Dynamic Structural Properties of Sweet Potato

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THE recent interest in mechanical properties of foods and other the development of a variety of testing methods. Some mechanical properties have demonstrated good correlation with sensory evaluation of the products, chemical composition, functional properties, etc. (Sherman 1970). The evaluation and understanding of the mechanical properties of biological materials have been greatly enhanced by the use of classical mechanics of time dependent systems. Mohsenin (1970) has illustrated several testing methods, using the principles of linear elastic, viscoelastic and fluid mechanics theories.

The sweet potato (*Ipomea Batatas)* is grown extensively in the United States and is high in digestible carbohydrates and food energy. Sweet potatoes also provide vitamin A and ascorbic acid necessary for human nutrition. Sweet potato roots can be characterized on the basis of sensory "mouthfeel" into two main categories. One is the "dry" fleshed type which is similar to Irish potato in consistency and is frequently preferred by consumers in the north. These dry fleshed varieties were grown initially in southern New Jersey and hence are alternatively called the Jersey type. The other category is termed the "moist" flesh type which has a slick or slimy feeling in the mouth. The difference between dry and moist flesh types is attributed primarily due to their mouthfeel characteristics (Rao et al. 1974) and is independent of the actual moisture content (Nelson 1973). Characterization of the mouthfeel quality by uniaxial compression and shear tests (Rao et al. 1974) by determining the flow behaviour (Rao et al. 1975) has been accomplished. The effect of alpha and beta amylase activities on the moist mouthfeel of sweet potatoes was investigated by Walter et al. (1975). Their report indicated that beta amylase activity was not correlated to mouthfeel quality but alpha amylase activity was significantly correlated to organoleptic properties. Wright and Splinter (1968) used various compression tests under several loading conditions to determine the mechanical behavior of sweet potato flesh.

The use of dynamic testing to determine a complex modulus has been mainly in areas of high speed aero and hydro dynamic vehicles (Lee 1956). Several researchers in textile technology have used dynamic properties of fibers in formation of synthetic fabrics. Hamann (1969), using the principles of linear viscoelasticity, utilized a sinusoidal cyclic loading procedure to evaluate the complex modulus of apple flesh. Wen and Mohsenin (1970) determined a tensile complex modulus for corn using low frequency testing. The present study was concerned with dynamic testing of dry and wet fleshed sweet potatoes to determine the time dependent complex modulus and its variation along the longitudinal axis of the roots. The relationship between fiber content of roots and mechanical stiffness, and the use of the complex modulus as a means of detecting differences between cultivars, were also investigated.

EXPERIMENTAL SPECIMENS

Sweet potato roots were obtained for this study from the North Carolina Agricultural Experiment Station. Two cultivars of sweet potatoes were used viz., a dry fleshed experimental cultivar Number 213 x 238-1 and a wet fleshed variety, Centennial. Both cultivars of sweet potato were US grade No. 1 harvested in October, 1972. They were cured at 30 C and 85 percent relative humidity for 10 days. After curing, the sweet potato roots were stored at 16 C and 55 percent relative humidity for 3 months. To obtain test specimens, each sweet potato was roughly marked into three divisions across the length of the axis and sample slices of approximately 15 mm thickness were cut from each of these three divisions. Then, using a cork borer, a cylindrical specimen of approximately 25 mm diameter was cut from each slice. Section 1 was always taken from the stem end, Section 2 from the middle, and Section 3 from the root end.

DYNAMIC TESTING

The dynamic testing apparatus designed by Hamann (1969) with slight construction modifications was used for sinusoidal uniaxial compression of the cylindrical specimen (Fig. 1). The sinusoidal force was provided by an electrodynamic shaker and an accelerometer was mounted on the shaker shaft. The specimen was held between two discs, one attached to the shaker and the other attached to a force transducer which in turn was mounted on a rigid vertical support. The transducer and accelerometer signals were amplified and fed into an oscilloscope on the vertical and horizontal channels respectively. The resulting Lissajous ellipse (Fig. 2) on the scope was analyzed to determine the force (from height), acceleration (from width) and the phase lag of acceleration. Since the input signal was a sine wave, the displacement was calculated from acceleration as:

