https://doi.org/10.17221/57/2020-RAE

A study on the influence of the loading rate and orientation on some mechanical properties of cassava tubers of different ages

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Citation: Ogunnigbo O., Adetan D., Morakinyo T., Olusunmade O., Ojerinde B. (2021): A study on the influence of the loading rate and orientation on some mechanical properties of cassava tubers of different ages. Res. Agr. Eng., 67: 34–44.

Abstract: The study determined the effects of the speed of loading and the loading orientation on some selected mechanical properties of the TME 419 cassava tuber variety at different ages of the tuber which are essential in the design and construction of the processing and handling equipment of a cassava peeler. The properties considered include the bioyield and rupture points, compressive and rupture strengths, toughness and firmness, and moduli of stiffness and toughness, which were carried out in the transverse and longitudinal loading direction using an Instron Universal Testing Machine (UTM). As the loading rate increased from 5.00 to10.00 mm·min^{-1} and the age of the tuber varies from 1.00 to 2.00 years, the bioyield and rupture points, compressive and rupture strengths, toughness, firmness, moduli of stiffness and toughness in the transverse and longitudinal direction varies from 1 619.61 to 3 636.19 N and 136.08 to 384.52 N, 0.48066 to 1.07913 N·mm^{-2} and 0.26604 to 0.75173 N·mm^{-2}, 766 to 1 055 N·mm^{-1} and 1 262 to 2 965 N·mm^{-1}, 303.98 to 553.68 mm·min^{-1} and 28.08 to 53.71 mm·min^{-1} 2.30 to 4.19 N·mm^{-2} and 5.376 to 8.94 N·mm^{-2} respectively. Generally, the values of the properties examined are higher in the longitudinal loading orientation than in the transverse and for a year and half old tuber which will be useful in designing an efficient cassava peeling system.

Keywords: compressive strength; longitudinal loading; loading speed; toughness; transverse loading

The cassava (*Manihot esculenta* Crantz) is a widely imported staple crop cultivated in Nigeria, it is believed to originate from Brazil. There are several cassava varieties which are differentiated by their botanical characteristics and the levels of hydrocyanic acid in the root and leaves, which are affected by environmental factors such as the soil type, temperature, rainfall, farming method, sunlight, etc. (Ademosun et al. 2012; Ilori et al. 2017). 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, (Ferraro et al. 2016). The carbohydrate content in cassava tuber is higher than that in the potato root, but less than that in sorghum, rice, yellow corn and wheat (Gil and Buitrago 2002). According to the Food and Agricultural Organization (FAO) data, Nigeria is the largest producer of cassavas in the world as the country produced 59.49 million tonnes, Democratic Republic of the Congo

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produced 31.6 million tonnes, Indonesia produced 19.05 million tonnes and Brazil produced 18.88 million tonnes, which account for about 44% of the world's total production (292 million tonnes) in 2017 (FAOSTAT 2019). Processing operations of cassava tubers mainly consist of peeling, washing, grating, pressing, drying, milling, sieving and frying. Most of these processing operations are still largely being performed manually, although they are labour intensive, time consuming and unfavourable for large scale production (Quaye et al. 2009; Ilori et al. 2017). According to Mohsenin (1986), damage to a product is defined as the failure of a product subjected to excessive deformation when it is forced through a fixed clearance or excessive force after impact. The mechanical damage of agricultural products are as a result of external forces under dynamic or static conditions or as a result of internal forces. Damage due to internal forces can be as a result of biological, physical changes or chemical changes. Mechanical damage due to external forces is as a result of mechanical injuries to the fruits and vegetables, grains, and so on. The failure of agricultural products is usually manifested through rupture in the external or internal cellular structure. Injuries could be divided into physiological disorders (badly misshapen fruit, growth cracks, or cracking), pre-harvest diseases (rust and shot hole), postharvest diseases (rots, including brown rot), pre-harvest mechanical injuries (healed lesions caused by rubbing or pest attacks) and postharvest mechanical injuries (bruises, cuts, and punctures) (Amorim et al. 2008). Mechanical damage occurs as a result of compressions and impacts produced during harvesting, transport, and manipulation processes. Damage can occur at the point at which the compression or impact takes place, or later, during storage. This damage has a direct effect on the quality and the product's prices. Baritelle et al. (2001) developed an equation to evaluate the relationship between impact bruising and commodity conditioning. This relationship estimated the bruise threshold as a function of the specimen mass and the radius of the curvature, the impact properties of the tissue and Poisson's ratio for impacts on a rigid flat surface. Knowledge of the mechanical properties, such as stress, strain, hardness and compressive strength, is important to engineers handling agricultural products (Balami et al. 2012).

