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ORIGINAL RESEARCH ARTICLE

EFFECT OF LOADING RATE ON VISCOELASTIC BEHAVIOUR OF CASSAVA ROOTS (MANIHOT ESCULENTA CRANTZ) IN BENDING

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ABSTRACT

The effect of loading rate on the viscoelastic response of cassava roots, at a moisture content of 52.13 ± 5.74% (w.b), to applied bending forces was studied. Experiments were conducted using a modified Instron Testing Machine (ITM) of 1 kN capacity, to investigate both creep and stress relaxation (viscoelastic) behaviour of cassava roots (variety TME 419) when static bending forces were applied at mid-span with loading rates of 2.7, 4.2, 5.3, 7.45, and 9.9 mm min^{-1}. The creep behaviour indicated that the creep compliance may be described using a 4-element model consisting of Maxwell and Kelvin models in series. The retardation time and the instantaneous creep compliance of cassava root were found to be 25.5 s and 0.03009 $(N\ mm^{-2})^{-1}$, respectively. The stress relaxation behaviour could be represented using a 2-element Maxwell approach with a parallel-orientated spring. The relaxation times are 20 and 500 s, for the range of the loading rates. Relaxation modulus was found to be a function of the degree of loading, rising as the degree of loading intensified and decreasing with time. As the loading rate increased from 2.7 – 9.9 mm min^{-1}, the relaxation modulus increased from 1.25 – 6.89 N mm^{-2}. The result of this study gives an idea of the food product attributes vis-à-vis its strength characteristics to mechanical damage. It guides the food process engineer in estimating the impact of stress on cassava roots during postharvest operations for optimum design of efficient cassava peeling machines and product storage quality. Prospects for further work were stated.

1.0 Introduction

Cassava, a root tuber (Figure 1), is a major source of calories for 200 to 300 million people in the Tropics Egbeocha *et al*., (2016) and Asoegwu and Makanjuola, (2021) and about 25-56% of dietary calories in Southern Nigeria come from cassava (Kolawole *et al*., 2010). Globally, cassava has experienced consistent growth of well above 3% annually (FAO, 2018). The cassava output of Nigeria has increased from 58.47 MT in 2018 to 73.91 MT in 2021 with a projection of 93.60 MT in 2023 (FAOSTAT, 2019; Nnodim, 2021). Several crops require urgent engineering solutions with cassava being more prominent in Nigeria Agbetoye *et al.,* (2006), as its production and processing demand high energy input (Aniedi *et al*., 2012). Akala (2021) stated that Nigeria has the economic potential to generate 427.3 million dollars (N188 bn) from domestic value-addition to cassava and earn additional 2.98 billion dollars (₦ 1.2 t) in the export of the commodity annually.

Figure 1: Bunch of tapered cassava roots.

Early work on mechanized harvesting of the cassava root in Nigeria was undertaken by Makanjuola *et al.* (1973). Within the last decade, many cassava peeling machines have been designed and constructed (Olukunle, 2005; Bamgboye and Adebayo, 2009; Jimoh and Olukunle, 2012) as well as planting machines for cassava stems and harvesting machines for cassava roots (Oriola and Raji, 2013). What remains now is taking a critical look into important root parameters for the proper development of cassava root post-harvest machines (Morrow and Mohsenin, 2006). Nweke (2003) suggests that the development of the machines will take into consideration the physical properties of the crop. According to Ikuemonisan *et al.* (2020), the majority of cassava farmers cultivate small farm areas which are not conducive or economical for mechanization. Yet, Abass *et al.* (2014) have argued that using improved inputs alone, without mechanization, will not sufficiently boost cassava root production in Nigeria.

Cassava roots have their major demerits as their bulk and their fast rate of denaturing, poor amino-acid value and bromide presence (Ospina and Wheatley, 1992). Rapid fresh root perishability means that extreme care must be taken during harvesting to avert roots' mechanical injury. Asoegwu and Makanjuola (2021) opine that as food manufacturing becomes more automated, equipment ought to be built to minimize the effect of mechanical injury.

The behavioural response of agro-based materials to external forces is time-dependent (Ndukwe *et al*., 2021) and their characterization entails the use of viscoelasticity theories that integrate viscous and elastic reactions. Since many agricultural products behave viscoelastically under mechanical loading (Mohsenin, 1986; Rodrı´guez-Sandoval *et al.,* 2009; Herak *et al*., 2014; Ijabo *et al*., 2019), the study of the effect of loading rate on the viscoelastic properties of cassava roots would yield those important root parameters needed for developing postharvest equipment. The parameters must be stated quantifiably similar to those used to describe the engineering qualities of materials like steel, wood, and concrete (Kingsley *et al.,* 2013). Engineering computations make use of rheological representations (Gołacki *et al.,* 2007).

One of the major problems in mechanizing cassava root production, harvesting, handling, storage and processing is that the over two hundred varieties grown in the world (Egbeocha *et al.,* 2016) produce roots that have broad variants in their physical attributes. The broad array of features of cassava peels poses a challenge. Roots' maturity period (9 to 36 months) affects all cassava physical properties.

Despite the above problems, there is a scarcity of essential data relating to the root reaction to bending and other stresses that post-harvest machines may impose. Furthermore, cassava roots as living bio-materials are largely made up of polymeric constituents holding different quantities of constituents: 25-30% dry matter and 70-75% moisture (Kolawole *et al*., 2010) and behave viscoelastically in response to loads (Ijabo *et al*., 2019) with the hazards of mechanical damage (Herak *et al.,* 2014; Herak *et al.,* 2015). Determination of their elastic and viscoelastic properties would help to express their behaviour mathematically and help develop mechanical models to simulate products to obtain a better understanding of their behaviour (Saeidirad *et al.,* 2013). This will aid in the development of methods that maximize machine efficiency while maintaining the greatest level of product superiority (Velásquez et al., 2007; Kolawole *et al.,* 2007). Stress relaxation is one of the defined tests to characterize the viscoelastic properties of food and agricultural materials. Stress relaxation data are very important because they provide useful and valuable information such as fruit firmness and ripening, food processing and predicting changes in the material during mechanical loading (Saeidirad *et al.,* 2013).

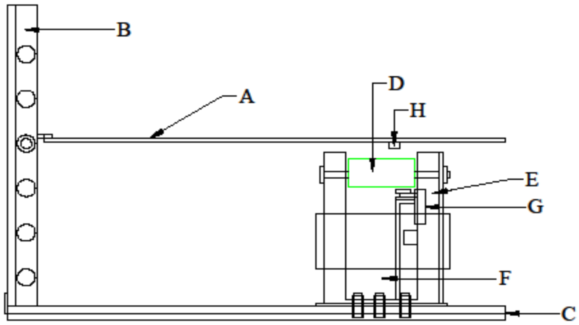
The study aims at analyzing the viscoelastic characteristics of cassava roots subjected to bending forces at mid-span, taking into consideration the tapered nature of the root. This would involve the study of the: (i) creep and stress-relaxing behaviour of the cassava roots; (ii) influence of loading rate on relaxation time, and (iii) propose rheological models to represent the creep compliance and modulus of relaxation.

