MODELING THE BREAKING CHARACTERISTICS OF CASSAVA ROOT LENGTHS UNDER CONTINUOUS BENDING LOADS

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ABSTRACT
This paper discusses the breaking characteristics of cassava root lengths at 52.13 + 5.74% moisture content (wet basis) as a step in understanding the behavior of the roots to applied forces especially during harvesting, processing and storage. The effects of different loading rates 2.0, 4.0, 6.0, 8.0, 10.0 mm/min and root diameters 49.89, 52.62, 56.55, 60.58, 66.08 mm on the following breaking parameters:- strength, energy, force, strain, deflection, time, elastic modulus and apparent modulus were studied. The experiment was carried out using a modified Instron Testing Machine. It was observed that the loading rate affected the following five parameters positively: apparent elastic modulus, breaking force, breaking strength, breaking elastic modulus and breaking energy. Root diameter affected only the apparent elastic modulus, breaking force, breaking strain and breaking energy positively. Both breaking time and breaking deflection were affected negatively by loading rate and cassava root diameter, respectively while breaking energy, breaking force and apparent elastic modulus were positively influenced by both loading rate and cassava root diameter. Breaking energy was 553 N-mm at 49.89 mm cassava root diameter and 2mm/min loading rate and 845 N-mm at 66.08 mm cassava root diameter and 10mm/min loading rate. Breaking elastic modulus at 49.89 mm cassava root diameter increased from 51.67 N/mm^2 at 2 mm/min loading rate to 144.84 N/mm^2 at 10 mm/min loading rate. At the highest cassava root diameter of 66.08 mm, breaking elastic modulus increased from 34.84 N/mm^2 at 2 mm/min loading rate to 99.38 N/mm^2 at 10 mm/min. Second order polynomial models relating the measured breaking parameters to both loading rate and cassava root diameter show the viscoelastic behavior and the mechanical properties of the cassava root. The results obtained will be useful in the design and development of harvesting, processing and storage structures, processes and machines for cassava root lengths.

KEYWORDS: Modelling, apparent elastic modulus, breaking strength, breaking elastic modulus, breaking energy.

1. INTRODUCTION
The roots of cassava (*Manihot esculentus* Crantz) are one of the major staple foods in Nigeria. Cassava tubers are rich in carbohydrates, but poor in both proteins and vitamins. Cassava tubers contain 80–90% carbohydrates, 1–3% crude proteins and 0.1–0.5% crude fat, (Katz and Weaver, 2003; Ferraro *et al*. 2016). Once harvested, cassava roots do not keep in a good condition for more than one or two days; (Onwueme, 1978). Freshly harvested cassava roots are bulky and the shelf life rarely exceeds two days after harvesting due to enzymatic reactions (Kolawole *et al.*, 2010). In practice farmers prudently harvest the quantity of roots they can process within a day and allow the remaining unharvested roots to “store” in the living conditions in the soil.

Cassava root harvesting requires mechanization which involves the design and development of its equipment. Its success is largely dependent on availability of relevant data on the engineering properties of the crop which will cause breakage of the root length such as force, strength, deflection, etc. The design of equipment for handling and processing of cassava requires a thorough understanding of these engineering properties of the cassava roots (Oriola and Raji, 2015). With the present efforts to mechanize the production and processing of cassava, the roots may need to be harvested using machines which may damage or bruise them. Once damaged, deterioration takes place fairly rapidly because of the rapid increase in the percentage of prussic acid. In addition, where commercial processing will involve collecting roots from farmers to feed a central processing plant, the roots may have to be transported over long distance of rough farm roads. Mechanization of cassava harvesting process may result in mechanical damage to the roots which will hasten deterioration during storage. Damage to the roots by harvesting machines must, therefore, be reduced to a minimum by designing machines that will apply appropriate forces to the roots. Uchechukwu-Agua *et al*. (2015) opined that mechanical damage occurs as a result of careless handling when harvesting, transportation from the field to the processing site and during processing and peeling of the root (Iyer *et al.*, 2010). Unfortunately, the effects of the injuries on the root are overlooked, but it has been reported as the major factor constituting the physiological deterioration of the root (Fadeyibi, 2012). In most cases, damages occur during harvest with the use of farm tools and machineries or in pulling of the root from the ground. The damages on the root during transportation could be caused by the vibration or compression in the packaging materials used. Amponsah *et al*. (2014) stated that cassava root breakage or damage is therefore a major factor to consider in the selection and adoption of any type of harvesting method depending on the end use of the harvested produce. Where cassava root damage or breakage is of concern, manual harvesting is preferred to mechanical harvesting (Amponsah, 2011). This will subject the roots to varying magnitudes of mechanical forces. Furthermore, storing of roots for more than a day may become inevitable thereby subjecting the roots to storage forces which may cause deterioration of the roots.

Cassava root engineering properties influence the level of damage sustainable by it during harvesting, processing, storage and other handling operations. Notable damages are crushing, bruises, cracks or breakages (Gakwaya, 1990). With the breakage of the cassava root length the shelf life of the root is shortened, leading to wastage, poor products yield, economic losses, reduction in market quality and poor commercialization (Van Oirschot *et al*., 2000). Knowledge of the mechanical properties, such as stress, strain, hardness and compressive strength, is important to engineers handling agricultural products (Balami *et al.*, 2012). The absence of sufficient data on the engineering properties of cassava roots has been one of the factors hindering the successful design of efficient cassava root peeling machines (Egbeocha *et al.*, 2016) and other process machines.

1.1 *Clarifications and Definitions*

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. Zweben *et al*. (1979) defines the flexural modulus or bending modulus as an intensive property that is computed as the ratio of stress to strain in flexural deformation, or the tendency for a material to resist bending. It is determined from the slope of a stress-strain curve produced by a flexural test (such as the ASTM D790), and uses units of force per area. When measured from the compressive inner side (i.e. from the load point), the flexural modulus is the bending or breaking modulus. When measured from the tensile outside side (i.e. from the reaction points), the flexural modulus is tensile or apparent elastic modulus. Ideally, the tensile (measure of flexibility) and flexural (measure of stiffness) moduli would be the same since they are both the materials' ability to resist deformation under loads, even though the loads they are resisting are different. However, the results are usually different because measurements are not made in an ideal state. With the tapered nature of the cassava root length, (Schroder *et al.,* 1973; Asoegwu, 1981) developed the following expressions: Breaking Strength = $64PL/\pi\ (d_1+d_2)^3$ N/mm^2; Breaking Strain = $3(d_1+d_2)^3\ Y/L^2$; Breaking Elastic Modulus = $8PL^3H/\pi Y$ N/mm^2; where Y = deflection (mm), d_1 = tail end diameter (mm), d_2 = proximal end diameter (mm), L = span/length (mm), P = loading force (N), H = shape factor.

Breaking strength is an important parameter required to predict the behavior or resistance to damage of agricultural root crops during mechanized harvesting. Breaking strength is the ability of a material to withstand a pulling or tensile force without rupture. Breaking strength is also known as fracture strength, tensile strength or ultimate tensile strength.

Flexural strength, also known as modulus of rupture, or bend strength, or transverse rupture strength is a material property, defined as the stress in a material just before it yields in a flexure test (Zweben, 1979). Breaking strain is the amount of strain that, if applied to a particular material, will cause it to break. It is the amount of strain which can cause something to break, according to the force or weight placed on it. Breaking time is the time it takes the cassava root to break in bending under load applied mid-span.

1.2 *Problem Statement/Aim of the Study*

Mechanical harvesting usually involves application of external forces that damage cassava in the form of breakages. In order to reduce the rate of deterioration of the roots during storage, due to breakages, there is a need to reduce damage to the roots during mechanical harvesting and post-harvest handling. It, therefore, becomes necessary to understand the relationship between some breaking parameters and the damage they cause to the roots. This is where the modeling of the results of this work comes in. This paper describes the breaking characteristics of cassava root lengths of different diameters under various continuous bending loads. Among the specific objectives of this investigation are the determination of the breaking parameters of strength, strain, deflection, energy, force and time as well as apparent elastic modulus and breaking modulus of elasticity and the modeling of their relationships. The results obtained may be very useful in the design of appropriate harvesting and handling machinery, structures and processes for cassava root lengths.