Several studies have been conducted in the engineering properties of the cassava root and in the design and fabrication of its processing machines/equipment. Kazeem and Abdulganiy (2013) reported on the influence of the age on the physical properties of three varieties of cassava tubers, Egbeocha et al. (2016) reported that most cassava peeling machines developed so far experience problems of high losses in the roots and its average peeling efficiency, which can be attributed to the variability in the root sizes and shapes. Olukunle and Jimoh (2012) suggested the need to design and develop a good, efficient and time conserving cassava peeling machine with a low loss of tubers, so as to reduce the energy expended in peeling. In a review by Adejumo et al. (2011), in a study of cassava starch quality, they highlighted the importance of detailed information, such as he varieties and root age, among other things, as these are among the major factors that greatly affect the quality of the starch. Root age is considerably influenced by the starch granule size, structure, size distribution and hydration properties (Sriroth et al. 1999). Aviara et.al. (2012) determined the influence of the moisture content and loading orientation on some mechanical properties of the *Mucuna flagellipes* nut. The research conducted by Kolawole et al. (2007) reveals some strength and elastic properties of the TMS 4(2) 1 425 cassava tuber, and reported a tensile stress varying from 0.235 to 0.116 $N \cdot mm^{-1}$ at a moisture content between 50 to 70 (% w.b.).

Nyorere and Iweka (2019) determined the compressive behaviour of cassava tubers under static quasi compression loading, as influenced by the age and variety; however, little information appears to exist on the loading rate and orientation for different ages of cassava tubers. The objective of this study was, therefore, to determine the mechanical properties of the TME 419 variety of cassava tubers and investigate the variation in the loading rate and orientation at different ages of the tuber

MATERIAL AND METHODS

Sample preparation. The cassava tubers (*Manihot utilissima*) used for the study were obtained from two different farm locations at Obafemi Awolowo University Teaching and Research farm, Osun State Nigeria. The tubers were categorised into three different years namely; one, one and half and two years. The tubers were harvested fully matured based on their age at harvest and the soil particles were completely removed before the testing commenced. The selected tubers were cut into standard sizes and without damage for placement into the machine.

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A local variety of the cassava tuber, TME 419 was considered in this study. The variety was selected based on a preliminary survey as one of the main varieties cultivated by the farmers in Ile – Ife and its environs. The research was carried out at the Food and Post-Harvest Laboratory of the Department of Agricultural Engineering and the Department of Mechanical Engineering Obafemi Awolowo University.

The moisture content was determined on a wet basis by dehydrating the samples at 105 °C for 24 h in a drying oven (Arlington, USA), according to the Association of Official Agricultural Chemists (AOAC) approved oven drying method (AOAC 2005) conducted in three replicates.

Experimental procedure. Compression tests were conducted on the tuber samples of different moisture levels which varied from 66.50 to 70.00% w.b. using a Universal Instron Testing Machine (UTM) (Instron, USA) controlled by a micro-computer. Two loading orientations, namely longitudinal (Figure 1A) and transverse (Figure 1B), were used. The tubers were compressed at a crosshead speed of 15mm·min^{-1}. As the compression began and progressed, a load deformation curve was automatically plotted in response to the compression of each tuber. Five randomly selected tubers per age were tested at each loading orientation and moisture content. This was replicated three times. The load-deformation curves obtained were analysed for the bioyield point, rupture point, compressive strength, rupture strength, toughness, firmness, modulus of toughness and modulus of stiffness.