2. Materıals and Methods

The cassava root samples (variety TME 419) utilized for the tests were freshly hand-harvested (from the experimental farm of the Department of Agronomy, University of Obafemi Awolowo University, Ile-Ife, Nigeria), straight, kink-free and tapered uniformly (Figure 1). The roots were about 15 months old and had a moisture content of 52.13 ± 5.74% (w.b.), measured thermo-gravimetrically, just before the tests were carried out. The cassava roots were harvested from the University Farm and the tests were conducted in the Agricultural Engineering laboratory of the Obafemi Awolowo University of Ife, Ile-Ife, Osun State, Nigeria, at a room temperature of about 27 ± 2°C. The homogeneity of the composite cassava root as well as its isotropic property in relation to its deformation from section to section was assumed.

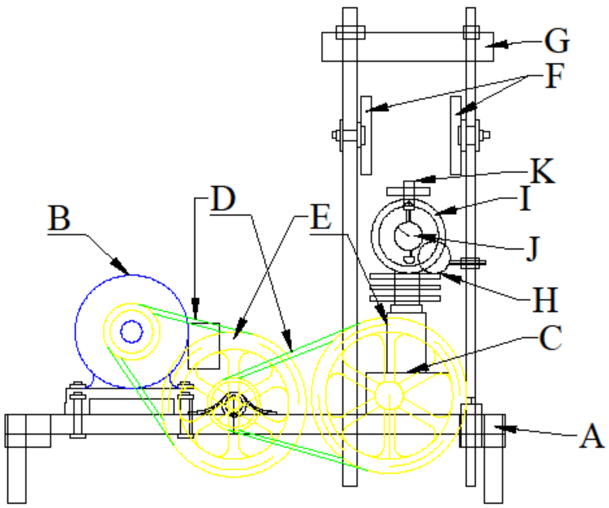
The creep equipment used by Morrow and Mohsenin (2006) was modified with rollers and adapted for simply-supported cassava roots. The cassava roots had a length for effective buckling resistance, L_{eff}, equivalent to the space in the middle of the frame wheels, 270mm. The modified creep equipment (Figure 2) was used for the bending creep test where a dead load was placed at the center of the cassava root sample, and structural deformations that changed over time were noted using dial gauges.

For the stress relaxation in the bending test, the Instron compression testing machine was fitted with rollers (span 270mm, out-to-out) and the application of a center load at a constant loading rate was from a variable speed motor through a suitably designed belt drive (Figure 3). The Instron compressive machine was driven by a 3 hp variable speed electric motor through a suitably designed belt drive. The modified universal ITM (3400 Series, 1 kN capacity) had a load measurement accuracy of ± 0.5% of reading down to 1/200th of load cell capacity, and a displacement accuracy of ± 0.02mm or 0.15% of displacement. A predictive analysis was carried out to determine the mean compliances of the groups of the studied cassava roots under static bending force. A plot of experimental and predicted was given to ascertain the degree of correlation of the model parameters.



Legend for creep Equipment	
A	Lever arm
B	Lever arm support
C	Metal base
D	Roller
E	Roller stand
F	Dial gauge stand
G	Dial gauge
H	Nut(for point loading)

Figure 2: Schematics of the static loading creep equipment



Legend for Stress Relaxation Equipment	
A	Metal base
B	Variable speed motor
C	Instron compression testing machine
D	V-Belt
E	Speed reduction pulley
F	Roller
G	Support frame
H	Dial guage displacement
I	Loading ring
J	Dial guage
K	Nut(for point loading)

Figure 3: Stress relaxation equipment.

2.1 Theoretical Considerations

Two types of tests are typically used to establish the force-deformation association of agricultural goods (Mohan, 1984; Chen and Sun, 1991; Lu and Abbot, 2004). The first type includes tests in which the studied sample is subjected to deformation forces at regular intervals of time and the equation governing the corresponding elastic problem is as expressed in Equation (1):

$$P(t) = k.E(t) \qquad (1)$$

Where P(t) is relaxation force (N) at the time, t s; E(t) is relaxation modulus (N mm^{-2}) at the time, t (s). Because biomaterials do not exhibit the ideal Hookean behaviour, there must be some make-up (k-factor) at play to make for creep and stress relaxation. The k-factor is a characteristic of the specimen's structural variables (a conversion factor). Uniaxial loading and testing on specimens with a uniform cross-section region are two examples of this first type. Evaluation of rheological properties determined from stress relaxation and creep tests performed on agricultural materials provides information on viscoelasticity that correlates these properties with end-use products (Figueroa *et al*., 2013). The creep phenomenon is used to describe the continued deformation of a viscoelastic material after the load has reached a constant state. Under constant deformation, stress relaxation describes the continued reduction in stress inside a viscoelastic material (Yang, 2018). The effect of fibers on the viscoelastic properties of short-fibre composites (using rice husk, palm kernel shell, and periwinkle) is difficult to understand. However, these properties are extremely important in load-bearing applications where there is the potential for creep or stress relaxation, or where the composites are exposed to any sort of dynamic loading, and hence it is important to be able to predict the influence of fibre reinforcement on the viscoelasticity (Obaid *et al*., 2017). This second type is not considered in this study. In this study, it is considered that the harvestability of cassava roots using machines may make them more prone to bending action. In this case, compression, shear or impact testing would not be applicable. For curved beams having uni-axial modulus, a binomial approximation is used for the elastic bending formula. Schroder *et al.* (2017) developed a mathematical expression (Equation 2) for the function of the geometric parameters:

$$\mathrm{k} = \frac{\mathrm{Y}}{8\mathrm{HL}^3} = \frac{\mathrm{P}}{\mathrm{E}\pi} \tag{2}$$

where:

$$\mathrm{H} = 2\left[\frac{\mathrm{U}}{\mathrm{d}_2^4} + \frac{\mathrm{V}}{\mathrm{d}_1^4}\right] - \left[\frac{\mathrm{Z}}{\mathrm{d}_2^4} + \frac{\mathrm{Q}}{\mathrm{d}_1^4}\right]$$

$$\mathrm{U} = \frac{1}{48} + \frac{\mathrm{a}}{48} + \frac{\mathrm{a}^2}{64} + \frac{\mathrm{a}^3}{96} + \frac{5\mathrm{a}^4}{767} + \frac{\mathrm{a}^5}{256}$$

$$\mathrm{V} = \frac{1}{48} - \frac{\mathrm{b}}{48} + \frac{\mathrm{b}^2}{64} - \frac{\mathrm{b}^3}{96} + \frac{5\mathrm{b}^4}{767} - \frac{\mathrm{b}^5}{256}$$

$$\mathrm{Z} = \frac{1}{8} + \frac{\mathrm{a}}{6} + \frac{5\mathrm{a}^2}{32} + \frac{\mathrm{a}^3}{8} + \frac{35\mathrm{a}^4}{384} + \frac{\mathrm{a}^5}{16}$$

$$\mathrm{Q} = \frac{1}{8} - \frac{\mathrm{b}}{6} + \frac{5\mathrm{a}^2}{32} - \frac{\mathrm{b}^3}{8} + \frac{35\mathrm{b}^4}{384} + \frac{\mathrm{b}^5}{16}$$

and

$$\mathrm{a} = \frac{\mathrm{d}_2 - \mathrm{d}_1}{\mathrm{d}_2}; \mathrm{b} = \frac{\mathrm{d}_2 - \mathrm{d}_1}{\mathrm{d}_1}$$