2. MATERIALS AND METHODS

The breaking characteristics of cassava roots of lengths 150 mm loaded mid-span in bending were studied using the Instron compressive machine driven by a 3 hp variable speed electric motor through a suitably designed belt drive (Figure 1). The Inston 3400 Series Universal Testing Machine of 1kN capacity, has load measurement accuracy of ±0.5% of reading down to 1/200th of load cell capacity, displacement accuracy of ±0.02mm or 0.15% of displacement. The behavior was observed using five different groups of specimens. Each group consisted of 125 cassava root lengths of approximately the same diameters whose mean diameter differs from the mean diameter of the other groups, (Table 1). The diameters were measured at three different points of the two extremities and the average taken (tail = d_1; butt or proximate = d_2). Twenty five (25) cassava root lengths from each group were tested at each of the five different constant loading rates of 2.0, 4.0, 6.0, 8.0 and 10.0 mm/min respectively. The moisture content (wet basis) of all roots tested was 52.13 + 5.74%. The specimens were mature, hand harvested, fresh, straight, and kink-free and tapered uniformly.

Each 150 mm long specimen was placed on the load ring of the equipment in its most natural horizontal position. The rollers were placed firmly at each end of the horizontal cassava root length of 150 mm to support the root in such a way that there is no slippage in the course of loading it mid-span during the experiment. The motor speed was selected to give the desired loading rate. When the motor was started, both force and the deflection of each specimen were recorded using the dial gauges attached to the load ring and the machine, at time intervals until the specimen breaks. The average breaking force, deflection and time for the twenty-five specimens in each group at the five different loading rates were determined.

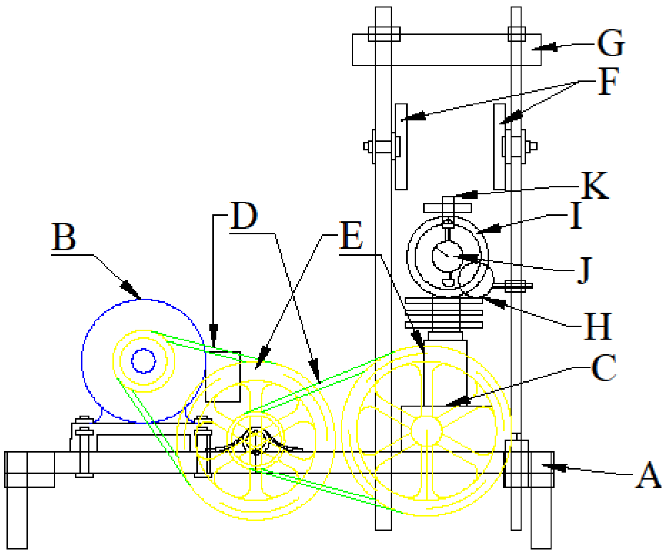

Fig. 1 Modified Instron Equipment Used in the Study (Asoegwu, 1981)
A: Metal base, B: Variable speed motor, C: Instron compression testing machine, D: V-Belt, E: Speed reduction pulley, F: Roller, G: Support frame, H: Dial guage displacement, I: Loading ring, J: Dial guage, K: Nut (for point loading)

Appropriate formulae were used to calculate the breaking parameters investigated in this experiment. The formulae were taken from standard Strength of Materials textbooks and modified to suit the tapered nature of the roots (Schroder *et al.*, 1973; Asoegwu, 1981). The regression models were obtained using Excel 2013 software.

Table 1. Cassava root sizes and loading rates used in the experiment

Mean diameter (mm)	Tail diameter, d_1 (mm)	Butt diameter, d_2 (mm)	(d_1+d_2) (mm)
66.08±1.07	65.01	67.15	132.16
60.58±0.92	59.66	61.50	121.16
56.55±0.75	55.80	57.30	113.10
52.62±0.88	51.74	53.50	105.24
49.89±1.01	48.88	50.90	99.78

Loading rates: 2.0, 4.0, 6.0, 8.0, 10.0 mm/min

ASSUMPTIONS

1. The composite cassava root is homogenous and isotropic, having physical properties that do not vary section by section.
2. The cassava roots, as other agricultural materials, behave visco-elastically (Asoegwu, 1981).

3. RESULTS AND DISCUSSION

The values of the breaking characteristics of the cassava root length were found to be a function of the loading rate and of the root diameter. Ogunnigbo *et al.* (2021) found the values of the mechanical properties of the cassava root to be a function of the loading rate with the relationship best expressed using polynomial equations of the second order. The relationships were best expressed according to Aviara *et al.* (2012) in the form: $Y = aX^2 \pm bX \pm c$; where: Y = the breaking characteristic; a, b and c = the regression coefficients; X = the loading rate (mm/min) or diameter (mm) of the cassava root, as the case may be; ± = representing whether + or – relationship.

3.1 *Force-Strain Curve*

The average force-strain curve of the cassava root lengths for the different diameter groups and rates of loading is given in Figure 2. The curve is similar to the 3-parameters characterization of the force deformation behavior of some engineering alloys as presented by Liebowitz and Eftis (1971), which depict viscoelasticity.

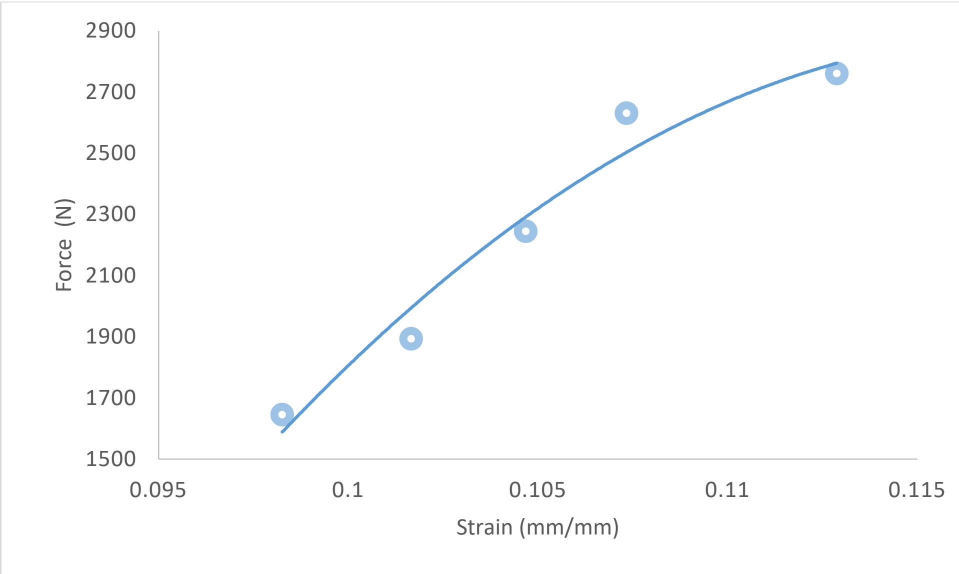

Figure 2: Average force-strain curve of cassava root length in bending.

The curve has an initial linear portion, confirming the assumption that, in bending, the composite cassava root length may be taken as homogenous since the effect of the peel and the pith may be said to be non-significant. Otherwise, the initial behavior might have been non-linear. The linear part corresponds with the limit of elasticity, and the curved part, the crest of which depicts the peak force, from where its corresponding deformation at peak could be determined. The shape of the curve has been reported for cassava roots by Oriola and Raji (2015); Nwagugu and Okonkwo (2009); Kolawole *et al*., (2007). The samples did not seem to show any bio-yield point in any of the loading rates tested as shown in Figure 2 most probably because it is not a radial compressive test of the root diameter that was done (Kolawole *et al*., 2007; Ilori *et al*., 2017; Ogunnigbo, *et al*., 2021). However, Figure 2 is typical of the stress vs. strain curve for bending of homogenous, isotropic materials (Licari and Swanson, 2011). The regression equation of the force-strain relationship of the cassava root length is a second order polynomial regression model given as Equation 1.

$$y = -3E{+}06x^2 + 779258x - 43119 \qquad R^2 = 0.963 \qquad (1)$$

where y = force and x = strain.

The equation is typical to the behavior of most visco-elastic materials.

3.2 *Apparent Elastic Modulus*

The apparent elastic modulus (measured from the tensile down side of the bent cassava root length) increased as loading rate increased for all diameter groups tested (Figure 3). However, for each loading rate, the apparent elastic modulus seems to be highest for the 60.58 mm diameter and lowest for the 49.89 mm. The values obtained ranged from 103.3 N/mm^2 for 49.89 mm cassava root diameter and 2mm/min loading rate to 425 N/mm^2 or 60.58 mm cassava root diameter and 10 mm/min loading rate.