The bioyield is defined as that point on the force-deformation curve at which the compressed tuber weakens and fails internally without any outward cracking (Iyilade et al. 2018). The rupture point is the point on the force deformation curve at which the tuber completely becomes broken and torn with the peel exposed (Anazodo 1982; Mohsenin 1986). The bioyield strength is taken as the stress at which the tuber fails in its internal cellular structure. The compressive strength is the stress at which the tuber begins to tear. The rupture strength is taken as the stress at which the cassava tuber variety becomes completely broken. The modulus of stiffness is estimated as the ratio of the average maximum force to the average maximum deformation at failure (Dinrifo and Faborode 1993). The TME 419 tuber variety was calculated from the force-deformation data following the method reported by Mamman et al. (2005). The modulus of toughness, which is the area under the force-deformation curve up to failure (Zoerb and Hall 1960; Mohsenin and Gohlich 1962), was determined from the force-deformation curve using a method which was given by Haque et al. (2001). The average of each property at the loading conditions was determined and regressed against the age and the different loading rates (5.00 to 15 mm·min^{-1})

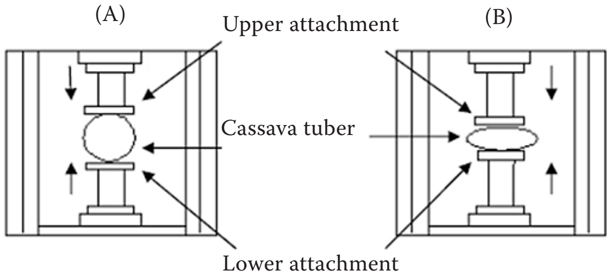

Figure 1. Compression of the TME 419 variety of cassava tuber in the (A) longitudinal and (B) transverse loading orientations using the universal testing machine

The toughness, which causes the rupture of bio materials, is defined as the area under the force – deformation curve up to the rupture point (Mohsenin 1986).

Firmness is a textural parameter that is important in the quality control of food materials. It is the required force needed to achieve a specified amount of deformation (Finney 1969).

Statistical Analysis. The relationships which exist between the properties and loading rate in both the transverse and longitudinal loading orientations were analysed using the Data Analysis Toolkit available on Microsoft Excel (version 2016) while a factorial ANOVA was conducted to compare the main effect of the tuber's age and loading orientations as well as their interaction effect on each property using the Statistical Package for Social Sciences (version 22).

RESULTS AND DISCUSSION

Mechanical properties – Loading rate relationship. The experimental results on the TME 419 variety of the cassava tuber shows that the loading rate of the tuber varies from 5.00–10.00 mm·min^{-1} across the three ages of the studied tubers.

The values of the mechanical properties of the tuber were found to be a function of the loading rate. The relationships which exist between the properties and the loading rate in both the transverse and longitudinal loading orientations were best expressed using

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polynomial equations of the second order. According to Aviara et al. (2012), the expression is in the form:

$$Y = a + bx + cx^2 \quad (1)$$

where: Y – the mechanical property; a, b and c – the regression coefficients; x – the loading speed (mm·min^{-1}) of the tubers.

Table 1 presents the experimental values of the observed mechanical properties while Table 2 shows the coefficients of the terms in the equation for the properties. The equations were found to have a very high determination coefficient (R^2 = 1) which shows a good description of the relationship.

Bioyield and rupture points. The bioyield and rupture points of the TME 419 tuber variety at the different tuber ages, loading rates and loading orientations are presented in Table 1. Under transverse loading, the bioyield, and rupture points of the tuber varies from 1 619.61 to 3 636.19 N, as the loading rate increased from 5.00 to10.00 mm·min^{-1} and the age of tuber varies from 1.00 to 2.00 years. A year-old tuber experienced the highest bioyield and rupture point which varied from 1 649.15 to 3 636.19 N while a year and half old tuber has the lowest bioyield and rupture point, which varied from 1 789.52 to 2 818.78 N. The observed results are in contrast with Nyorere and Iweka (2019), who determined the compressive behaviour of cassava tubers under quasi static compression loading as influenced by age and variety. On the longitudinal orientation, the bioyield and rupture points of the tuber increased from 136.08 to 384.52 N, as the loading rate increased from 5.00 to10.00 mm·min^{-1} and age of tuber varied from 1.00 to 2.00 years. A year and half old tuber experienced the highest bioyield and rupture point, which varied from 295.98 to 384.52 N, while a two year old tuber has the lowest bioyield and rupture point, which varied from 136.08 to 322.01 N. The differences in the bioyield and rupture force across the tuber age may be due to several factors, such as the moisture content, climatic conditions and the soil factors at the time of harvest. The observed results in the transverse orientation are in agreement with that obtained by Balami et al. (2014) whose work determined some engineering properties of cassava tubers grown in northern Nigeria.

