Caribbean Journal of Multidisciplinary Studies
Volume 1, No. 1, pp. 75-82, May 2022

Determining Viscoelastic Behaviour in Sweet Potato (*Ipomoea batatas* L.) Tissue

Miguel Jagessar
The University of Trinidad and Tobago
E-mail: miguel.jagessar@utt.edu.tt

Abstract

This study determined the stress relaxation behaviour of sweet potato (*Ipomoea batatas* L.) tissue samples (n=9) having 1 cm^3 volume each, taken at an approximate mid-length of a transverse section of three randomly selected root tubers locally grown in Trinidad and Tobago. A Baoshishan Digital Force Gauge HP-500N with manual force test stand and digital displacement scale was utilised for testing. A flat disc indenter, having a 15 mm diameter was used to apply a constant deformation of approximately 3.14 mm (s=0.12 mm) at a rate of loading of approximately 0.5 mm/sec. Force decay was digitally recorded over an approximate period of two minutes. The method of successive residuals was used to determine stress relaxation times (T_{rel}) for tissue samples. The stress relaxation rheological model for sweet potato tissue was determined to be a two-term exponential equation, where $\sigma(t) = 94.12\ e^{-t/1877.25} + 24.78\ e^{-t/4.07}$ (N/cm^2). Theoretical apparent Modulus of Elasticity and Shear Modulus (Poisson's Ratio, ν=0.43) was calculated to be 373.9 N/cm^2 and 91.42 N/cm^2 respectively. Thin slices of approximately 1mm of each root tuber were prepared for dehydration at 150°F for 12 hours in a convection dryer. Moisture content was determined to be 69.23% by weight.

Keywords: sweet potato, viscoelasticity, stress relaxation

***Dr Miguel Jagessar** has more than 18 years of experience in tertiary education. He has a BSc in Mechanical Engineering (UWI), an MPhil in Agricultural Engineering (UWI) and a PhD in Biomechanics (UTT in collaboration with The University of British Columbia). He is an academic, an entrepreneur, an engineer, a natural bodybuilder, and an inventor. His specialty is engineering design which spans several diverse areas such as mechanisation of food processes, biomechanics, ergonomics, computer aided engineering, design, and manufacture of exercise equipment. In December 2020, he was awarded a patent by the United States Patent and Trademark Office (USPTO) for his invention of the Therapeutic Exercise Contour Support, better known as the "TECS". Dr Jagessar is currently an Assistant Professor at The University of Trinidad and Tobago where he continues to research in the areas of Biomechanics, Food Engineering, Sport Engineering, Computer Aided Engineering and Entrepreneurship.*

Introduction

Ipomoea batatas L, commonly known as sweet potato, is an herbaceous perennial in the family Convolvulaceae grown for its edible storage roots. The sweet potato plant is a branching, creeping vine with spirally arranged lobed, heart-shaped leaves, and white or lavender flowers. Historical research establishes that sweet potato originated in the New World, either in the Central or South American lowlands. Root and tuber crops are an important staple around the world. They add variety to the diet in addition to offering numerous desirable nutritional and health benefits such as anti-oxidative, hypoglycemic and immunomodulatory activities amongst others (Chandrasekara & Kumar, 2016). The CARICOM Region has identified cassava (*Manihot esculenta*), sweet potato (*Ipomoea batatas* L.) and yam (*Dioscorea alata*) as the root and tuber crops with the highest potential for value-added development and for addressing the region's food and nutrition security needs (IICA, 2013).