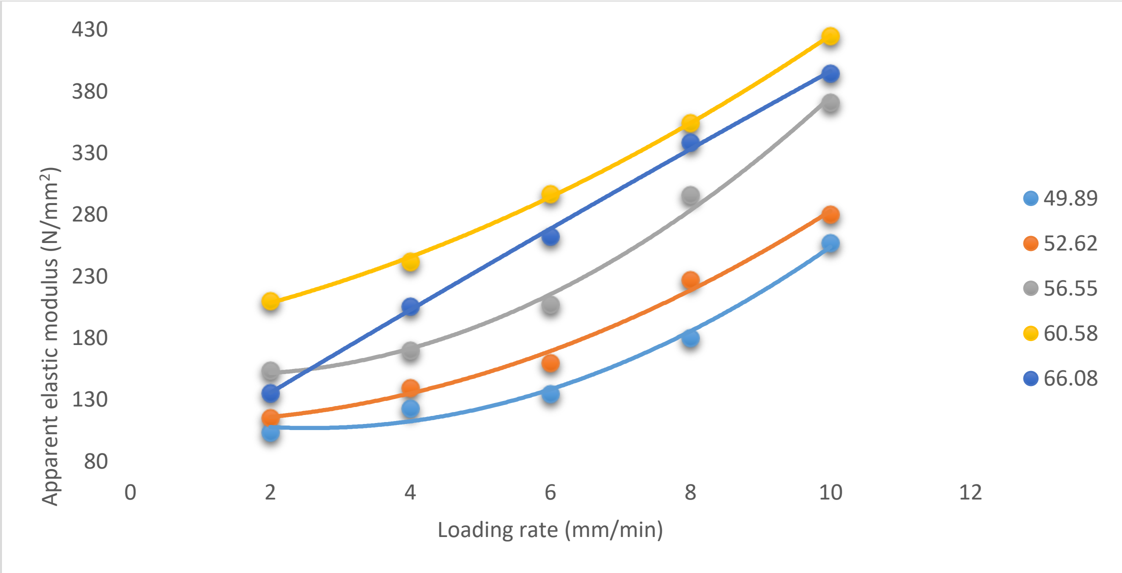

Figure 3: Effect of loading rate and cassava root diameter on apparent elastic modulus.

At all loading rates, the apparent elastic modulus seems in-sensitive to root diameters 49.89 and 52.62 mm as they did not vary significantly as shown in the R^2 values of Equations 2 and 3. This seeming inconsistency need to be further investigated since Anazodo and Morris (1981) found corn cob apparent elastic modulus insensitive to corn cob diameter, when subjected to radial compression. At high cassava root diameters (56.55, 60.58 and 66.08 mm) the coefficient of determination in Equations 4, 5 and 6, showed very high correlation between loading rate and apparent elastic modulus. The second order polynomial equation models given in Equations 2 to 6 show again the viscoelastic behavior of cassava roots in bending.

$$y49 = 2.6554x^2 - 13.599x + 124.46 \qquad R^2 = 0.9878 \qquad (2)$$
$$y52 = 1.8768x^2 - 1.6364x + 111.76 \qquad R^2 = 0.9899 \qquad (3)$$
$$y56 = 3.0089x^2 - 8.1021x + 155.84 \qquad R^2 = 0.9927 \qquad (4)$$
$$y60 = 1.4107x^2 + 10.201x + 182.5 \qquad R^2 = 0.9992 \qquad (5)$$
$$y66 = -0.1696x^2 + 34.631x + 67.08 \qquad R^2 = 0.9981 \qquad (6)$$

From Figure 4 it is observed that the apparent elastic modulus increased from 159.7 N/mm^2 to 267.4 N/mm^2 as the cassava root diameter increased from 49.89 mm to 68.89 mm and given by Equation 7.

Ideally, apparent elastic modulus, flexural or bending modulus of elasticity is equivalent to the tensile modulus (Young's modulus) or compressive modulus of elasticity. In reality, these values may be different, especially for polymers which are often viscoelastic (time dependent) materials (Askeland, 2016), such as cassava root which is assumed a homogeneous and isotropic material.

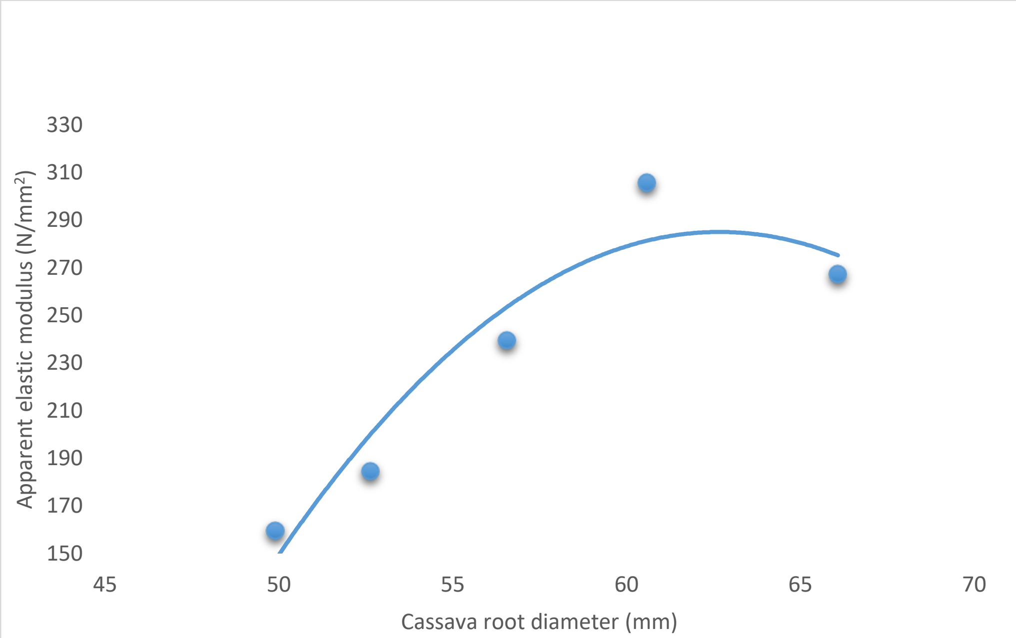

Figure 4: Effect of cassava root diameter on the apparent elastic modulus in bending

$$y = -0.8434x^2 + 105.72x - 3027.9 \qquad R^2 = 0.913 \qquad 7$$

3.3 *Breaking Elastic Modulus*

While breaking elastic modulus (measured from the load point of the upper side of the bent cassava root length) increased as loading rate increased, it decreased as cassava root diameter increased as shown in Figure 5. At 2 mm/min loading rate, the breaking elastic modulus was 51.67 N/mm^2 at the lowest cassava root diameter (49.89 mm) and 34.84 N/mm^2 at the highest cassava root diameter (66.08 mm), while at the highest loading rate (10 mm/min) it was 144.84 N/mm^2 for the lowest cassava root diameter and 99.38 N/mm^2 for the highest cassava root diameter. The polynomial regression models of this relationship are given in Equations 8 to 12 with $R^2 > 0.99$. The radial elastic modulus of cassava root obtained by Yang *et al.* (2011) of 7.22 N/mm^2 seemed to be too low compared to the least value of 34.84 N/mm^2 obtained in this work because of the method of loading.

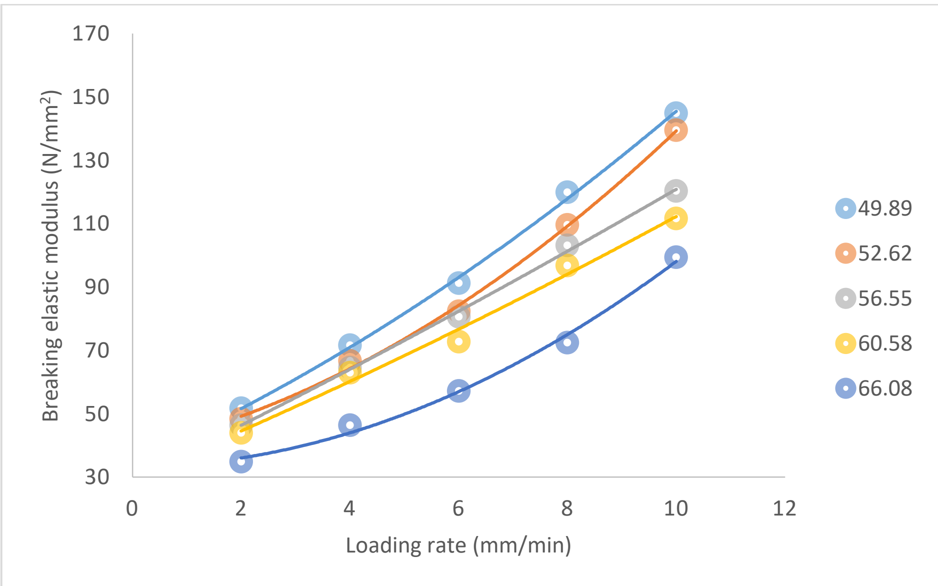

Figure 5: Effect of loading rate and cassava root diameter on breaking elastic modulus