This expression (Equation 2) was used in calculating the parameters of the studied cassava root samples. For this study, the following numerical values for the cassava roots were used: d_l = 49.41 mm, d_2 = 60.29 mm, a = 0.18, b = 0.22, U = 0.0251, V = 0.0169, Z = 0.1608, Q = 0.0947, H = -1.8592 x 10^{-8} mm^{-4}, mean k = 2.00 mm^2, L = 270 mm.

In creep loading, a constant stress σ, usually applied at time zero, causes a time-dependent strain ε(*t*) where the time = *t*. Compliance is defined as the ratio of strain to stress. The creep compliance *J* is defined by Equation (3).

$$J(\sigma, t) = \frac{\varepsilon t}{\sigma} \tag{3}$$

When the strains are small, the creep compliance function becomes independent of stress *σ*; the creep strain, for a linear viscoelastic solid, is given by Equation (4).

$$\varepsilon(t) = \sigma J(t) \tag{4}$$

ε(t)=σJ(t)

According to Mills (2007), it is often easier to measure the creep compliance function *J* (*t*) than the relaxation modulus *E* (*t*), because it is easier to apply a constant load than a constant strain in a fraction of a second. Linear viscoelasticity theory can relate *E* (*t*) to *J* (*t*). Unless the polymer is near a transition temperature, the creep compliance is a slowly varying function of time, so creep compliance may be given as Equation (5).

$$J(t) \cong \frac{1}{E(t)} \tag{5}$$

Creep and stress relaxation are two distinct viscoelastic behaviours that bio-materials can exhibit. The functions relaxation modulus *G* and creep compliance *J* are two other important functions in the field of rheology. For creep, the application of a constant load (or uniform force) and the resultant time-dependent deformation are studied. The data are plotted in terms of shear stress compliance versus time (Steffe, 1996; Nishinari, 2004). This behaviour is represented by the 4-element model (Barnes, 2000; Zhiyuan *et al.*, 2021) (Figure 4) expressed by the following Equations (6) and (7):

$$\varepsilon(t) = \frac{\sigma}{E_1} + \frac{\sigma}{E_2}\left(1 - e^{-\frac{t}{\alpha}}\right) + \frac{\sigma}{\gamma_1}t \quad (6)$$

Dividing Equation 6 by stress, σ, the creep compliance expression is estimated as Equation (7):

$$J(t) = J_0 + J\left(1 - e^{-\frac{t}{\propto}}\right) + \frac{t}{\gamma_1} \quad (7)$$

If a material behaves as is defined by Equations (3) to (7) its behaviour can be described as linear viscoelastic (Gradin *et al.,* 1989).

In a stress relaxation experiment, the cassava root is subjected to a constant strain at time zero, and the resultant stress is measured as a function of time. The force (stress) necessary to maintain this initial deformation is measured per interval of time and represented in terms of the shear stress relaxation modulus (Wu and Abbott, 2002; Rajabipour *et al.*, 2004; Hassan *et al.*, 2005). The decay of this constant force, a natural consequence of the material structure, is called stress relaxation - a time-dependent reduction of the stress in materials under constant strain (Figure 4). Of the three ways generally used to keep strain constant, straining a stiff spring element (large force per deformation) in series with the sample (low force/deformation), was used (Ferry, 1999).

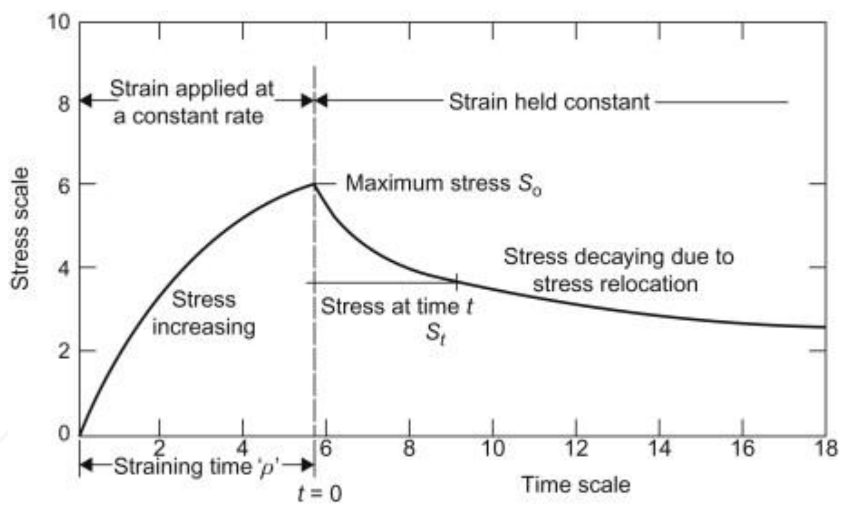


Figure 4: Stress–time curve. (Source: Ashter, 2014).

The stress relaxation behaviour can be characterized by a universal Maxwell representation, comprising numerous Maxwell components arranged parallel-wise (Ahmed and Ramaswamy, 2006; Golacki and Stropek, 2001). The mechanical reactions of biomaterials may be predicted and interpreted using viscoelastic relaxation patterns. These patterns must normally be determined from viscoelastic relaxation studies for bio-based materials (Babaei *et al.,* 2016). A typical stress-time curve is given in Figure 4.

Using the correspondence principles (Saeidirad *et al.*, 2013), and the superposition principles, researchers have evolved a mathematical expression for the solution of the viscoelastic bending equation in terms of relaxation modulus (Blahovec, 2001; Herak *et al*., 2015; Alvis *et al.,* 2010). The relaxation modulus, which is amongst the most vital viscoelastic parameters, is generally represented by a proxy or Dirichlet power series. Relaxation modulus, E(t) is a property of material viscoelasticity that describes how stress relaxes over time (t). To analyze and design material-handling equipment, it is critical to precisely model stress relaxation and viscoelastic deformation in bio-products (Xu and Engquist, 2018) and substitute the outcomes of the numerical test into the exponential expression of time as proposed by Kingsley *et al.* (2013); expressed by Equation (8) as:

$$E(\mathrm{t}) = \frac{8\mathrm{HL}^3}{\mathrm{Y}}\mathrm{P}(\mathrm{t}) = \mathrm{E}_\infty + \mathrm{E}_1 \mathrm{e}^{-\frac{\mathrm{t}}{\propto}} \quad (8)$$

Relaxation modulus, E(t) is a characteristic of material viscoelasticity (N mm^{-2}) as used to describe the stress relaxation of materials with time, t (s). It is important to accurately simulate the stress relaxation and viscoelastic deformation of cassava roots in order to evaluate and design materials.