Proper post-harvest techniques such as storage, handling and processing are critical for maintaining food safety and quality of derived products from root and tuber crops. During bulk storage and processing methods such as slicing, grating, and crushing or pulverising, root crops and tubers are subjected to mechanical stresses. Excessive compressive stresses can give rise to damaged biological tissue, which results in unwanted waste. Typical varieties of the common potato tuber were found to have compressive strength ranging from 1.4 to 1.77 MPa as reported by Konstankiewicz et al. (2001). Suddenly applied compressive stresses are common during handling and storage because produce is typically stored in bags or containers. The development of appropriate processing equipment and storage and handling methods require investigations into parameters such as physical properties, which include density, shape, size, and moisture content as well as rheological properties of root and tuber crops. Mechanical properties of agricultural products, being time-dependent, must logically be studied by applying the principles of rheology and viscoelasticity in which both viscous and elastic responses are taken into consideration (Mohsenin, 1986). Some examples of rheological properties are time-dependent stress and strain behaviour, creep, stress relaxation, and viscosity.

Viscoelastic materials which include biological materials combine both solid-like and liquid-like characteristics. Mechanical models consisting of springs and dashpots are used to explain and interpret the rheological behaviour of linear viscoelastic materials. The generalised Maxwell model is usually used to represent stress relaxation. It is composed of n Maxwell elements with a spring in parallel with the nth element (Mohsenin, 1986). Stress relaxation is typical viscoelastic behaviour exhibited in biological materials when a constant strain is applied and the stress decays with time. The reaction force is time dependent. Several studies (Cakir et al., 2002; Canet et al., 2009; Konstankiewicz et al., 2001) have examined the viscoelastic nature of food materials. Canet et al. (2009), for example, examined textural properties of potato tissue. Cakir et al. (2002) determined Poisson's ratio and Young's Modulus for onion varieties. Viscoelastic and mechanical behaviour have been explored for other foods such as apple and pumpkin tissue, cheddar cheese, and cassava as well as tomato juice amongst others.

At the microscopic level, Konstankiewicz et al. (2001) examined the influence of structural parameters of potato tuber tissue on its mechanical properties. They determined that the parameters of the structure, such as cell area and cell perimeter, exert a significant influence on mechanical parameters, such as strength and modulus of elasticity. This is an important finding in that the force response of biological materials will vary with a change in cell area and perimeter. It can be hypothesised that as the root tuber respires, the cell's area and perimeter change as material is lost. At the macroscopic level, limited studies on stress relaxation of sweet potato have been examined. Stress relaxation behaviour of sweet potato tissue can be important in guiding processing and handling methods in the food industry. This viscoelastic nature of locally grown sweet potato will be discussed.

Materials and Methods

A random sample of freshly harvested sweet potato was obtained from a local vendor. These were stored at a room temperature of approximately 27°C. Of the lot, three medium sized samples of similar size were selected for testing. At approximate mid-length of the root tuber Figure1, three tissue samples of 1 cm^3 (Figure 2) were carefully prepared for compression testing. A Baoshishan Digital Force Gauge HP-500N with manual force test stand and digital displacement scale was utilised for testing (Figure 3). Samples (n=9) were deformed to an average of 3.14 mm (s=0.12 mm) at an approximate rate of loading of 0.5 mm/sec. Compressive force was applied via a 15 mm diameter flat disc indenter, which was coupled to the digital force gauge. Care was taken to ensure the force was applied over the entire surface of the samples. Loading and force decay data were captured, exported to Excel and analysed. Force decay was captured over an approximate period of 2 minutes or until it was observed that the decay flatlined. Moisture content was determined by weight before and after dehydration. Thin slices of approximately 1 mm of each root tuber were prepared for dehydration at 150°F for 12 hours in a convection dryer. Moisture content was determined to be 69.23%.