Oriola and Raji (2015) got breaking elastic modulus or stiffness modulus, represented by the Young's modulus of their samples to range from 4.81 to 6.24 N/mm^2 between moisture contents of 50 and 60% which are about one tenth of the results obtained in this work. Kolawole *et al.* (2010) and Agbetoye and Kolawole (2002) obtained average moduli of elasticity of 1.02 and 2.50 N/mm^2 at moisture contents of 55 and 50% (wet basis), respectively, which are lower in value than ours, most probably because of the method of loading.

$$y49 = 0.3436x^2 + 7.6111x + 35.042 \qquad R^2 = 0.9985 \qquad 8$$
$$y52 = 0.6259x^2 + 3.7478x + 39.232 \qquad R^2 = 0.998 \qquad 9$$
$$y56 = 0.0784x^2 + 8.3768x + 29.286 \qquad R^2 = 0.998 \qquad 10$$
$$y60 = 0.1075x^2 + 7.174x + 29.8 \qquad R^2 = 0.9892 \qquad 11$$
$$y66 = 0.6304x^2 + 0.1927x + 33.142 \qquad R^2 = 0.9938 \qquad 12$$

At the cassava root diameter of moisture content of 52.13 + 5.74%, the breaking elastic modulus had a negative polynomial regression relationship with cassava root diameter when loaded mid-span in bending as seen in Figure 6 and Equation 13. The high R^2 is very significant in the relationship.

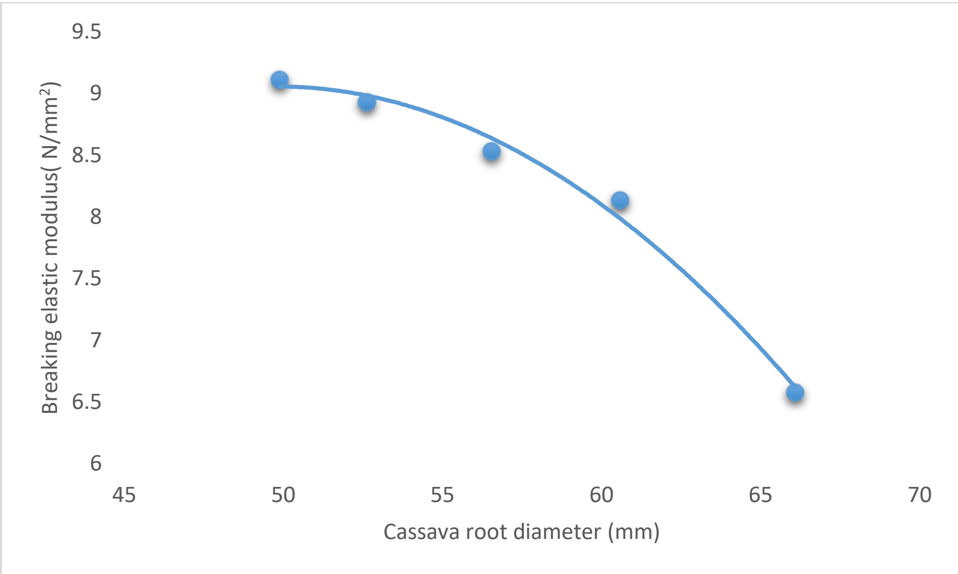

Figure 6: Effect of cassava root diameter on breaking elastic modulus in bending.

$$y = -0.0092x^2 + 0.9126x - 13.659 \qquad R^2 = 0.9902 \qquad 13$$

From Figure 6 the relationship between diameter of cassava roots and breaking elastic modulus was negative for all loading rates tested. The relationship is polynomial in this bending test. However, Sanchez-Castillo *et al*. (2017) found that negative power law equation models fitted the results they got for the three species of cassava in tensile loading for elastic modulus against cassava root diameter. The important fact is that the relationship is in negative form. From Figure 6, the negative relationship between cassava root diameter and breaking elastic modulus points to the fact that bigger roots have less elasticity.

3.4 *Breaking Force*

The breaking force (N) increased with both increasing root diameters and loading rates (Figure 7). Smaller force is required to break the cassava root of small diameter mid-span at any loading rate. It increased from 1.14 kN at 49.89 mm diameter and 2 mm/min loading rate to 3.423 kN at 66.08 mm diameter and 10mm/min loading rate, an increase of over 200%. The polynomial regression models of breaking force against loading rates for different cassava root diameters are given in Equations 14 to 18 with $R^2 > 0.99$. Oriola and Raji (2015) reported that for cassava roots of moisture content (50 – 55% w.b.) the mean peak compressive force of cylindrical cassava roots ranged between 428.34 and 551.68 N which is close to the 499 N reported by Nwagugu and Okonkwo (2009) for compressive force along the fiber direction of the sweet cassava root. These results are much less than reported in this work (1.14 – 3.423 kN) because the cassava root lengths were loaded mid-span to breakage point, taking a higher force. However, for average cassava root diameter of between 62 – 65 mm and 150 mm cassava root length, Ilori *et al.* (2017) got average compressive cracking force to be 1.722 kN and 1.770 kN for cassava varieties TMS 4(2)1425 and TMS 30572, respectively. These results are within the range of the breaking force obtained in this work with the bending load applied mid-span.

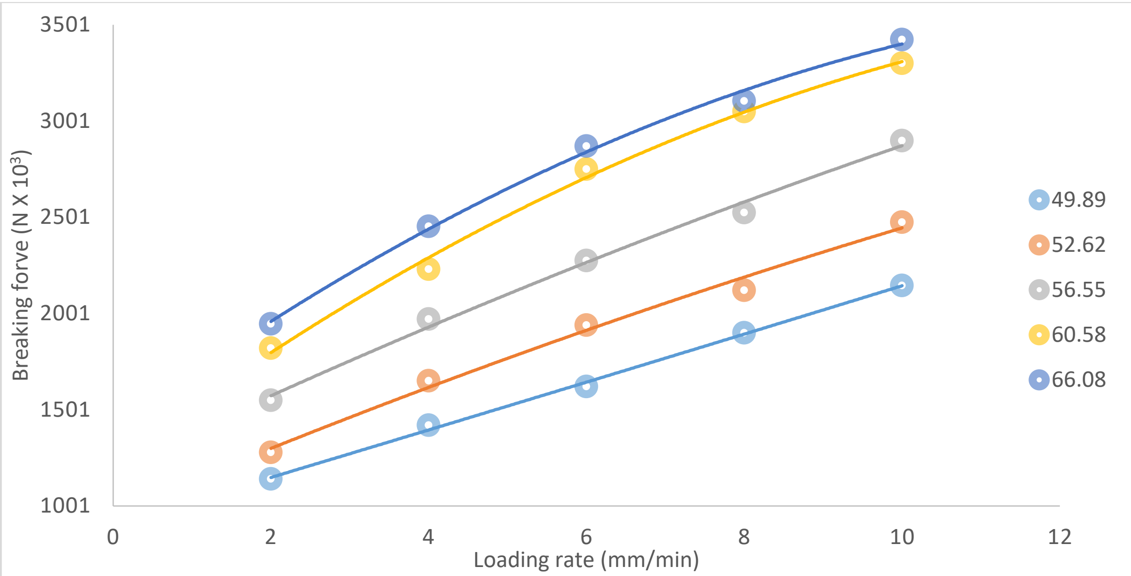

Figure 7: Breaking force vs. Loading rate for varying cassava root diameters in bending

$y49 = 0.0002x^2 + 0.1224x + 0.903$	$R^2 = 0.9979$	14
$y52 = -0.0026x^2 + 0.1741x + 0.9614$	$R^2 = 0.9904$	15
$y56 = -0.0027x^2 + 0.1948x + 1.1938$	$R^2 = 0.9943$	16
$y60 = -0.0096x^2 + 0.3047x + 1.226$	$R^2 = 0.9958$	17
$y66 = -0.01x^2 + 0.2998x + 1.3994$	$R^2 = 0.9964$	18

The effect of cassava root diameter on the breaking force in bending is given in Figure 8 and Equation 19 which again is a second order polynomial regression model with $R^2 > 0.99$.

$$y = -0.003x^2 + 0.424x - 11.982 \qquad R^2 = 0.9904 \qquad 19$$

The breaking force increases as the cassava root diameter increases. Ilori and Adetan (2013) observed a similar trend with the radial compressive cracking force of cassava roots of different diameter sizes and lengths. They got, for cassava root diameters of 50 – 70 mm, radial compressive cracking force range of 1.24 – 1.87 kN for lengths between 100 and 150 mm which is within the range obtained in this work. For 150 mm length cassava root diameters of 49.89 mm to 66.08 mm, loaded mid-span, the braking force increased from 1.65 to 2.76 kN.