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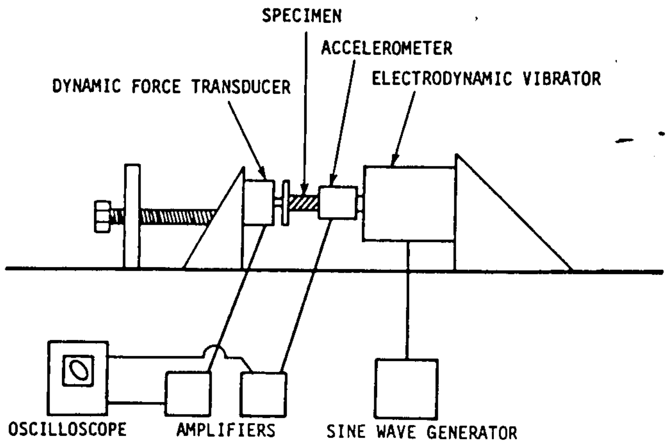

FIG. 1 Schematic diagram of apparatus.

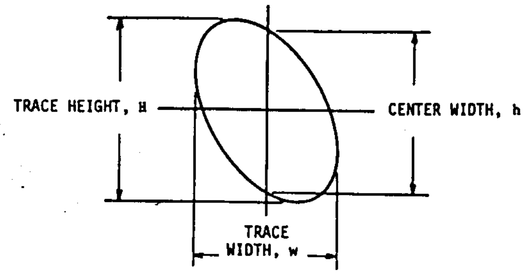

FIG. 2 Oscilloscope trace (Lissajous Ellipse).

$$D = D_o \text{Sin } \omega t$$

and

$$a = \frac{d^2}{dt^2} D$$

$$= \frac{d^2}{dt^2} D_o \text{ Sin } \omega t$$

$$= -D_o \omega^2 \text{ Sin } \omega t$$

therefore

$$D = -\frac{a}{\omega^2}$$

where
- a = the acceleration
- D = the displacement
- ω = the frequency
- t = the time

Knowing force and displacement, the absolute value of complex modulus was calculated as follows:

$$E\,(i\omega) = E' + i\,E''$$

Where $E\,(i\omega)$ is the complex modulus, E' the real or storage component and E'' the imaginary or loss component. Also,

$$E\,(i\omega) = |E| \cos \Theta + i\,|E| \text{ Sin } \Theta$$

where Θ is the phase angle by which the strain lags the stress.

The absolute value $|E|$ then is

$$|E| = \frac{F_o/A}{D_o/L}$$

Where F_o is the force amplitude, A the area of cross section of the specimen, D_o the displacement amplitude and L the length of the specimen. The phase angle Θ was determined as

$$\Theta = \text{Sin}^{-1} \frac{h}{H}$$

where h was the vertical width of ellipse at center and H the total height of ellipse.

Each specimen was tested at frequencies from 40 Hz to 240 Hz in increments of 20 Hz. Thirty specimens of each cultivar of sweet potato were utilized since a specimen was prepared from each of the three sections from each sweet potato with 10 potato replications. The sinusoidally applied force was held constant for all tests by achieving a constant height of ellipse and constant gain of force amplifier. A sample of the data for Centennial sweet potato for section 1, replication 1 is shown in Table 1.

CRUDE FIBER

The term crude fiber denotes the insoluble residue after treating a sample with dilute acid and dilute alkali (AOAC 1970). The insoluble residue contains about 97 percent in weight of cellulose and lignin. Hydrolytic degradation of other carbohydrates leaves the fiber which is composed of 60-80 percent cellulose and 4-67 percent lignin (Joslyn 1970). The crude fiber has been used in the chemical determination of quality in vegetables and as a measurement of nutrient value.

The cylindrical specimen of sweet potato from each section of the three sections along the length was first weighed and dried at 60 °C for 24 hrs and reweighed to determine the moisture content. The dried sweet potato cylinders were then treated with 1.25 percent H_2SO_4 (0.255 N) and 1.25 percent NaOH (0.313 N) according to the procedure outlined in AOAC (1970). The residue left after digestion and filtration was dried, weighed and ignited. Fiber content was determined by weight loss during ashing.