2.2 Methods

Two test methods were used in this work: the static bending creep test and the stress relaxation test. The creep test in this work used a fixed load (or stress) at a constant temperature and measured the increase in the stain as a function of time (Woodford, 2000). Maintaining a constant temperature during a creep test is critical due to the possible thermal expansion or shrinkage of the material.

2.2.1 Static bending creep test

The objective of a creep test is to predict the life span of a material under certain operating conditions. Creep strength provides an indication of the service life of a material under specified operating conditions. It provides the mechanical stress value that will cause the material to fail, while held at constant temperature for a certain amount of time (Jalali *et al*., 2019). In the creep test, loads below those necessary to cause instantaneous fracture are applied to the material, and the deformation over some time (creep strain) under constant load is measured, usually with an extensometer or strain gauge (Hofer and Rao, 1977). The creep test, using the 3-point bending beam is a standard test method (RIHMT, 2011), for determining the viscoelastic parameters of materials, which are commonly used to evaluate the creep properties of materials (Sun *et al*., 2019). On the rollers of the modified creep equipment (Figure 2), cassava roots of different diameters: 40 ± 1.2 ≤ d ≤ 60 ± 2.3 mm) were each positioned in the most stable natural position, at which it did not roll. With the help of a dead weight of 0.5 kg on the lever arm, the root was deformed at mid-span. For a 3-point bending test of the tapered cassava root length L supported on the reaction point rollers, the cassava root has d_1 and d_2 diameters at the reaction points and diameter d at the load point. The cassava root is assumed homogenous and isotropic. When bending occurs, the surface where the force is applied experiences compression forces while the opposite surface experiences tensile forces making this measure most suited to isotropic materials (Asoegwu and Makanjuola, 2021). Deformations were measured at 5 seconds intervals using a dial gauge. At the end of 180 seconds, the load was removed and the recovered deformations were recorded at 5 seconds intervals for 90 seconds when deformation ceased to decrease. These tests were repeated with a dead load of 1 kg on the 75 root samples in each of the groups of cassava roots with mean diameters of 40 ± 1.2 mm, 50 ± 0.7 mm, and 60 ± 2.3 mm, respectively. The sample stress/strain graph is given in Figure 5.

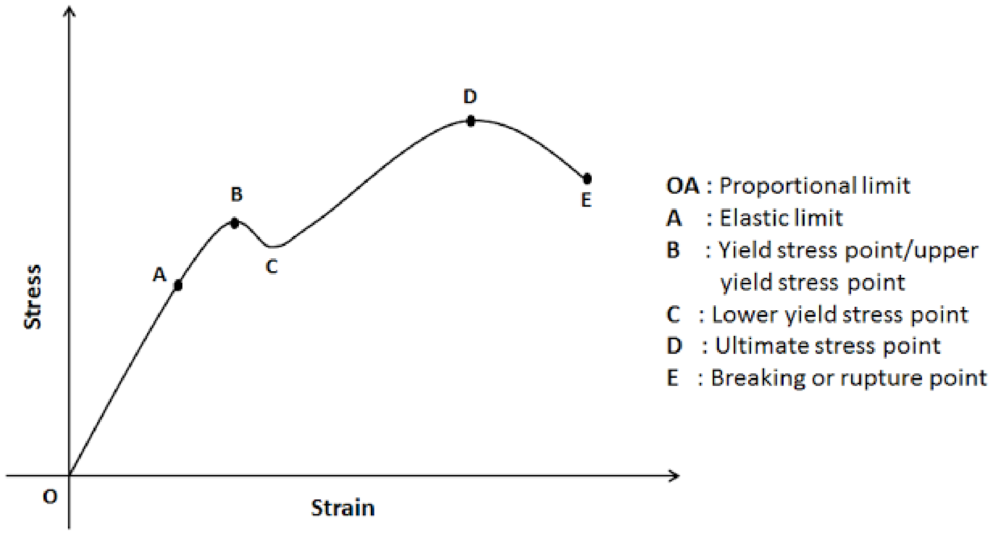


Figure 5: Sample of a stress/strain plot.

The compliance (strain/stress) for each time interval was estimated by the following Equations (9) and (10) (Herak *et al.*, 2015):

$$\varepsilon_{max} = \frac{3(d_1+d_2)y}{L^2} \tag{9}$$

$$\varepsilon_{max} = \frac{64PL}{(d_1+d_2)^3} \tag{10}$$

The creep compliance for each time interval of 5 to 180 s was obtained for each load. The mean was calculated and plotted against time. A burger model with 4 elements was used for the creep test.

2.2.2 Stress relaxation tests

With the help of the Instron equipment, Figure 3, each cassava root in another set of 50 roots (tail = d_l = 50 ± 2.4 mm; butt or proximate = d_2 = 60 ± 1.8 mm) placed in its most stable position on the rollers, was strained to a constant deformation for 30 seconds at a constant loading rate while the force and the deflection were recorded at 5 seconds intervals. Then the time-dependent decrease in force under a constant strain was recorded at 5 seconds intervals until the relaxation force became a constant value. The experiments were carried out on a total of 50 specimens at each of the five loading rates (2.7, 4.2, 5.3, 7.45, and 9.9 mm min^{-1}) applied mid-span, at moisture contents measured just before the tests. Relaxation time was determined, by measuring the time it takes for stress to decrease to stress/2.718. In other words, it is the time in which the relaxation process carries the system a fraction of 1/e toward the equilibrium position. Relaxation time was determined for each loading rate while the relaxation modulus was calculated using Equation (8). The relationship between E and η is given by the equation $\tau = \eta / E$ where τ is known as the relaxation time for a mechanical system exposed to controlled stress. A generalized Maxwell model has frequently been used to interpret stress relaxation data of linear viscoelastic material. The model contains n Maxwell elements and a spring in parallel; each element of the Maxwell model consists of a dashpot and a spring in series (Watts and Bilanski, 1991; Gorji-Chakespari, 2010). The graph of the relaxation modulus versus time was plotted.

2.2.3 Analysis of results

Relevant statistics were used to analyze the data obtained and some were presented in figures and equations. Experimental results on stress relaxation tests were fitted into the time-exponential equation. The graphs of the creep and creep recovery were plotted against time. The experimental and predicted results of the creep compliance were plotted on a graph. The graphs of stress relaxation versus time were also plotted.