Ohwovoriole *et al*. (1988) and Adetan *et al*. (2003) have established that cassava root strength properties increase with root diameter. This establishes an obvious fact that bigger diameters require bigger forces to break as observed by Sanchez-Castillo *et al.* (2017).

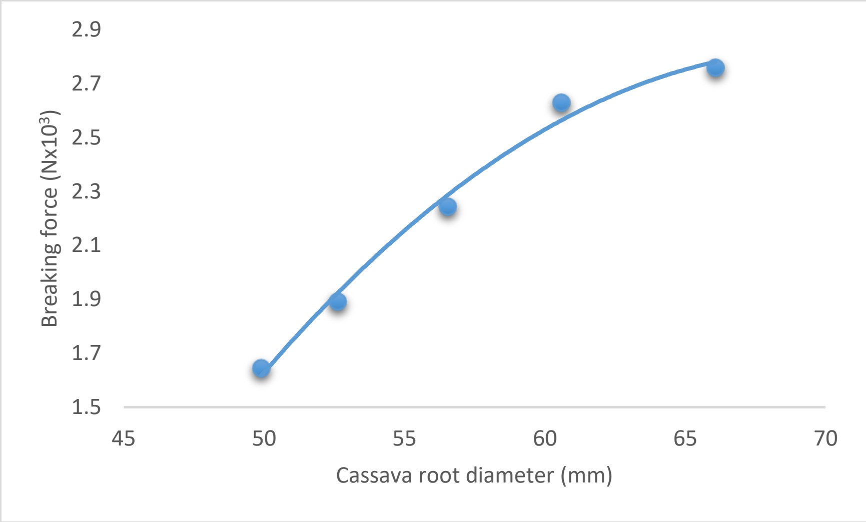

Figure 8: Effect of cassava root diameter on breaking force in bending

3.5 *Breaking Deflection*

The breaking deflection (mm) decreased with increase in loading rate but increased with increasing cassava root diameter when subjected to bending load mid-span. The highest breaking deflection (29.9 mm) occurred with the least cassava root diameter (49.89 mm) at 2 mm/min loading rate, with the least breaking deflection (15.1 mm) at the 10 mm/min loading rate as shown in Figure 9. At high loading rates of 6 – 10 mm/min, the breaking deflection for cassava root diameters 56.55 – 60.5 8 mm were not significantly different and seem to have a linear relationship. This needs to be investigated further to decipher the meaning of the relationship.

The second order polynomial regression models for the effect of loading rate on the breaking deflection of cassava root in bending are given in Equations 20 to 24 with high $R^2 > 0.99$ for all cassava root diameters.

$$y49 = -0.1161x^2 + 0.1979x + 29.82 \qquad R^2 = 0.9947 \qquad (20)$$
$$y52 = -0.0875x^2 - 0.155x + 29.32 \qquad R^2 = 0.9971 \qquad (21)$$
$$y56 = -0.0161x^2 - 1.0621x + 29.34 \qquad R^2 = 0.9969 \qquad (22)$$
$$y60 = -0.0179x^2 - 0.9157x + 27.4 \qquad R^2 = 0.993 \qquad (23)$$
$$y66 = -0.0286x^2 - 0.8371x + 26.36 \qquad R^2 = 0.9966 \qquad (24)$$

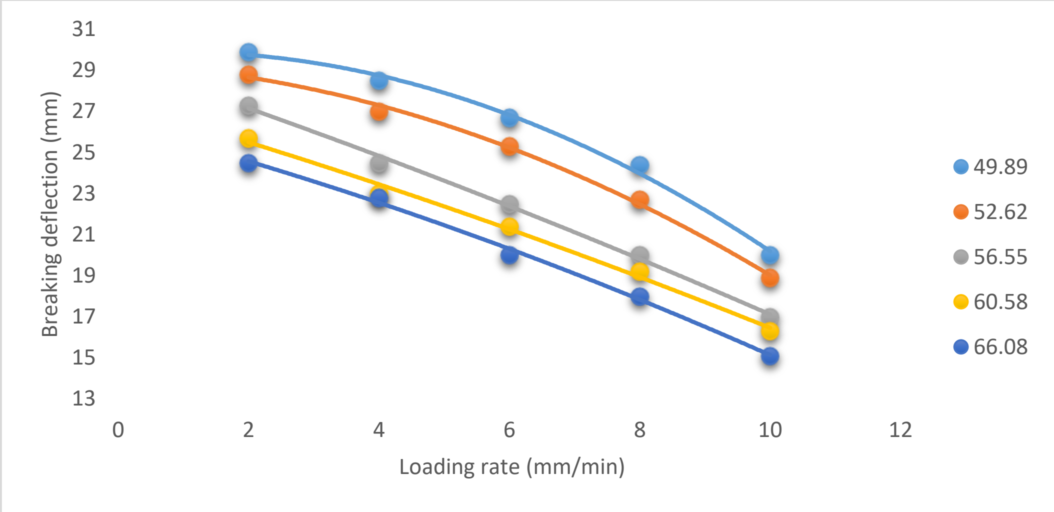

Figure 9: Effect of loading rate on breaking deflection of cassava root in bending

Figure 10 and Equation 25 show the negative effect increasing cassava root diameter has on breaking deflection. This means that the breaking deflection required to break the cassava root diameter decreases while the breaking force increases as the diameter of cassava root increases (Figure 8).

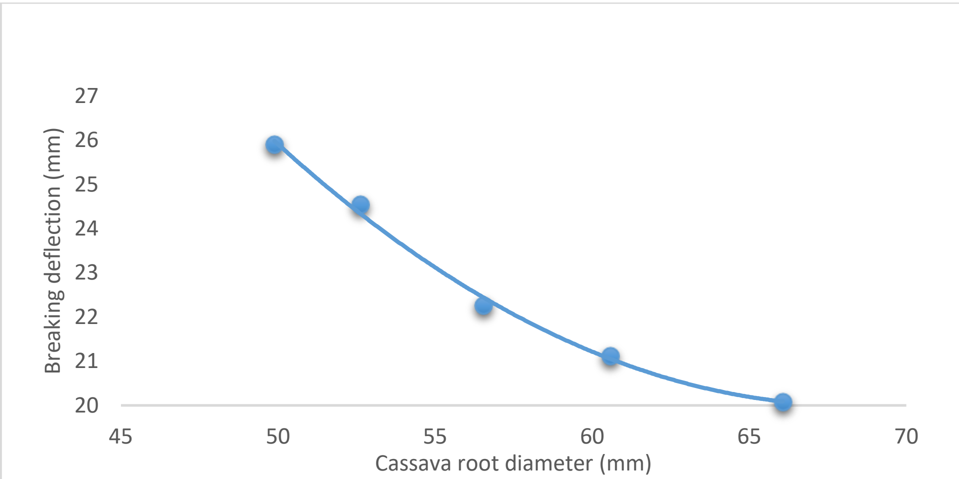

Figure 10: Effect of cassava root diameter on the breaking deflection in bending

The breaking deflection drops as the diameter of cassava root increases (Figure 10) because some of the big diameter roots are so matured that naturally before harvesting them, they had already developed inner central cracks which served as easy crack initiation points thereby reducing the amount of deflection to break them. Ilori and Adetan (2015) observed same for cracking force.

$$y = 0.0176x^2 - 2.4093x + 102.29 \qquad R^2 = 0.9964 \qquad 25$$

3.6 *Breaking Energy*

The breaking energy (N-mm) in this work increased as both loading rate and cassava root diameter increased (Figure 11) at moisture content of 52.13 + 5.74% (wet basis). At 2 mm/min loading rate and 49.89 mm and 68.08 mm cassava root diameters, the breaking energy was 553 N-mm and 845 N-mm, respectively, an increase of about 34.6%. While at 10 mm/min loading rate and same diameters as above, it was 655 N-mm and 845 N-mm, respectively, an increase of 22.5%. The percentage difference in breaking energy between diameters decreases as cassava root diameter increases. The second order polynomial regression models for the effects of loading rates on breaking energy (N-mm) for different cassava root diameters are given in Equations 26 to 30 with $R^2 > 0.98$. Oriola and Raji (2015) identified the toughness of the roots, represented by the energy to break, to range from 480 to 667 N-mm, which is within the range obtained in this work.

$$y49 = 0.375x^2 + 8.95x + 531.4 \qquad R^2 = 0.9859 \qquad (26)$$
$$y52 = -0.0179x^2 + 9.7643x + 608.2 \qquad R^2 = 0.9919 \qquad (27)$$
$$y56 = -0.1071x^2 + 8.7857x + 657.6 \qquad R^2 = 0.9979 \qquad (28)$$
$$y60 = 0.3571x^2 + 2.9143x + 710.6 \qquad R^2 = 0.9931 \qquad (29)$$
$$y66 = 0.9464x^2 - 1.3071x + 762.2 \qquad R^2 = 0.9959 \qquad (30)$$

Cassava root diameter has a positive second order polynomial regression relationship (R^2 = 0.9867) with breaking energy (N-mm) as shown in Figure 12 and Equation 31. It ranged from 601.6 to 796 N-mm for cassava root diameter range of 49.89 to 66.08 mm.