TABLE 1. SAMPLE DATA FOR CENTENNIAL SWEET POTATO. FIRST SECTION CYLINDRICAL SPECIMEN WITH A DIAMETER OF 2.49 cm AND A LENGTH OF 1.67 cm*

Frequency Hz	Accelerations width of ellipse (scope units)	Gain	h (scope units)	Stress (kPa)	Strain $\times 10^3$	Absolute modulus $\times 10^{-4}$ (kPa)	Phase angle $\times 10^2$ (radians)
40	6.0	40.00	0.0	87.17	4.37	2.00	—
60	5.8	20.00	0.0	87.17	4.59	1.90	—
80	6.0	13.00	0.4	87.17	4.24	2.06	6.8
100	6.3	9.00	0.5	87.17	4.48	1.95	8.4
120	6.2	5.85	0.7	87.17	5.10	1.71	11.7
160	6.2	3.95	0.5	87.17	4.11	2.13	8.4
180	6.6	3.30	0.5	87.17	4.15	2.10	8.4
200	6.4	2.70	0.5	87.17	3.92	2.23	8.4
220	6.2	2.20	0.5	87.17	3.77	2.31	6.6
240	6.2	1.82	0.5	87.17	3.91	2.23	8.4

*Force was always held to 4 units on the scope and a constant gain of one. h is the vertical width of the ellipse at the center.

TABLE 2. MEAN VALUES OF ABSOLUTE COMPLEX MODULUS, PHASE ANGLE, FIBER PERCENT AND MOISTURE CONTENT FOR THE 3 SECTIONS OF CENTENNIAL AND NUMBER 213X238-1 SWEET POTATOES

	CENTENNIAL						NUMBER 213X238-1					
	Section 1		Section 2		Section 3		Section 1		Section 2		Section 3	
Frequency	$\|E\|x10^{-4}$ (kN m^{-2})	$\Theta x10^2$ (rad)	$\|E\|x10^{-4}$ (kN m^{-2})	$\Theta x10^2$ (rad)	$\|E\|x10^{-4}$ (kN m^{-2})	$\Theta x10^2$ (rad)	$\|E\|x10^{-4}$ (kN m^{-2})	$\Theta x10^2$ (rad)	$\|E\|x10^{-4}$ (kN m^{-2})	$\Theta x10^2$ (rad)	$\|E\|x10^{-4}$ (kN m^{-2})	$\Theta x10^2$ (rad)
40	1.88	—	1.50	—	1.62	—	1.87	—	1.80	—	1.77	—
60	1.80	8.5	1.52	8.7	1.63	8.7	1.86	7.2	1.83	7.7	1.80	8.9
80	1.91	8.5	1.58	9.3	1.72	8.7	1.88	9.4	1.89	7.5	1.91	8.5
100	1.75	9.9	1.49	10.2	1.65	9.7	1.74	9.9	1.77	9.8	1.74	9.9
120	1.79	10.5	1.53	10.2	1.64	10.5	1.74	10.4	1.75	10.2	1.71	10.0
160	2.02	10.2	1.73	10.9	1.78	10.4	2.00	9.2	1.97	9.5	1.96	10.0
180	2.07	10.2	1.79	10.9	1.83	10.2	2.12	9.0	2.07	10.2	1.99	9.7
200	2.15	10.9	1.85	11.5	1.87	10.7	2.27	10.0	2.15	11.2	2.05	10.5
220	2.21	8.7	1.97	9.9	2.01	9.2	2.28	8.4	2.21	8.7	2.14	8.8
240	2.25	8.7	1.97	9.2	2.04	8.8	2.32	8.2	2.26	8.7	2.16	8.7
Moisture content (percent dry basis)	305.2		311.9		353.6		363.1		406.1		466.8	
Fiber (percent)	12.58		7.12		7.77		11.55		8.00		10.61	