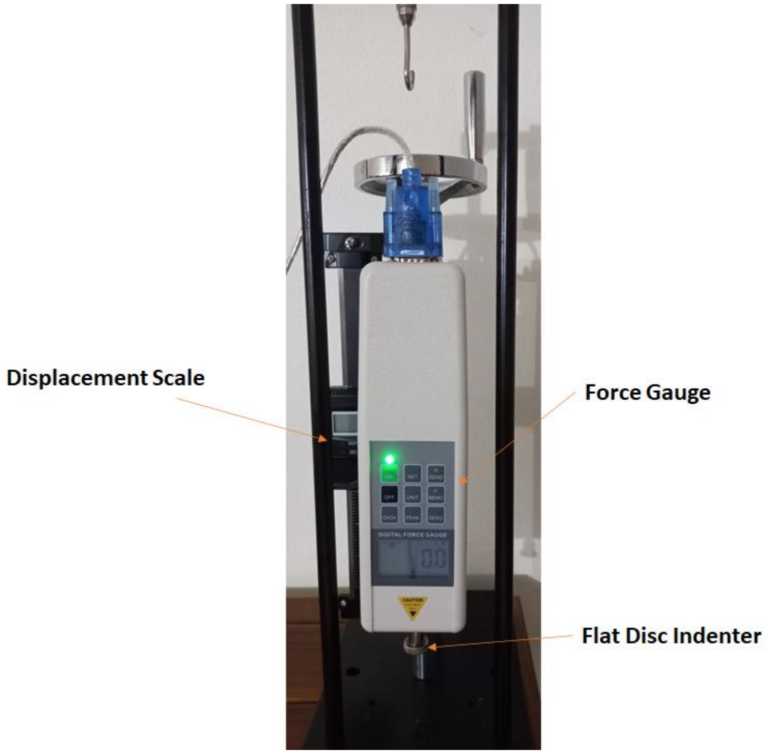
Figure 1
Slices Cut at Approximate Mid-length of Tuber for Sample Preparation

Figure 2

One cm^3 Samples for Compression Testing

Figure 3

Digital Force Gauge with Displacement Scale and 15 mm Flat Disc Indenter



Results

The method of successive residuals was used to determine stress relaxation times (T_{rel}) as illustrated in Figure 4. Assuming a constant cross-sectional area of 1 cm^2, time constants of 1st and 2nd exponential terms, T_{rel} were determined from the following equation:

$$Tr\,el = \frac{t_2 - t_1}{(ln\,\sigma_1 - ln\,\sigma_2)}$$

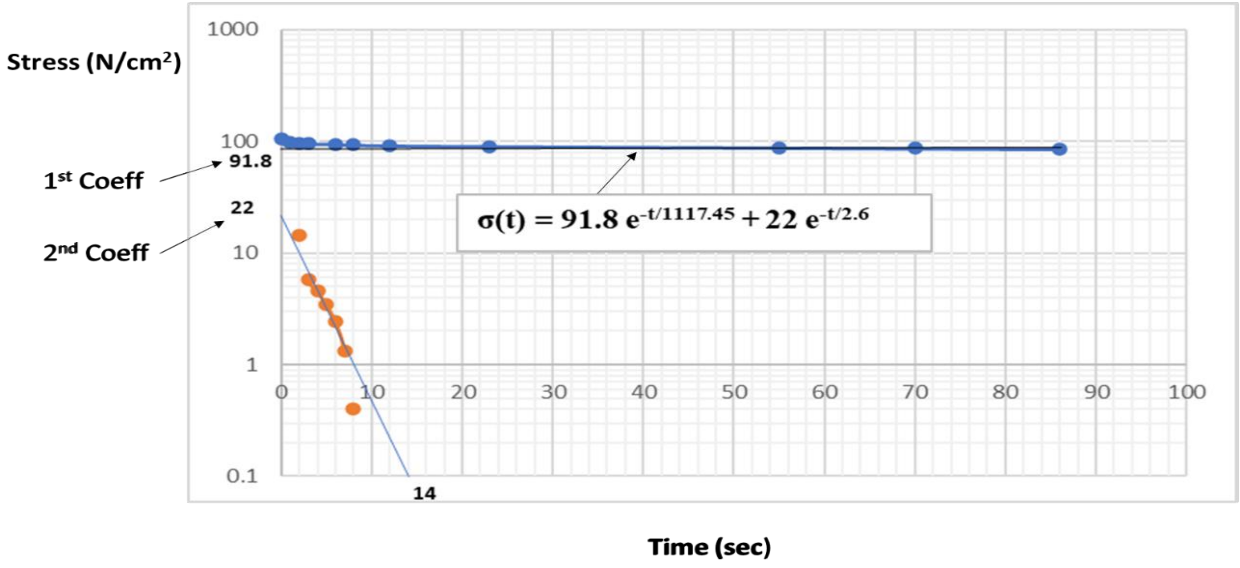
Coefficients of 1st and 2nd exponentials were attained at intercepts of 1st and 2nd tangents respectively as depicted in Figure 4.