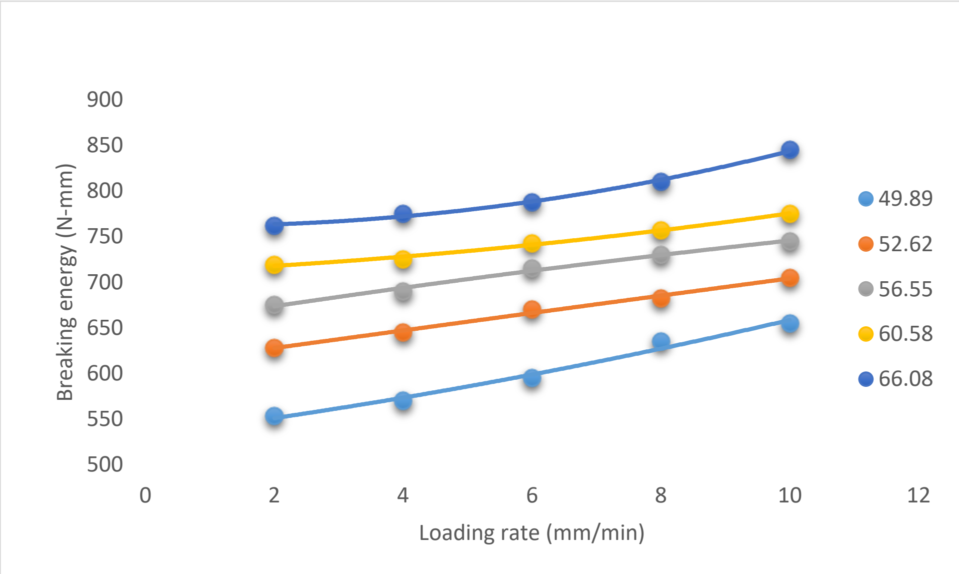

Figure 11: Effect of loading rate on the breaking energy of cassava root in bending

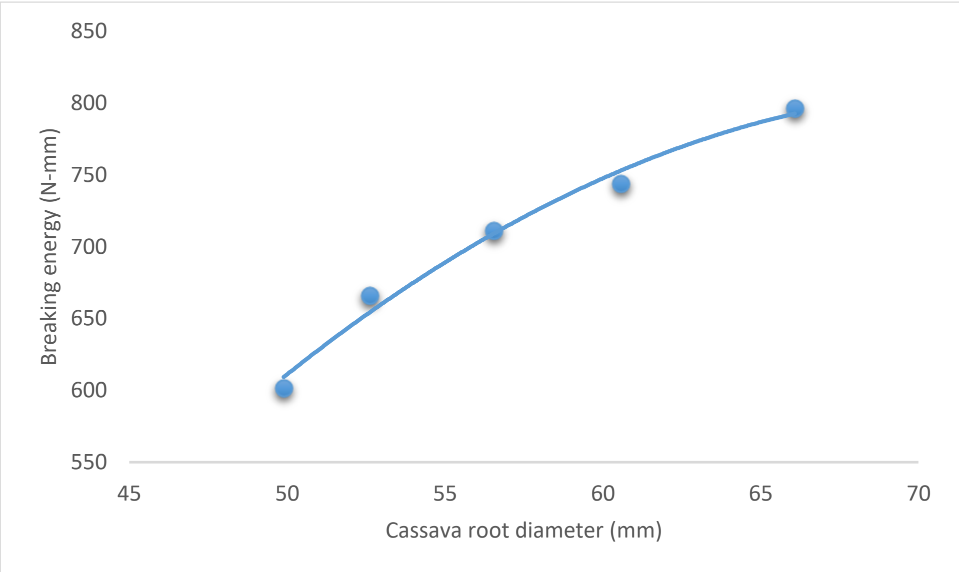

Figure 12: Effect of cassava root diameter on breaking energy in bending

$y = -0.3865x^2 + 56.155x - 1230.3$ $R^2 = 0.9867$ 31

On the average, the breaking energy increased from 667.4 N-mm at 2mm/min to 745 N-mm at 10mm/min for all cassava root diameters. On the other hand it increased from 601.6 N-mm at 49.89 mm diameter to 796 N-mm at 66.08 mm for all loading rates.

3.7 *Breaking Strength*

Cassava roots are extremely susceptible to damage during mechanized harvesting due to the application of vertical, slanting and/or horizontal forces on the root by the harvesting tools. Breaking strength (N/mm^2) increased with increase in loading rate but decreased with increase in cassava root diameter (Figure 13). At loading rate of 2mm/min, breaking strength was 6.33 N/mm^2 at 49.89 mm cassava root diameter and 4.64 N/mm^2 at 66.08 mm diameter, an increase of 26.7%. Meanwhile, at 10 mm/min loading rate the breaking strength values were 11.88 N/mm^2 and 8.16 N/mm^2 at 49.89 mm and 66.08 mm root diameters, respectively, an increase of 31.3%. It seems that as the loading rate increased, the incremental difference in breaking strength between diameters also increased. Yang *et al*. (2011) reported cassava root strength of 2.66 N/mm^2 which is less than our results, probably because of the varieties involves and also the method of loading.

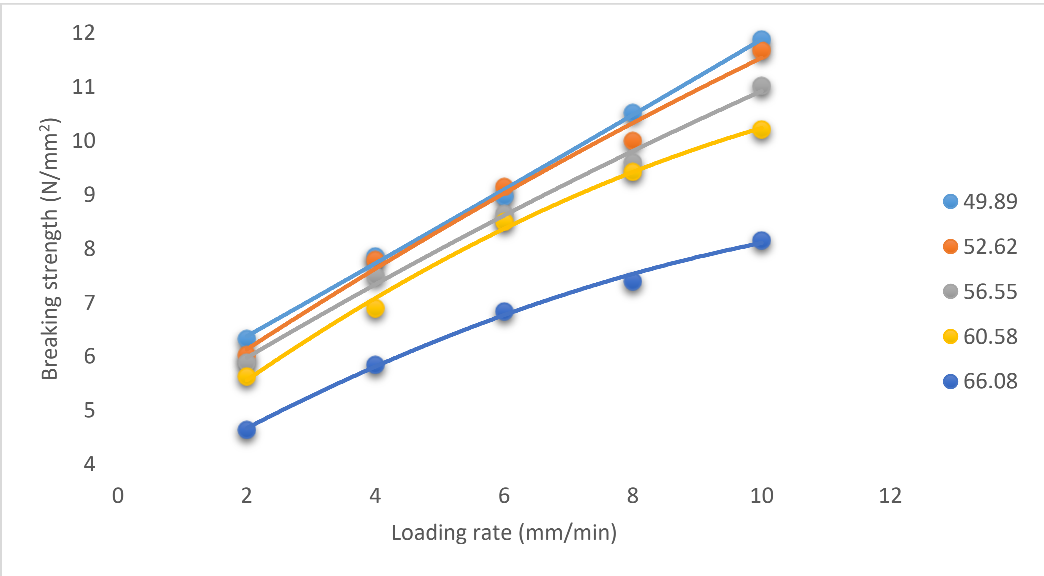

Figure 13: Effect of loading rate and cassava root diameter on the breaking strength in bending

At lower loading rates of 2, 4 and 6 mm/min, the values of the breaking strength were not significantly different (P>0.05) from each other for cassava root diameters 49.89 – 60.08 mm. The largest diameter, 66.08 mm, had the least breaking strength for all the loading rates. The second order polynomial regression models for the effect of loading rate of the breaking strength for the different cassava root diameters are given in Equations 32 – 36 with high $R^2 > 0.99$.