RESULTS AND DISCUSSION

The data for each section of each sweet potato cultivar was analyzed to determine the absolute value of the complex modulus and the phase angle. The coefficient of variation ranged from 3.2 percent to 17.6 percent for the 10 replications and no definite pattern was found in the coefficient of variation for the different sections, frequencies or variety. These results along with the mean fiber and moisture contents are presented in Table 2. The values of phase angle at 40 Hz were omitted because of a high degree of variation in the Lissajous pattern. A graph of absolute modulus as a function of forcing frequency is shown in Fig. 3. Values of average absolute modulus at 100 and 120 Hz are shown in the Figure but were omitted when connecting points with lines since modulus values for all cultivars and sections were lower than the general trend would predict. The reason for lower values is apparatus resonance, which occurs in this range of frequency. The value of resonant frequency depends on the particular apparatus and will vary from instrument to instrument. All the three sections taken from the number 214x238-1 sweet potato and the first section of Centennial are in a band which is distinguishably higher than the other two sections from Centennial in the region of frequencies tested. This indicates that the number 213x238-1 sweet potato is mechanically stiffer than the Centennial sweet potato provided that the section 1 is not considered.

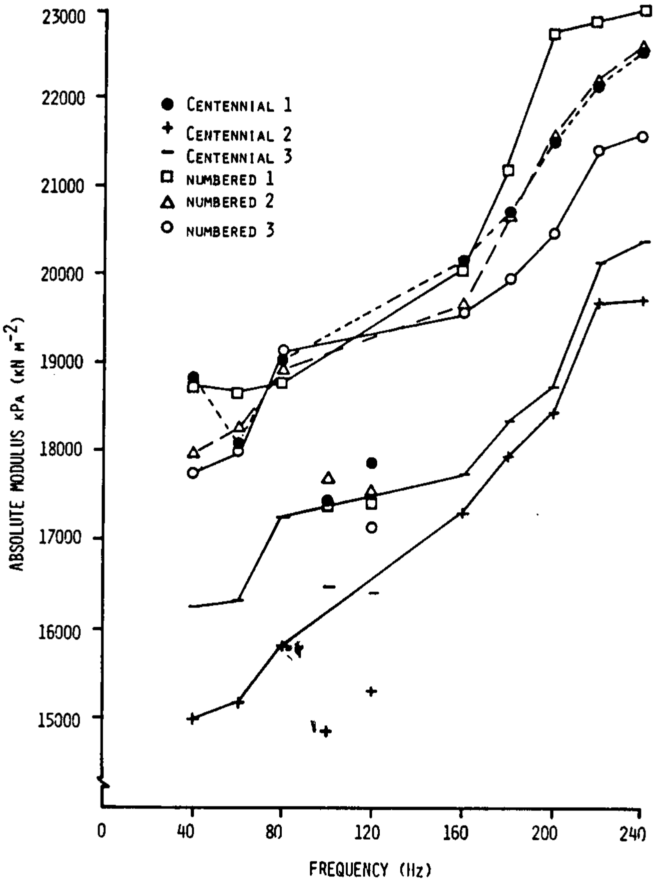

FIG. 3 Absolute value of complex modulus as a function of frequency for each cultivar and section.

TABLE 3. F-VALUE AND PROBABILITY LEVEL FOR ABSOLUTE VALUE OF COMPLEX MODULUS OF SWEET POTATOES COMPARING CULTIVAR AND SECTION

Frequency (Hz)	Between cultivar	Between sections	Cultivar section
40	15.94 * 0.022†	27.04 0.008	11.11 0.035
60	49.96 0.004	17.30 0.019	9.43 0.060
80	23.36 0.014	12.39 0.030	15.26 0.023
100	24.14 0.013	8.62 0.057	13.38 0.027
120	12.71 0.027	13.36 0.028	15.36 0.023
160	19.54 0.018	11.58 0.022	8.49 0.056
180	28.22 0.011	22.75 0.012	7.55 0.052
200	28.58 0.010	35.33 0.004	4.48 0.065
220	23.97 0.014	17.74 0.018	4.21 0.066
240	27.27 0.011	22.87 0.011	6.61 0.053

*Indicates the F-value.
†Indicates the significance level.