3. Results and Discussion

Figure 6a shows the creep and recovery curves for different diameters when loaded with 0.5 kg. A considerable difference exists at a 5% probability level amongst the strains experienced by the specimens under varying stresses occasioned by diameter differences. The curves were similar to those loaded with 1.0 kg (Figure 6b). When loaded with 0.5 kg for 180 s, the stress on the different-sized cassava roots ranged from 0.0231 to 0.0523 Nmm^{-2}, giving a maximum strain range of 1.0 to 2.0×10^{-3} mm mm^{-1}. With the 1.0 kg load for 180 s, the constant stress ranged from 0.0323 to 0.1039 Nmm^{-2} giving the maximum strain attained ranging from 2.6 to 4.4×10^{-3} mm mm^{-1}. The strain-time curves (Figures 6a and 6b) were similar to those obtained by Zhiyuan *et al.* (2021). Cassava root diameters affected the creep and recovery curves as shown in Figures 6a and 6b.

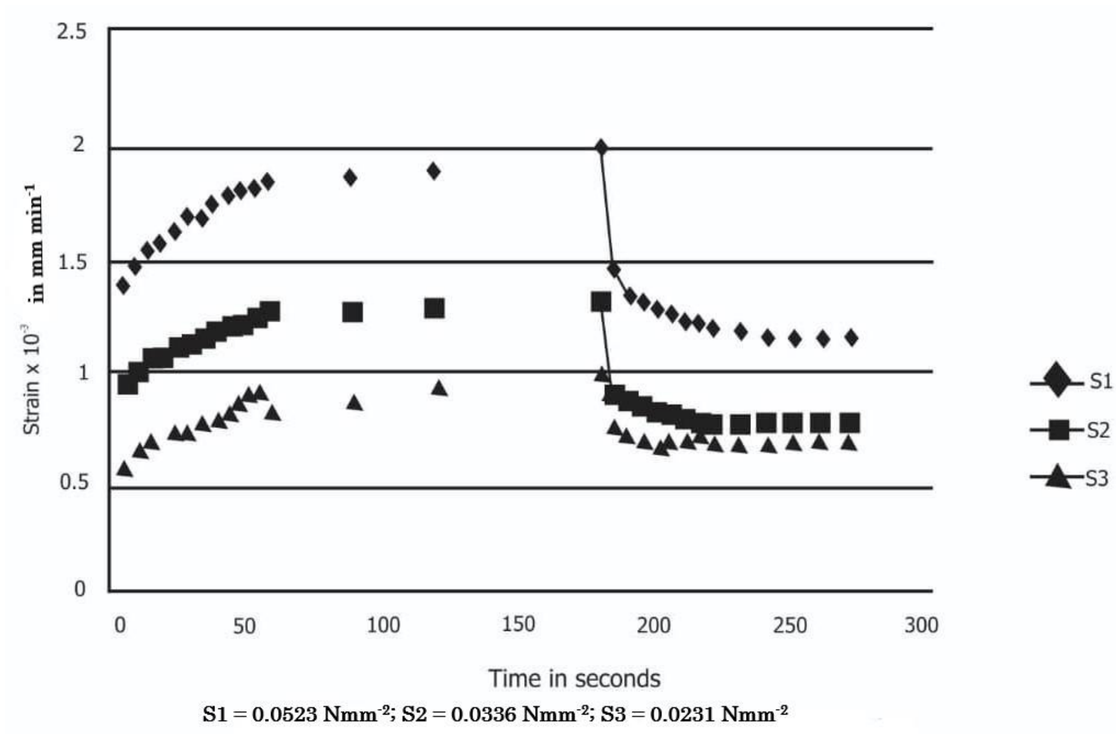


Figure 6a: Creep curves, when loaded with 0.5 kg for 180 s and strain, recovered.

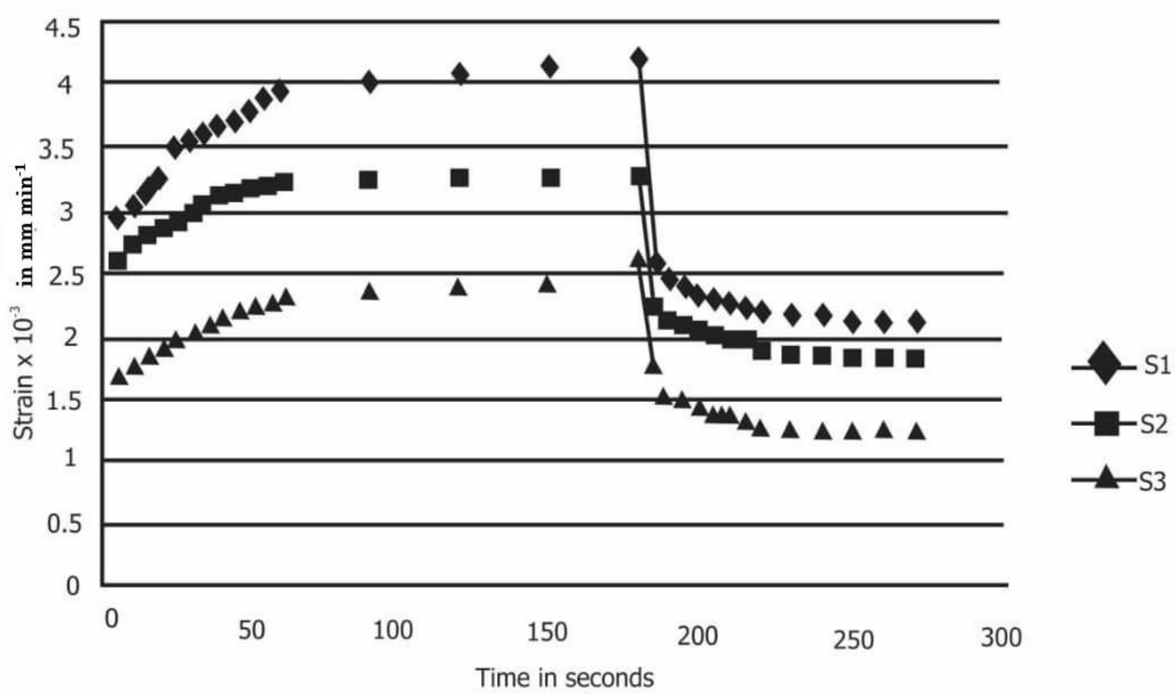


Figure 6b: Creep curves when loaded with 1.0 kg for 180 s and strain recovered for 90 s.

However, it was observed that no significant difference between the mean compliances of the groups of cassava roots studied exists. The mean compliance curves of the experimental and predicted values for cassava roots under static bending force are shown in Figure 7.