The values of the bioyield and rupture points suggest that the tuber would require a lower force level for the peel to become broken when loaded on the transverse axis than on the longitudinal axis. The second order polynomial equations with the coefficients of the terms, as presented in Table 2, gave the best fit for the relationship that exists between the bioyield, rupture points and loading rate of the tuber in the different loading axes.

Compressive and rupture strengths. The compressive and rupture strengths of the tuber at the different tuber ages, loading rates and loading orientations are presented in Table 1. It can be seen that the compressive and rupture strengths of the tuber varied from 0.48066 to 1.07913 N·mm^{-2}, as the loading rate increased from 5.00 to10.00 mm·min^{-1} and the age of the tubers varied from 1.00 to 2.00 years under transverse loading. A year-old tuber experienced the highest compressive and rupture strength which varied from 0.72116 to 1.07913 N·mm^{-2} while a year and a half old tuber had the lowest compressive and rupture strength which varied from 0.53109 to 0.83654 N·mm^{-2}. As reported by Reponte et. al. (2004), the orientation affected the bioyield strength, rupture strength, Young's modulus and shear yield energy of the cassava tubers.

On the other hand, under longitudinal loading for the compressive strength, the properties varied from 0.26604 to 0.75173 N·mm^{-2}, as the loading rate increased from 5.00 to10.00 mm·min^{-1} and the age of the tubers varied from 1.00 to 2.00 years. The highest compressive strength was observed for a year and half tuber which varied from 0.40962 to 0.75173 N·mm^{-2} while the two year old tuber had the lowest compressive strength at 0.26604 to 0.52933 N·mm^{-2}. Also, for rupture strength, the properties varied from 0.12864 to 0.53182 N·mm^{-2}, as the loading rate increased from 5.00 to10.00 mm·min^{-1} and age of the tuber varied from 1.00 to 2.00 years. The highest rupture strength was observed for a year-old tuber which varied from 0.41926 to 0.53182 N·mm^{-2} while a year and a half old tuber recorded the lowest rupture strength at 0.46064 to 0.31501 N·mm^{-2}. The obtained results are in close agreement with those obtained by Oriola and Raji (2015) who presented the compressive strength properties of cassava tubers. Plant variation factors which make agricultural products behave nonlinearly are responsible for the differences in the properties.

The strength of TME 419 cassava tuber was higher in the longitudinal loading than in the transverse loading. This may be as a result of the smaller contact areas that occurred when loading in the longitudinal

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Table 1. Mechanical properties of the TME 419 variety of cassava at the different loading rates and loading orientations for the different ages of the tuber