Coefficients of exponentials and stress relaxation times were determined for all nine samples and tabulated below in Table 1. The mean of coefficients of exponentials and stress relaxation times were computed and used in the two-term exponential equation, which represents the stress relaxation rheological model for sweet potato tissue. Therefore, the two-term exponential equation was determined to be as follows:

$$\sigma(t) = 94.12\ e^{-t/1877.25} + 24.78\ e^{-t/4.07}$$

Figure 4

Force-relaxation for Sweet Potato Tissue at 69.23% Moisture Content and 31.8% Deformation, represented by a Two-term Exponential Equation



Assuming elasticity was maintained at 31.8% deformation, a theoretical initial Modulus of Elasticity at t=0 was determined as follows:

$$E = \sigma \div \varepsilon = \frac{118.9}{0.318} = 373.9\ E = \sigma \div \varepsilon = \frac{118.9}{0.318} = 373.9\ \text{N/cm}^2$$

Shear Modulus, G can also be estimated as 91.42 N/cm^2, given the following equation where Poisson’s Ratio, $= 0.43$:

$$G = \frac{E}{2(1+\nu)}$$

Table 1

Deformations, 1st and 2nd Coefficients and Stress Relaxation Times for Individual and Sample Means

Sample #	**Def (mm)**	**Coeff 1**	**Coeff 2**	**Trel 1**	**Trel 2**
1	3.28	91.8	22	1117.45	2.60
2	3.18	90	37	1609.56	3.38
3	3.11	91.25	9	1774.53	10.29
4	3.00	95	28	2293.44	3.37
5	3.18	105	27	2346.46	2.68
6	3.14	95	23	1792.71	3.31
7	2.91	89	30	1582.32	2.28
8	3.15	96	20	2355.18	5.28
9	3.34	94	27	2023.56	3.39
Mean	3.14	94.12	24.78	1877.25	4.07
Std Dev	0.12	4.48	7.30	393.96	2.34

Key: Def- deformation
Coeff 1- 1st coefficient of 1st exponential term,
Coeff 2- 2nd coefficient of 2nd exponential term,
Trel 1- stress relaxation time of 1st exponential term,
Trel 2- stress relaxation time of 2nd exponential term.

Discussion

The stress relaxation rheological model determined for sweet potato tissue was a two-term exponential equation. This was consistent with the findings of Zoerb and Hall (1960) for pea beans. There was no apparent approach to zero stress or levelling of stress. Therefore, the two-term exponential equation is indicative of two Maxwell models in parallel. Each Maxwell model comprises a dashpot and a spring in series. Timbers (1964) found a three-term exponential expression for potato tuber over a 10-minute period. As time for relaxation is extended, more terms may be needed to fully describe the rheological model. However, the contribution to the overall decay in stress becomes negligible.

Rate of loading directly affects the force response in biological material. Hence, this must be controlled and reported. Ogunnigbo et al. (2021) determined the effect of speed of loading on cassava tuber at different ages of the tuber for the bio-yield and rupture points, compressive and rupture strengths, toughness, firmness, moduli of stiffness and toughness in the transverse and longitudinal direction. They reported an increase in magnitude for each mechanical property for the increase in speed of loading from 5 to 10 mm/min. In real-life situations, stresses on tissue in processing and handling can be sudden. In this study, a rate of loading of 0.5 mm/sec was utilised. At increased rates of loading, the force response may increase. This factor is critical in the design of processing equipment. Therefore, actual rates of loading experienced during processing should be determined for the design of effective and efficient machinery.