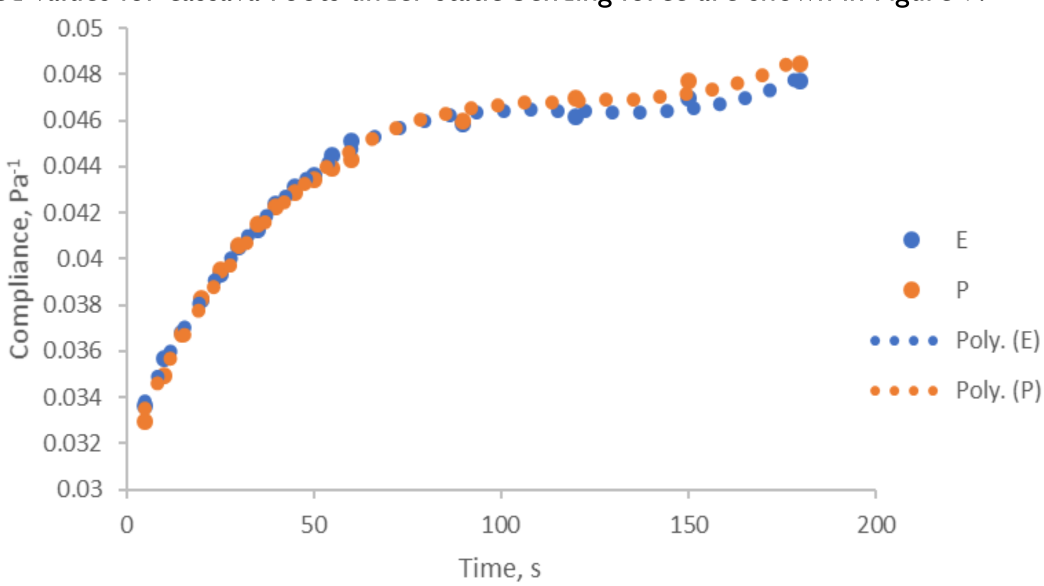


Figure 7: Mean creep compliance versus time relations for cassava roots in bending (P = predicted; E = experimental).

From Figure 7, the compliance relationship with time is a 3-order polynomial function represented by Equations (11) and (12), while the plot of the experimental and the predicted creep compliance (Figure 8) has a linear trend (Eq.13).

$$Creep_{expt} = 8E - 09t^3 - 3E - 06t^2 + 0.0004t + 0.0321 \qquad R^2 = 0.9969 \qquad (11)$$

$$Creep_{pred} = 8E - 09t^3 - 3E - 06t^2 + 0.0004t + 0.0318 \quad R^2 = 0.9942 \tag{12}$$

$$Creep_{pred} = 1.0629Creep_{expt} - 0.0027 \quad R^2 = 0.9908 \tag{13}$$

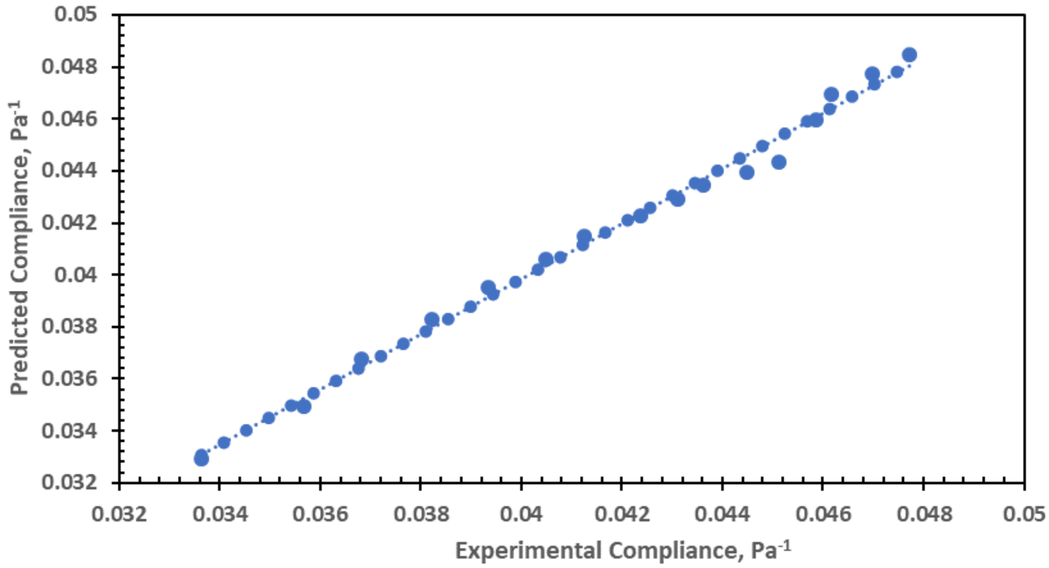


Figure 8: Linear graph of the predicted and experimental values of compliance.

The R^2 of Equations (11) to (13) are more than 0.99 showing that over 99% of the dependent variable are explained by the independent variables which indicate the goodness of fit (Nwakuba *et al.,* 2018; Uzoma *et al.,* 2020; Nwakuba *et al*., 2021). The regression of the experimental against the predicted compliance values exhibited a high linear coefficient of determination, R^2 = 0.9908 which indicates that about 99.08% of the experimental inconsistency was explained by the 4-element model of the exponential function (Equation 8). Sun *et al.* (2019) agree that R^2 values above 99.5% signify that the model properly represents viscoelasticity.

When the time-dependent strain is divided by the fixed stress, a unique creep compliance curve results; that is, at each time there is only one value for this ratio, which is compliance. (Ngai *et al.,* 2013). The compliance curve for cassava root is similar to that found by Gorji-Chakespari *et al.* (2010) for two Iranian apple varieties. The compliance expression given as Equation (7) is predicted by a 4-component representation involving one Maxwell and one Kelvin representation in sequence connection, called the Burgers model (Figure 9) (Yang *et al*., 2006). The Burgers model is a common model that can describe material viscoelastic behaviour (Zhang *et al*., 2015). Substituting the statistically obtained results in Equation (7) above yields Equation (14).

$$\mathrm{J(t)} = 03009 + 0.01419\left(1 - \mathrm{e}^{-\frac{\mathrm{t}}{25.5}}\right) + \frac{\mathrm{t}}{43000} \tag{14}$$

From Equation (14) the retardation time and the instantaneous creep compliance of cassava root were found to be 25.5 seconds and 0.03009 $(\mathrm{Nmm}^{-2})^{-1}$, respectively. According to Gorji-Chakespari *et al.* (2010), the retardation time was 15 seconds for the *Shafi Abadi* variety; and for *Golab, Kohanz* was 12 seconds. For fresh and cooked potato tissues, Alvarez *et al.* (1998) determined retardation times as 136.58 and 54.89 seconds, respectively. Because the retardation period/impedance is an essential consideration in preservation duration (in storage), then fresh potato has a longer storage duration than apple and cassava root.