Mechanical properties		Loading speed ($mm \cdot min^{-1}$)					
		transverse loading			longitudinal loading		
	age (yr)	5	10	15	5	10	15
Bioyield point (N)	1	2 429.97 (4.20)	1 649.15 (4.41)	3 636.19 (3.08)	327.53 (4.55)	348.46 (3.84)	328.77 (3.10)
	$1^{0.5}$	1 789.52 (4.06)	2 818.78 (3.18)	1 844.99 (3.11)	295.98 (2.97)	384.52 (3.01)	209.53 (2.84)
	2	1 619.61 (3.66)	2 162.28 (2.93)	3 001.30 (3.05)	136.08 (2.86)	322.01 (2.99)	270.75 (3.09)
Rupture point (N)	1	2 429.97 (2.91)	1 649.15 (3.17)	3 636.19 (2.88)	214.45 (2.08)	151.33 (2.03)	272.03 (1.98)
	$1^{0.5}$	1 789.52 (3.26)	2 818.78 (2.81)	1 844.99 (3.02)	235.62 (1.70)	259.14 (2.05)	161.13 (1.98)
	2	1 619.61 (2.93)	2 162.28 (3.15)	3 001.30 (2.97)	65.80 (1.93)	254.72 (2.18)	175.92 (2.03)
Compressive strength ($N \cdot mm^{-2}$)	1	0.72116 (0.023)	0.48943 (0.018)	1.07913 (0.021)	0.64033 (0.025)	0.68125 (0.022)	0.64274 (0.024)
	$1^{0.5}$	0.53109 (0.019)	0.83654 (0.020)	0.54755 (0.016)	0.57864 (0.019)	0.75173 (0.021)	0.40962 (0.018)
	2	0.48066 (0.016)	0.64171 (0.019)	0.89071 (0.018)	0.26604 (0.015)	0.62953 (0.018)	0.52933 (0.020)
Rupture strength ($N \cdot mm^{-2}$)	1	0.72116 (0.018)	0.48943 (0.015)	1.07913 (0.017)	0.41926 (0.015)	0.29586 (0.012)	0.53182 (0.017)
	$1^{0.5}$	0.53109 (0.015)	0.83654 (0.017)	0.54755 (0.014)	0.46064 (0.016)	0.50662 (0.015)	0.31501 (0.014)
	2	0.48066 (0.015)	0.64171 (0.019)	0.89071 (0.017)	0.12864 (0.011)	0.49799 (0.014)	0.34392 (0.016)
Toughness (N·mm)	1	867.00 (3.20)	822.00 (3.06)	766.00 (3.21)	1 262.00 (4.73)	1 284.00 (4.55)	1 513.00 (4.39)
	$1^{0.5}$	972.00 (3.81)	954.00 (4.04)	839.00 (3.95)	2 076.00 (4.67)	2 076.00 (4.67)	2 287.00 (4.52)
	2	1 055.00 (3.49)	981.00 (4.14)	897.00 (3.90)	2 860.00 (4.32)	2 860.00 (4.32)	2 965.00 (4.05)
Firmness ($N \cdot mm^{-1}$)	1	497.94 (2.31)	372.10 (2.70)	428.80 (2.16)	35.56 (1.99)	28.08 (1.86)	38.18 (1.94)
	$1^{0.5}$	442.96 (2.18)	553.68 (2.47	303.98 (2.29)	33.42 (1.78)	39.26 (1.53)	53.71 (1.81)
	2	390.30 (2.40)	449.82 (2.33)	354.73 (2.38)	28.61 (1.59)	39.49 (1.57)	41.89 (1.79)
Modulus of stiffness ($N \cdot mm^{-2}$)	1	3.77 (0.22)	2.82 (0.18)	3.25 (0.15)	6.95 (0.31)	8.34 (0.27)	5.91 (0.30)
	$1^{0.5}$	3.35 (0.19)	4.19 (0.17)	2.30 (0.15)	5.38 (0.25)	7.46 (0.31)	8.94 (0.29)
	2	2.96 (0.15	3.41 (0.20)	2.69 (0.19)	7.58 (0.27)	6.39 (0.25)	8.26 (0.30)

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Table 1. to be continued

Mechanical properties	Loading speed (mm·min^{-1})						
		transverse loading			longitudinal loading		
	age (yr)	5	10	15	5	10	15
Modulus of toughness (N·mm^{-2})	1	3.77 (0.20)	2.82 (0.17)	3.25 (0.20)	4.30 (0.21)	3.43 (0.19)	4.36 (0.20)
	$1^{0.5}$	3.35 (0.16)	4.19 (0.19	2.30 (0.14)	4.03 (0.20)	4.73 (0.23)	5.66 (0.21)
	2	2.96 (0.15)	3.41 (0.18)	2.69 (0.14)	2.97 (0.15)	4.71 (0.18)	5.06 (0.20)

Numbers in parenthesis represent the standard deviation

axis and it confirms the higher resistance of the peel to the expected breaking in this loading orientation. The relationship that exists between the compressive and rupture strengths of the cassava tuber can be adequately represented by second order polynomial equations with the terms of the coefficients presented in Table 2.

Toughness and firmness. The toughness and firmness of the TME 419 variety of the cassava tubers at the different tuber ages, loading rates and loading

Table 2. Coefficient of the terms in the general equation expressing the mechanical properties of the TME 419 tuber as a function of the loading rate