$y49 = 0.0018x^2 + 0.6666x + 5.034$ $R^2 = 0.998$ 32
$y52 = -0.012x^2 + 0.8191x + 4.542$ $R^2 = 0.9902$ 33
$y56 = -0.0104x^2 + 0.7423x + 4.534$ $R^2 = 0.9942$ 34
$y60 = -0.0295x^2 + 0.9381x + 3.802$ $R^2 = 0.996$ 35
$y66 = -0.0237x^2 + 0.7145x + 3.336$ $R^2 = 0.9963$ 36

For all loading rates, the breaking strength decreased with increase in cassava root diameter as shown in Figure 14 and Equation 37. This doesn't seem to agree with Kolawole *et al*. (2010) who stated that the cassava root strength properties generally increase with increase in tuber diameter because tubers increase in diameter and fiber content with age of plants.

$$y = -0.0092x^2 + 0.9126x - 13.659 \qquad R^2 = 0.9902 \qquad 37$$

The negative relationship between cassava root diameter and bending strength points to the fact that the bigger the root diameter, the less the bending strength. Sanchez-Castillo *et al*. (2017) got the same trend between cassava root and tensile strength but with power law regression relationship, while Ilori *et al*. (2017) found the mechanical compressive cracking force required to break the tubers of the two cassava varieties (TMS 30572 and TMS 4(2)1425) to decrease with increase in diameter of cassava roots. It should be noted that for the breaking of the cassava root by harvesting machinery, breaking strength is an important parameter to consider. And the relationships given above will serve as a starting point in the calculation of the breaking or bending strength.

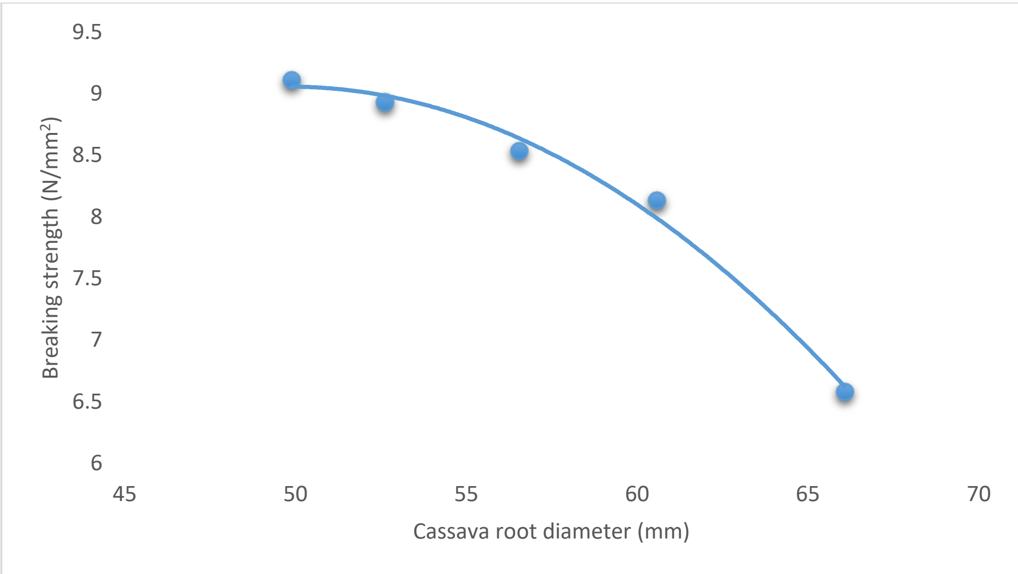

Figure 14: Effect of cassava root diameter on the breaking strength in bending

3.8 *Breaking Time*

Because of the elastic flexibility of the most slender cassava roots of 49.89 mm diameter, the breaking time was highest at 465 sec at 2 mm/min loading rate and least at 80 sec at 10 mm/min loading rate. Figure 15 shows the effect of loading rate on cassava breaking time for various root diameters. Their second order polynomial regression models are given in Equations 38 to 42 with $R^2 > 0.99$.

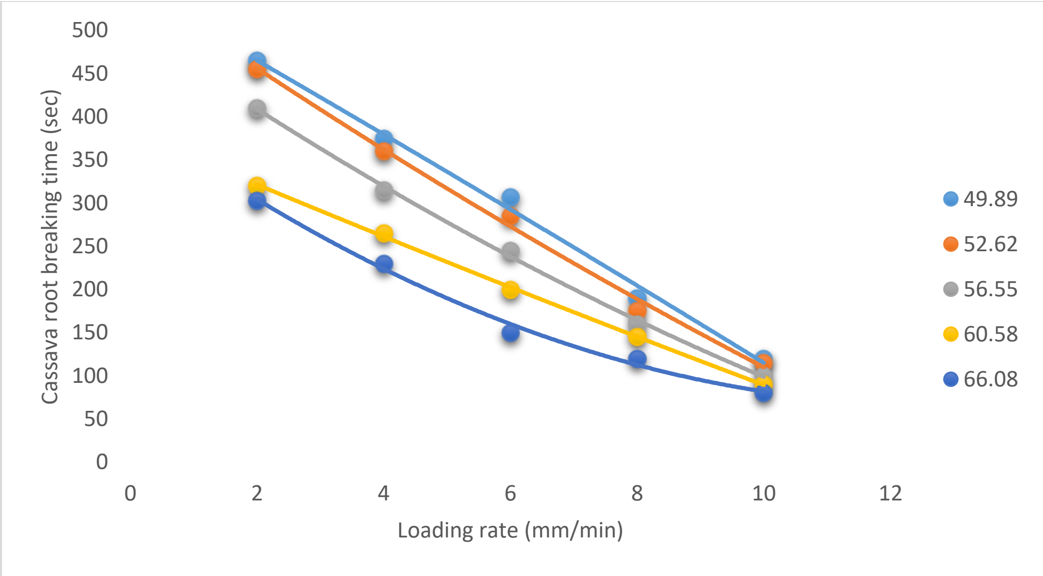

Figure 15: Effect of loading rate on cassava breaking time for various root diameters

This shows that breaking time decreased with increasing loading rate and increasing cassava root diameter. For all cassava root diameters breaking time decreased from 390.6 to 101 sec for loading rates 2 to 10 mm/min, respectively. At the highest loading rate of 10 mm/min, the breaking time decreased from 120sec for 49.89 mm diameter to 80 sec for 66.08 mm diameter. The more slender cassava roots took more time to break for all loading rates tested. This may be because the endosperm of slender cassava root is tenderer, not fully matured but very elastic and prolongs the time to break.

$y49 = -0.1607x^2 - 41.821x + 549.4$ $\quad R^2 = 0.994$ $\quad$ 38

$y52 = 0.625x^2 - 50.75x + 555$ $\quad R^2 = 0.9951$ $\quad$ 39

$y56 = 0.9821x^2 - 50.536x + 506$ $\quad R^2 = 0.9985$ $\quad$ 40

$y60 = 0.1786x^2 - 31.143x + 383$ $\quad R^2 = 0.9993$ $\quad$ 41

$y66 = 2.0714x^2 - 52.657x + 401.4$ $\quad R^2 = 0.9939$ $\quad$ 42

The effect of cassava root diameter on the breaking time is shown in Figure 16. The time required to break the cassava root decreases as the diameter increases. As cassava roots age and mature they increase in fiber content and size. There could be internal cracks present in the most matured roots. These cracks form the starting points from which failure easily progresses and thereby lowers the time to break. This assertion has been made by Ilori and Adetan (2013) and Kolawole *et al.* (2010). Therefore, it may be ok that there is this declining time to break the cassava root as the root diameter increases. The second order polynomial regression model for the relationship of breaking time and cassava root is given in Equation 43.