A theoretical Modulus of Elasticity was determined based on the assumption of linear elasticity. However, biological materials exhibit nonlinear behaviour. This is due to the combination of flow and elastic elements of biological tissues. Usually, an apparent modulus is quoted for biological materials. Therefore, it is critical to determine apparent elastic behaviour from the loading-unloading test. This can assist researchers in determining the appropriate constant strain that should be applied, whilst maintaining apparent elasticity during stress relaxation tests.

Lastly, it was difficult for the investigator to prepare standardised samples with precise dimensions. This would have affected results. The design of appropriate cutting tools and dies can be of great assistance. However, the nature of stresses developed with standardised samples and whole tubers are different. Mohsenin (1986) reports that during compression testing of intact materials, such as seeds and grains, an egg, fruits and vegetables, the loading device is compressed against a convex body which results in a complex stress distribution particularly if the skin of such materials as fruits is left intact. Unpeeled tubers with their thick skin can provide added force response to compressive loads. Therefore, depending on the stage of processing or handling, mechanical and rheological testing procedures should closely match the forces applied during real-life processing and handling.

Conclusions and Recommendations

This study confirmed that sweet potato tissue exhibited stress relaxation properties which were due to viscoelastic behaviour. Rheological properties attained can be utilised for designing processing and handling equipment. For example, compressive stresses can be determined from the two-term exponential equation at specific periods of loading during handling. This can assist in setting the time response for machine control.

Fresh produce was used for testing. However, root tuber crops can be stored before handling and processing. It would be important to examine how the rheological model is affected with storage as the biological tissue respires and loses dry matter. Rheological models of standardised samples and whole root tubers must be explored. If the rheological models of prepared samples do not deviate from whole samples, then inferences can be made for applied forces on whole samples during handling and processing. However, it may be best to test whole samples, wherein the processing or handling method is mirrored with the testing method. The apparent Modulus of Elasticity should be determined from loading and unloading tests where most or all the elastic energy is recovered.

References

Cakir, E., Alayunt, F., & Ozden, K. (2002). A study on the determination of Poisson's ratio and Modulus of Elasticity of some onion varieties. *Asian Journal of Plant Sciences*, *1* (4), 376-378.

Canet, W., Fernandez, C. & Alvarez, M. D. (2009). Some objective instrumental methods for evaluating the texture of solid potato tissue. *(Solanum tuberosum L.*). *Food*, *3* (Special Issue 1), 1-12.

Chandrasekara, A. & Kumar, T. J. (2016). Roots and tuber crops as functional foods: A review on phytochemical constituents and their potential health benefits. *International Journal of Food Science*. http://dx.doi.org/10.1155/2016/3631647

IICA and CARDI. (2013). Roots and tuber processing in the Caribbean: Status and guidelines. *Inter-American Institute for Cooperation on Agriculture (IICA) and Caribbean Agricultural Research and Development Institute (CARDI).* https://www.fao.org/family-farming/detail/en/c/341812/

Konstankiewicz, K., Pawlak, K., & Zdunek, A. (2001). Influence of structural parameters of potato tuber cells on their mechanical properties. *International Agrophysics*, *15*, 243-246.

Mohsenin, N. N. (1986). *Physical properties of plant and animal materials. Vol.1 Structure, physical characteristics and mechanical properties*. Gordon and Breach, Science Publishers, Inc.

Ogunnigbo, O.C., Dare, A., Tunde, M., Olusola, O.F., & Joshua, O. (2021). A study on the influence of the loading rate and orientation on some mechanical properties of cassava tubers of different ages. *Research in Agricultural Engineering*, *67*, 34-44.

Timbers, G. E. (1964). *Some mechanical and rheological properties of the netted gem potato*. [Master of Science thesis, University of British Columbia]. https://open.library.ubc.ca/soa/cIRcle/collections/ubctheses/831/items/1.0104834

Zoerb, G. C., & Hall, C. W. (1960). Some mechanical and rheological properties of grains. *Journal of Agricultural Engineering Research*, *5*(83), 1249-1256.