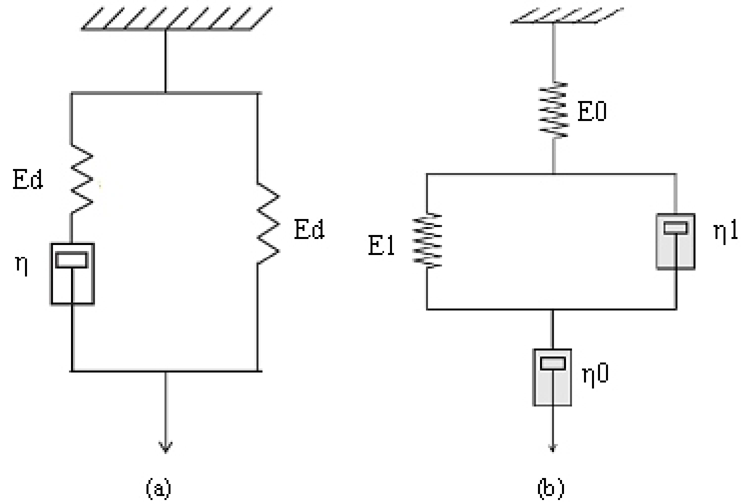


Figure 9: Generalized Maxwell model with 3 elements for stress relaxation test (a) and Burger model with 4 elements for creep test (b), (Gorji-Chakespari *et al.,* 2010; Dzadz *et al.,* 2015; Dong *et al.*, 2021).

Experimental results on stress relaxation tests were built into the time-exponential equation, Equation (8), as proposed by Saeidirad *et al.* (2013) and Kingsley *et al.* (2013). The equation coefficients, obtained from the statistical analysis, reveal that a two-component Maxwell representation with a parallel-array spring may be used to represent the stress relaxation response of cassava root. The relaxation times are 20 and 500 s, respectively. This is shown in Equations (15a) to (15e) for the different loading rates (R_1 to R_5) which significantly ($P \leq 0.05$) affected the relaxation modulus, E(t).

$$E(t) = 3.00 + 2.064e^{-0.05t} + 1.285e^{-0.002t} \ldots \text{for } R_1 = 2.7 \text{ mm min}^{-1} \quad (15a)$$

$$E(t) = 3.75 + 1.007e^{-0.05t} + 2.502e^{-0.002t} \ldots \text{for } R_2 = 4.2 \text{ mm min}^{-1} \quad (15b)$$

$$E(t) = 7.13 + 3.621e^{-0.05t} + 1.285e^{-0.002t} \ldots \text{for } R_3 = 5.3 \text{ mm min}^{-1} \quad (15c)$$

$$E(t) = 14.25 + 6.523e^{-0.05t} + 7.320^{-0.002t} \ldots \text{for } R_4 = 7.45 \text{ mm min}^{-1} \quad (15d)$$

$$E(t) = 16.75 + 7.535e^{-0.05t} + 8.179e^{-0.002t} \ldots \text{for } R_5 = 9.9 \text{ mm min}^{-1} \quad (15e)$$

Figure 10 illustrates the influence of the rate of loading on the relaxation time and relaxation modulus of cassava root in bending. Whereas relaxation modulus increased with an increase in loading rate, relaxation time decreased with an increased loading rate. Similar results have been reported on some other agricultural products, e.g., fruit tissue (Sakurai and Nevins, 1992); tomato skin (Rajabipour *et al.*, 2004); dates (Hassan *et al.,* 2005); carrot root (Gołacki and Stropek, 2001). The curve has a pattern that is comparable to that of a viscoelastic substance.

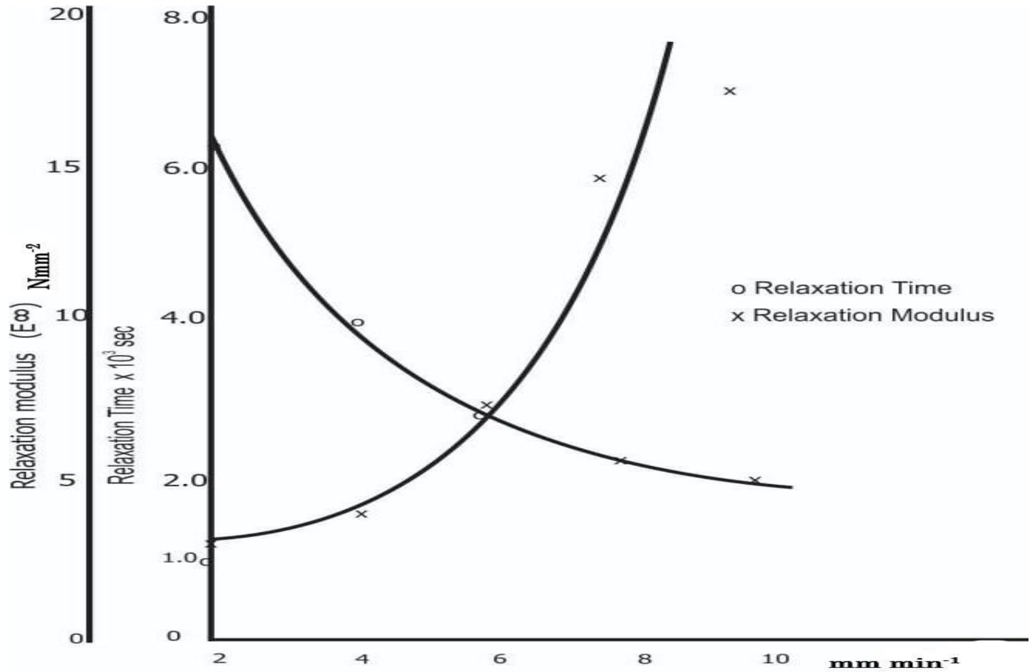


Figure 10: Influence of degree of loading on relaxation period and relaxation modulus.

The effect of time on the relaxation modulus of cassava root (Figure 11) indicates that the relaxation modulus decreased with time. This also is true for viscoelastic materials such as potato tuber, boiled potatoes, wheat dough, and osmotic drying of apples and bananas (Blahovec, 2003; Kaur et *al.,* 2002; Li *et al.,* 2003; Safari-Ardi and Phan-Thien, 1998; Krokida *et al.,* 2000). Even for non-agricultural materials such as high-viscosity asphalt sand (HVAS), Sun *et al.* (2019) found the relaxation modulus to decrease with time.

