower hysteresis loss, and higher degree of elasticity than those of less firm apple.

Viscous properties evaluated by a dynamic test may have the same physical meanings as hysteresis properties such as loss work and hysteresis loss analyzed by the hysteresis test. This study performed the hysteresis test using the texture analyzer to measure hysteresis parameters of apples and compared them with viscoelastic parameters obtained by the oscillatory test in the previous study (Lee et al., 2012).

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Table 1
Physical properties of Golden Delicious (GD), Fuji (FJ) and Red Delicious (RD) apple fleshes.

Type of tests	Apple	Item	Weight (10^{-3} kg_f)	Length (10^{-3} m)	Diameter (10^{-3} m)	Density[b] (kg_f/m^3)
Hysteresis test	GD	Mean	3.31	13.5	19.5	823.9
		SD[c]	0.13	0.25	0.12	25.8
	FJ	Mean	3.45	13.6	19.5	850.5
		SD	0.15	0.46	0.08	21.6
	RD	Mean	3.35	13.4	19.5	838.3
		SD	0.21	0.40	0.10	35.4
Oscillatory test[a]	GD	Mean	3.37	13.7	19.5	825.3
		SD	0.08	0.25	0.12	17.6
	FJ	Mean	3.49	13.6	19.6	852.7
		SD	0.12	0.37	0.07	19.5
	RD	Mean	3.36	13.6	19.5	829.9
		SD	0.15	0.34	0.16	29.0

[a] Referred to the previous study (Lee et al., 2012).
[b] Density = Weight/($\pi/4 \times$ Diameter$^2 \times$ Length).
[c] SD: standard deviation ($n = 30$ for each variety).

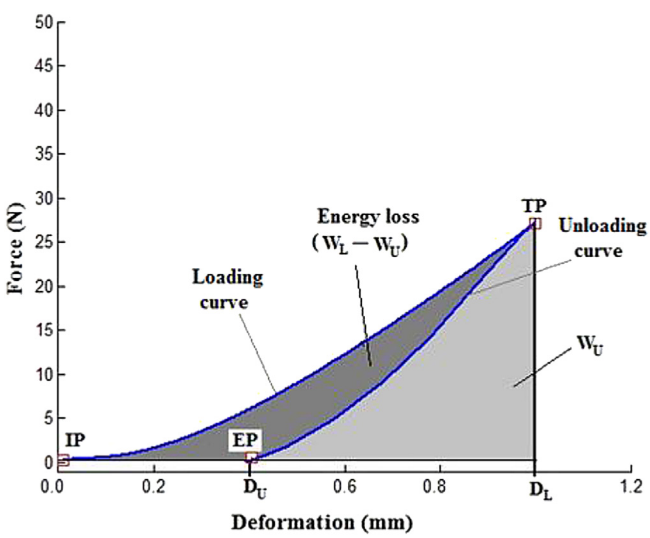

Fig. 1. Schematic representation of hysteresis parameters in the force–deformation curve.

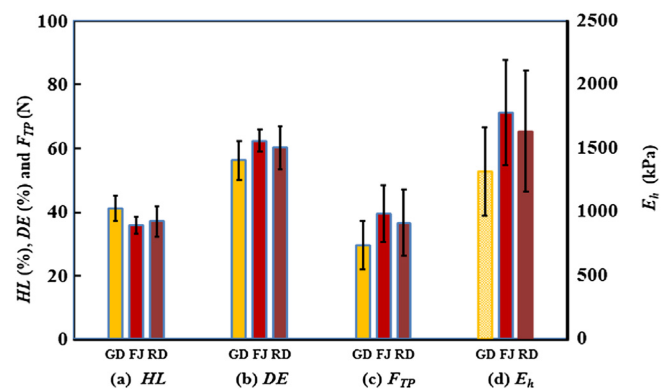

Fig. 2. Mean values and standard deviations of hysteresis parameters of Golden Delicious (GD), Fuji (FJ) and Red Delicious (RD) apple fleshes measured by the hysteresis test.

2. Materials and methods

2.1. Samples

Fruit samples were selected from Golden Delicious, Fuji and Red Delicious apples purchased at market places and then kept in laboratory conditions of about 20 °C and 60% RH for 6–12 h before tests were conducted. Apple flesh slices, 16–18 mm in thickness, were made by slicing vertically to an axial of a whole apple, and then cylindrical flesh tissues of Φ19.5 mm and L13.5 mm were extruded perpendicularly to the flesh slice using the cylindrical sampler. Out of extruded apple tissues, three slices were selected for the hysteresis test of this study and two slices were selected for the oscillatory test in the previous study (Lee et al., 2012).

Length and diameter of a cylindrical sample were measured by a standard digital caliper (resolution: 0.01 mm, model: EC16, Tresna, USA), and weight was measured by an electric microbalance of platform type (resolution: 1 μg, max. scale: 10 g). A density of specimen was calculated from specimen sizes and weight as shown in Table 1. The hysteresis test used 270 tissues (three varieties × thirty apples × 3 replicates). As indicated in Table 1, there was no difference between two tests in physical properties of

Table 2
Dynamic compressive properties of apple fleshes measured by the oscillatory test at the frequency of 10 Hz.

Apple	Item	δ (deg.)	E' (kPa)	E'' (kPa)	$\lvert E^* \rvert$ (kPa)	W_{diss} (J/m^3)
Golden delicious	Mean	19.3	3008	1066	3192	90.4
	SD[a]	1.1	723	293	778	24.1
Fuji	Mean	20.5	3647	1362	3893	115.9
	SD	0.6	498	195	534	19.32
Red delicious	Mean	20.4	3604	1347	3847	114.8
	SD	0.7	877	344	941	27.5
Mean ratio[b]	FJ/GD	1.060	1.213	1.277	1.220	1.282
	RD/GD	1.058	1.198	1.263	1.205	1.270

[a] SD: standard deviation ($n = 30$ for each variety).
[b] Mean ratio: mean values of FJ and RD divided by mean value of GD for each properties.

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