An analysis of variance of the absolute modulus and phase angle between the two cultivars, between sections of the cultivars and between sections within cultivar showed that phase angle was not significantly different; however, there were significant differences in absolute modulus. The results of the analysis are summarized in Table 3. There were also significant differences when comparing each section of the two cultivars by pairing sections, i.e. comparing 1st section of number and Centennial, the 2nd section of numbered and Centennial and the 3rd section of numbered and Centennial. Based on the LSD values at 5 percent, it was found that significant differences were more pronounced while comparing 2nd and 3rd sections of Centennial with those of numbered than the 1st sections of the two cultivars. Comparing the absolute modulus of specimens taken from different sections of the same cultivar showed no significant differences (at 5 percent level) for the numbered cultivar. In the case of Centennial sweet potatoes, the differences in absolute modulus were significant between 1st section and 2nd and between 1st and 3rd, but there was no significant difference between the 2nd and 3rd sections.

The absolute modulus results were pooled with fiber weight, fiber percent and moisture content to determine the correlation between these variables. The multiple and product moment correlations were calculated for all frequencies and are reported in Table 4 along with significance levels. Fiber weight and moisture content seemed to have no correlation with absolute modulus values. This observation was more or less expected since moisture content of the numbered was higher than that of Centennial but it is known (Rao et al. 1975) that numbered has a dry mouthfeel compared to Centennial. Also, actual moisture content is independent of dry-moist mouthfeel characteristics by sensory perception for sweet potatoes (Nelson 1973).

Fiber percent was found to have a good correlation with absolute modulus at all the test frequencies. The tests at frequencies of 40, 140 and 160 Hz provided the strongest correlation (correlation coefficient ⩾0.84, significant at 2 percent level). Since these results are obtained from a linear correlation, other types of correlations were tried between absolute modulus and fiber percent, *viz*, exponential, logarithmic, root and polynomial. The logarithm of percent fiber provided the best fit with a correlation coefficient of 0.91 significant at the 1 percent level for 40 Hz. In other words, an exponential increase in percent fiber would result in a linear increase in the value of absolute modulus for the cultivars tested. Some of the other frequencies also provided good correlation between absolute modulus and percent fiber.

The results of this work indicate that dynamic testing of sweet potatoes is a means of detecting differences between cultivars but care must be exercised in obtaining test specimens since some sweet potato cultivars are not homogeneous. The Centennial sweet potato has a different modulus value depending on the cross section from which the specimen is obtained while the experimental cultivar has a modulus value independent of specimen location along the axis. Specimens for comparing cultivars should be taken from the center of the sweet potato to minimize sectional differences. The percent fiber in sweet potatoes appears to be correlated to mechanical stiffness as measured by dynamic testing in spite of the sectional differences. Although results of this research indicate that an exponential or logarithmic type relationship exists between fiber percent and absolute modulus, the exact general relationship can be obtained only after future investigations including several other cultivars.

TABLE 4. CORRELATION COEFFICIENTS AND LEVELS OF SIGNIFICANCE BETWEEN ABSOLUTE MODULUS, FIBER AND MOISTURE FOR SWEET POTATOES

Frequency (Hz)	Fiber weight gm	Fiber percent (percent)	Ln fiber percent	Moisture content (percent dry basis)
40	0.57*	0.84	0.91	0.24
	0.23†	0.02	0.01	0.65
80	0.39	0.73	0.81	0.48
	0.50	0.05	0.04	0.33
120	0.49	0.74	0.80	0.30
	0.32	0.05	0.05	0.57
160	0.53	0.84	0.90	0.31
	0.28	0.02	0.02	0.56
180	0.43	0.74	0.81	0.26
	0.61	0.05	0.04	0.62
220	0.41	0.73	0.80	0.28
	0.58	0.05	0.04	0.60
240	0.45	0.73	0.79	0.23
	0.62	0.05	0.05	0.69

*Indicates correlation coefficient.
†Indicates significance level.

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