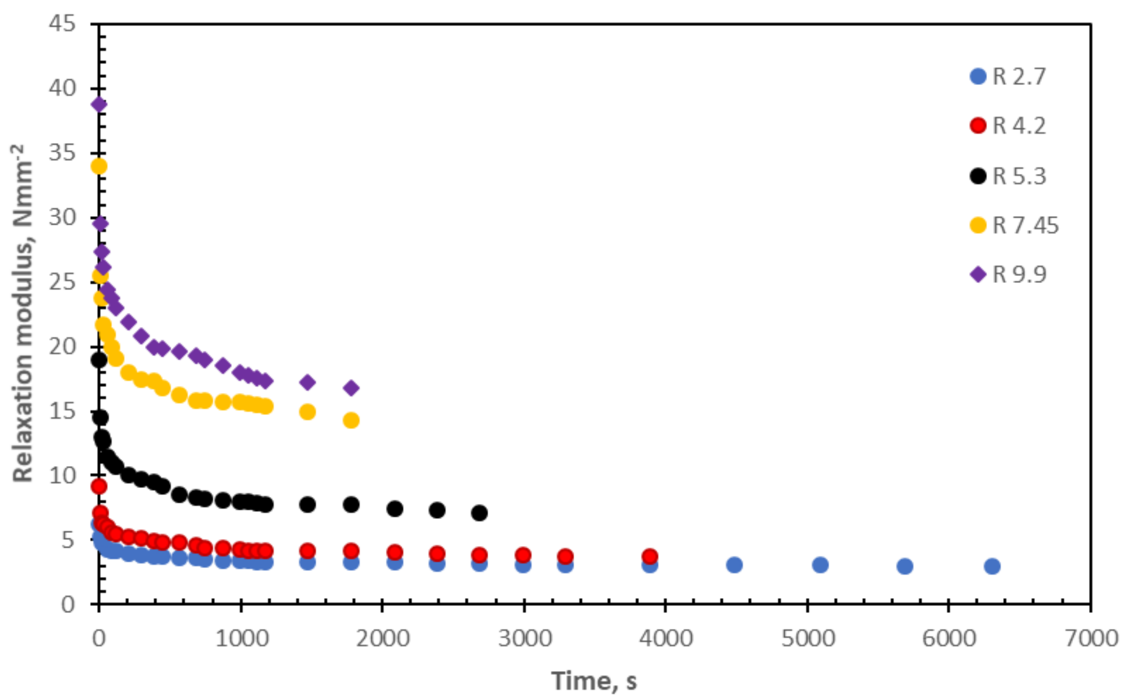


Figure 11: Relaxation modulus of cassava roots in bending due to varying loading rates (R, mm/min).

The relaxation times for Shafi Abadi and Golab Kohanz types of Iranian apples are 90 and 78 s, respectively (Gorji-Chakespari *et al.*, 2010). Wang (2003) discovered that the relaxation time for a pear is 30.33 s, which might be due to the pear's soft textural feature when compared to an apple. In this current study, the relaxation time for cassava root is 500 s showing that the cassava root is harder than both apple and pear. Also, Figure 11 shows that the relaxation modulus increased with increasing loading rate for cassava roots in bending (McClung et al., 2017).

3.1 Engineering Implication of the Results

Creep compliance is obtained when a load deforms a viscoelastic material and the deformation as a function of time is studied. The knowledge of these product features aids the design engineer to analyze the impact of stress on the food product during harvesting, storage or transportation (Figueroa *et al*., 2013; Li *et al.,* 2022). For example, when cassava roots are harvested, it must be known how high they may be heaped without injuring the ones underneath or causing mechanical hysteresis. The knowledge of cassava roots' response to various forms of applied forces is a foundation of an account of material parameters often employed to estimate their resistive ability to physical injury, end-use, and preservation quality. Linear viscoelastic equations can be used to explain several phenomena found in many moisture-rich food substances (Yang, 2018).

The relaxation modulus is a characteristic of a viscoelastic material's tendency for stresses from a fixed strain to decrease with time. This material property helps the engineer to study the influence of deformation on food products in the course of collision, processing, and packing as induced by time (Xu and Engquist, 2018). Being the equivalent of Young's modulus, the relaxation modulus is used for estimations of crack factors and stress at the yield point of food products.

Products are exposed to a wide spectrum of impact loads as food production gets increasingly industrialized. The machinery must be built to keep the impact to a minimum so that no harm is done (Asoegwu and Makanjuola, 2021). Therefore, the allowable loading levels should be determined. In addition to elastic characteristics, creep or stress relaxation gives textural information.

4. Conclusıon

Cassava roots having a moisture content of about 52.13% (w.b.) behave viscoelastically when subjected to bending forces arising from 0.5 to 1.0 kg static load or 2.0 to 10.0 mm min^{-1} loading rates. Their creep behaviour in bending may be described by a 4-component function made up of one Maxwell and one Kevin model in series. The rheology of such material is mathematically expressed as:

$$J(t) - J_0 + J(1 - e^{-\frac{t}{\propto}}) + \frac{t}{\gamma_1}$$

The generalized Maxwell model with 3 elements was used to describe stress relaxation while the Burger model with 4 elements was used for the creep behaviour in bending. The equation is given thus:

$$E(t) = E_\infty + E_1 e^{\frac{-t}{\propto_1}} + E_2 e^{\frac{-t}{\propto_2}}$$

The development of postharvest equipment requires root parameters that can only be obtained via research on the impact of loading rate on the viscoelastic properties of cassava roots. From this study, therefore, the rate of loading affected both relaxation modulus and relaxation time. Relaxation modulus decreased with an increase in time and increased with an increase in loading rate. This is in agreement with the general viscoelastic behaviour of plant-based materials. Relaxation time always decreases with increasing loading rate.

It might be necessary to point out that further research is required at other maturity ages, greater rates of loading, higher static loads, other levels of moisture content and most probably other temperatures before deductions as to the relative importance of any of these variables can be stated. Similarly, when conducting tests, it's important to remember that all applied loads have to be sufficiently mild not to surpass the root's bio-yield threshold.

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Notation

$\varepsilon(t)$	Strain
σ	stress (N mm^{-2})
E_1	instantaneous elastic modulus (N mm^{-2})
E_2	retarded elastic modulus (N mm^{-2})
$\propto_1;\ \propto_2 = \frac{\gamma_1}{E_1} = \frac{\gamma_2}{E_2}$	retardation time (sec)
$\gamma_1;\ \gamma_2$	viscosity coefficient (Ns mm^{-2})
J(t)	creep compliance (I Nm^{-2})$^{-1}$
E	exponential logarithm.
E(t)	relaxation modulus (N mm^{-2}) at the time, t (s).
E_∞	relaxation modulus (N mm^{-2}) after a very long time.
E_i	relaxation modulus of ith Maxwell element.
n	Number n, and presence of time (s) of ith Maxwell element.
d_i	tail end diameter (mm).
d_2	proximal end diameter (mm).
Y	deflection (mm); constant deflection for stress relaxation (mm).
L	span (mm).
P	loading force (N).
P(t)	relaxation force (N) at the time, t (s).
K	The function of moisture content of the geometric parameters of the specimen