Mechanical properties	Loading orientation coefficients							R^2
		transverse loading			longitudinal loading			
	age (year)	a	b	c	a	b	c	
Bioyield point (N)	1	5 978.6	–986.52	55.357	265.98	16.372	–0.8124	
	$1^{0.5}$	–1 242.8	806.77	–40.061	–56.09	96.767	–5.2706	
	2	1 373.3	19.629	5.927	–287.04	108.34	–4.7438	
Rupture point (N)	1	5 978.6	–986.52	55.357	461.39	–67.77	3.6764	
	$1^{0.5}$	–1 242.8	806.77	–40.061	90.57	41.163	–2.4306	
	2	1 373.3	19.629	5.927	–390.84	118.1	–5.3544	
Compressive strength (N·mm^{-2})	1	1.7743	–0.2928	0.0164	0.52	0.032	–0.0016	
	$1^{0.5}$	–0.3688	0.2394	–0.0119	–0.1096	0.1892	–0.0103	
	2	0.4076	0.0058	0.0018	–0.5611	0.2118	–0.0093	
Rupture strength (N·mm^{-2})	1	1.7743	–0.2928	0.0164	0.9020	–0.1325	0.0072	
	$1^{0.5}$	–0.3688	0.2394	–0.0119	0.1771	0.0805	–0.0048	
	2	0.4076	0.0058	0.0018	–0.7641	0.2309	–0.0105	
Toughness (N·mm^{-1})	1	901.00	–5.70	–0.22	1 447.00	–57.70	4.14	1
	$1^{0.5}$	893.00	25.50	–1.94	2 167.00	–31.30	2.62	
	2	1 119.00	–11.80	–0.20	2 842.00	1.30	0.46	
Firmness (N·mm^{-1})	1	806.32	–79.930	3.6508	60.62	–6.770	0.3516	
	$1^{0.5}$	–28.18	130.270	–7.2084	36.19	–1.415	0.1722	
	2	176.17	58.287	–3.0922	9.25	4.720	–0.1696	
Modulus of stiffness (N·mm^{-2})	1	6.10	–0.604	0.0276	1.72	1.424	–0.0764	
	$1^{0.5}$	–0.22	0.987	–0.0546	2.70	0.596	–0.012	
	2	1.34	0.441	–0.0234	11.83	–1.156	0.0612	
Modulus of toughness (N·mm^{-2})	1	6.1	–0.604	0.0276	6.97	–0.714	0.0360	
	$1^{0.5}$	–0.22	0.987	–0.0546	3.56	0.071	0.0046	
	2	1.34	0.441	–0.0234	–0.16	0.765	–0.0278	

a, b, c – regression coefficient; R^2 – coefficient of determination

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orientations are presented in Table 1. The obtained results show that the toughness of the tuber varied from 766 to 1 055 N·mm^{-1}. It was observed to increase as the tuber age increased, but decreased as the loading orientations reduces when loading was undertaken in the transverse direction. While in the longitudinal direction, it varied from 1 262 to 2 965 N·mm^{-1}. It was equally observed that a direct linear relationship exists between the age of the tuber and the loading rate on the toughness of the tuber. The obtained results are slightly lower than that by Oriola and Raji (2015). This may be due to the tuber variant as well as the age at which the properties were tested.

Also, the firmness of the tuber varied from 303.98 to 553.68 N·mm^{-1}. The year and a half old tubers were observed to record the highest firmness at a loading rate of 10 mm·min^{-1} while the least occurred at a 15 mm·min^{-1} loading rate for the transverse loading. In the longitudinal direction, the firmness of the tuber varied from 28.08 to 53.71 N·mm^{-1}. Similarly, the year and a half tuber recorded the highest firmness when loaded at 15 mm·min^{-1} while the year old tuber recorded the lowest firmness at 28.08 N·mm^{-1}. The obtained results are slightly higher than what was reported by Rasmi and Rajesh (2017) on the firmness of cassava tubers.

The toughness of the TME 419 cassava tubers in the longitudinal direction shows that more work is required to cause the rupture of the tuber when compared to the transverse loading. Also, the firmness of the tuber in the transverse direction was observed to be higher than that in the longitudinal direction. This indicates that a high force was required to achieve just a small amount of deformation of the tuber. The difference in the toughness and firmness may be as a result of the tuber morphology and contact areas that occur when loading in a certain orientation. The relationship that exists between the toughness and firmness of the tuber can be adequately represented by second order polynomial equations with the terms of the coefficients presented in Table 2.