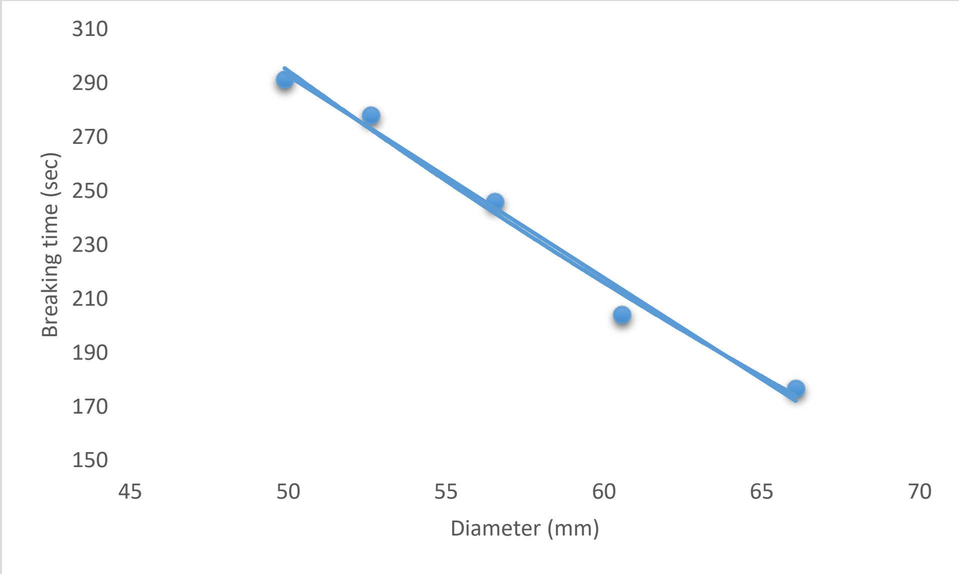

Figure 16: Effect of cassava root diameter on breaking time for all loading rates

$y = 0.06x^2 - 14.459x + 867.59$ $R^2 = 0.9863$ 43

On the average, considering all loading rates, it was observed that the breaking time for the cassava roots decreased from 291.4 sec for the 49.89 mm diameter to 176.6 sec for the highest diameter of 66.08 mm.

3.9 *Breaking Strain*

Breaking strain of cassava roots decreased at 49.89 mm root diameter from 0.1228 at 2 mm/min loading rate to 0.0721 at 10 mm/min. Also at 66.08 mm cassava root diameter, breaking strain decreased from 0.1332 at 2 mm/min to 0.0881 at 10 mm/min. Breaking strain of cassava roots increased as cassava root diameter increased but decreased with increase in loading rate as shown in Figure 17. The regression models are second order polynomial with $R^2 > 0.99$ and given in Equations 44 – 48.

$y49 = -9E\text{-}05x^2 - 0.0051x + 0.1328$ $R^2 = 0.9969$ 44
$y52 = -0.0001x^2 - 0.0041x + 0.1322$ $R^2 = 0.9905$ 45
$y56 = -0.0002x^2 - 0.0033x + 0.1342$ $R^2 = 0.9978$ 46
$y60 = -0.0003x^2 - 0.0024x + 0.1338$ $R^2 = 0.9993$ 47
$y66 = -0.0003x^2 - 0.0025x + 0.1395$ $R^2 = 0.9992$ 48

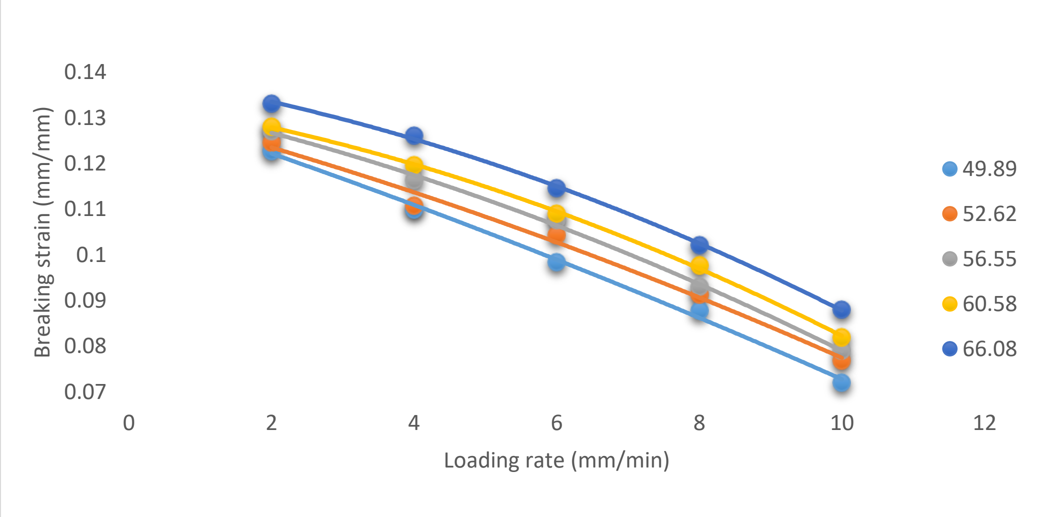

Figure 17: Effect of loading rate on the breaking strain on different cassava root diameters

On the average, the breaking strain decreased from 0.12718 at 2 mm/min to 0.07964 at 10 mm/min. However, as the cassava root diameter increased from 49.89 mm to 66.08 mm, the breaking strain increased from 0.09826 to 0.11288, respectively, as shown in Figure 18 and Equation 49. This has the same trend as the breaking force of the cassava root (Figure 8).

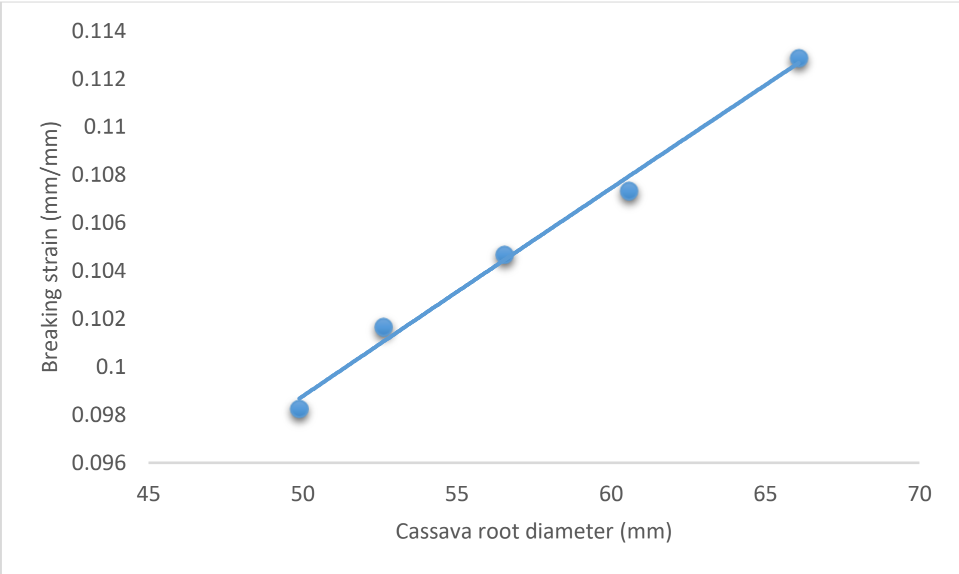

Figure 18: Effect of cassava root diameter on the breaking strain in bending

$$y = -5E\text{-}07x^2 + 0.0009x + 0.0539 \qquad R^2 = 0.992 \qquad 49$$

This second order polynomial model makes valid the fact that the behavior of cassava root is viscoelastic.

4. CONCLUSION

The relationships between the breaking parameters, the loading rate and the specimen diameter of freshly, hand harvested, mature cassava root lengths were investigated. Five slow loading rates and five root diameter ranges were used. Analysis of experimental data revealed:

a. That apparent elastic modulus, breaking energy and breaking force were the three rupture or breaking parameters affected positively by both the loading rate and root diameter.

b. That second order polynomial regression models were able to define the relationships between the breaking parameters and both loading rate and cassava root diameter with $R^2 > 0.91$.
c. That although loading rate significantly affected the breaking elastic modulus positively, specimen diameter did negatively, confirming that breaking elastic modulus is a firmness index rather than a strength index.
d. That loading rate and cassava root diameter negatively affected the breaking parameters of time and deflection.
e. That compared to other works in Literature, some values obtained in this work differed appreciably because of the method of loading, mid-span, to induce bending. Others used mainly radial compression or axial elongation to induce breakage.
f. That based on how machines might interact with cassava roots during harvesting, this work is novel in the designing of systems and machines for harvesting cassava roots.
g. That the loading rate is the more important factor in the breaking characteristics of cassava root since it significantly affected all measured breaking parameters except breaking strain, breaking time and breaking deflection.

4.1 *Engineering Implications of the Study*

One important implication of this study is that since cassava root lengths are sensitive to rate of loading, engineers engaged in the design and development of machines to harvest complete plants now may use the fundamental information to determine the roots' responses to bending forces. Also, because the apparent elastic modulus and breaking elastic modulus exhibited increases as the loading rate is increased, this information is of particular importance in evaluating the cassava roots responses to applied forces. Knowing these properties, one can calculate deflection caused by a given force normal to the root if the shape factor (H) is known or can be determined.

From the foregoing, the selection of loading rate becomes imperative in the successful harvesting and handling of the cassava roots for minimized mechanical damage. Also, since breaking deformation and breaking time decrease as loading rate increases, then the rate of loading to be selected should be as fast as possible, consistent with the physical limitations of the machines.

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