Moduli of stiffness and toughness. The moduli of stiffness and toughness of the TME 419 tuber at a loading speed 5.00–10.00 mm·min^{-1} in the different loading orientations and ages of the tubers are presented in Table 1. For transverse loading, the moduli of stiffness and toughness varied from 2.30 to 4.19 N·mm^{-2}. The highest moduli of stiffness was obtained at 4.19 N·mm^{-2} when the loading rate was 10 mm·min^{-1} while the lowest moduli of stiffness was obtained for a year and half old tuber at 2.30 N·mm^{-2}. Under the longitudinal loading, the moduli of stiffness and toughness varied from 5.376 to 8.94 N·mm^{-2}. The highest moduli of stiffness was obtained at 8.94 N·mm^{-2} when the loading rate was 15 mm·min^{-1} while the lowest moduli of stiffness was obtained at 5.376 N·mm^{-2} at a loading rate of 5 mm·min^{-1}. More so, the moduli of toughness was observed to vary from 2.97 to 5.06 N·mm^{-2} for the tuber when loading was performed in the longitudinal direction across the tuber age. The highest moduli of toughness occurred at 5.66 N·mm^{-2} when it was loaded for a one-and-a-half-year-old tuber at a rate of 15 mm·min^{-1}. The obtained results are closely related to those obtained by Oriola and Raji (2015), but slightly higher than that obtained by Kolawole et al (2007) whose work was on the strength and elastic properties of cassava tubers. The relationship that exists between the moduli of stiffness and the toughness of the tuber and the loading rate in the different loading axes and ages was found to be parabolic and could be expressed using the second order polynomial equations with terms of the coefficients presented in Table 2. The results could also be helpful in determining the ability of the tubers to withstand a load on each other during storage.

Generalisation of the effect of the loading rate, tuber age and loading orientation on the mechanical properties of the TME 419 cassava tuber. The results reported in this study show that the age of the tubers, the loading speed and axis of loading have a substantial influence on the mechanical properties of the TME 419 cassava tuber. All the mechanical properties showed similar trends with an increase in the loading speed by decreasing when loaded in the transverse direction and increasing when loaded longitudinally except for the modulus of resilience that increased under both loading orientations. Similar relationships between the moisture content and some mechanical properties under the lateral and longitudinal loading orientations were reported by Anazodo (1981) and Mamman et al. (2005) for corn cobs, soy beans, cashew nuts, wheat and *Balanites aegyptiaca* nuts, respectively. Second order polynomial models relating each of the properties to the tuber loading speed confirmed the behaviour of the mechanical properties. At all loading rates, the mechanical properties studied were higher when the tuber was loaded longitudinally than when it was loaded axially.

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This could imply that the binding forces within the cassava flesh and peel may be weaker at the transverse axis than at the longitudinal axis; hence the tuber peel would be easier to crack for peeling when loaded transversely. The decrease in the mechanical properties of the cassava tuber with the loading rates and the ages of the tubers under transverse loading suggests that to save energy and produce a high efficiency, the tuber should be cracked at a high loading speed. However, cracking at high loading speeds could crush the cassava flesh layer and result in a eduction in the product quality. Since the product quality is very important, it may be recommended that the tuber should be cracked

Table 3. Test of the between – subject effects at the different ages, loading rates and orientation of the cassava tubers

Dependent variables	Source	Sum of squares (type III)	*df*	Mean square	*F*	Significance
Bioyield point (N)	corrected model	2 175 752.793	8	271 969.099	0.120	0.997
	intercept	30 877 801.565	1	30 877 801.565	13.581	0.005
	age	187 959.126	2	93 979.563	0.041	0.960
	load rate	611 788.184	2	305 894.092	0.135	0.876
	age* load rate	1 376 005.483	4	344 001.371	0.151	0.958
	error	20 462 723.307	9	2 273 635.923		
	total	53 516 277.665	18			
	corrected total	22 638 476.100	17			
	R^2 = 0.096 (adjusted R^2 = –0.707)					
Rupture point (N)	corrected model	2 209 619.692	8	276 202.462	0.112	0.997
	intercept	28 733 076.674	1	28 733 076.674	11.673	0.008
	age	151 601.150	2	75 800.575	0.031	0.970
	load rate	644 418.009	2	322 209.004	0.131	0.879
	age* load rate	1 413 600.533	4	353 400.133	0.144	0.961
	error	22 153 597.791	9	2 461 510.866		
	total	53 096 294.157	18			
	corrected total	24 363 217.483	17			
	R^2 = 0.091 (adjusted R^2 = –0.718)					
Compressive strength ($N \cdot mm^{-2}$)	corrected model	0.371	8	0.046	1.903	0.178
	intercept	7.153	1	7.153	293.268	0.000
	age	0.060	2	0.030	1.221	0.340
	load rate	0.080	2	0.040	1.641	0.247
	age* load rate	0.232	4	0.058	2.376	0.129
	error	0.220	9	0.024		
	total	7.744	18			
	corrected total	0.591	17			
	R^2 = 0.629 (adjusted R^2 = 0.298)					
Rupture strength ($N \cdot mm^{-2}$)	corrected model	0.373	8	0.047	0.807	0.613
	intercept	5.246	1	5.246	90.837	0.000
	age	0.026	2	0.013	0.224	0.803
	load rate	0.078	2	0.039	0.676	0.533
	age* load rate	0.269	4	0.067	1.164	0.388
	error	0.520	9	0.058		
	total	6.139	18			
	corrected total	0.893	17			
R^2 = 0.418 (adjusted R^2 = –0.100)						

*Significance at P = 0.05 level; F – F statistic; R^2 – coefficient of determination

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Table 4. Test of the between – subject effects at the different ages, loading rates and orientation of the cassava tubers

Dependent variables	Source	Sum of squares (type III)	*df*	Mean square	*F*	Significance
Toughness (N·mm)	corrected model	2 219 835.000	8	277 479.375	0.297	0.949
	intercept	41 760 660.500	1	41 760 660.500	44.706	0.000
	age	2 208 675.000	2	1 104 337.500	1.182	0.350
	load rate	4 192.333	2	2 096.167	0.002	0.998
	age* load rate	6 967.667	4	1 741.917	0.002	1.000
	error	8 407 145.500	9	934 127.278		
	total	52 387 641.000	18			
	corrected total	10 626 980.500	17			
	R^2 = 0.209 (adjusted R^2 = –0.494)					
Firmness ($N \cdot mm^{-1}$)	corrected model	21 998.171	8	2 749.771	0.036	1.000
	intercept	948 757.717	1	948 757.717	12.404	0.006
	age	1 377.850	2	688.925	0.009	0.991
	load rate	6 340.422	2	3 170.211	0.041	0.960
	age* load rate	14 279.899	4	3 569.975	0.047	0.995
	error	688 387.130	9	76 487.459		
	total	1 659 143.018	18			
	corrected total	710 385.301	17			
	R^2 = 0.031 (adjusted R^2 = –0.830)					
Modulus of stiffness ($N \cdot mm^{-2}$)	corrected model	3.972	8	0.496	0.053	1.000
	intercept	490.367	1	490.367	52.598	0.000
	age	0.028	2	0.014	0.002	0.998
	load rate	0.572	2	0.286	0.031	0.970
	age* load rate	3.371	4	0.843	0.090	0.983
	error	83.906	9	9.323		
	total	578.244	18			
	corrected total	87.877	17			
	R^2 = 0.045 (adjusted R^2 = –0.804)					
Modulus of rupture ($N \cdot mm^{-2}$)	corrected model	3.514	8	0.439	0.372	0.911
	intercept	256.813	1	256.813	217.682	0.000
	age	0.639	2	0.319	0.271	0.769
	load rate	0.412	2	0.206	0.175	0.843
	age* load rate	2.463	4	0.616	0.522	0.723
	error	10.618	9	1.180		
	total	270.945	18			
	corrected total	14.131	17			
R^2 = 0.249 (adjusted R squared = –0.419)						

*Significance at P = 0.05 level; F – F statistic; R^2 – coefficient of determination

in the transverse orientation at a low loading rate between 5.00 and 10.00 $mm \cdot min^{-1}$ for a one year and a half old tuber, so that an intact cassava peel could be obtained, because within this loading rate range, it was observed that the minima and maxima values of the properties occurred. In general, the statistical inference conducted from Tables 3 and 4, shows that no significant difference exists in the main effect of the age and the loading rate of the tuber as well as their interaction effect on the mechanical properties of the tubers at $P < 0.05$

CONCLUSION

The investigation into the mechanical properties of the TME 419 cassava tuber revealed the following:

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(*i*) The bioyield and rupture points as well as compressive and rupture strengths of the TME 419 tube decreased parabolically under transverse loading and increased under longitudinal loading as the loading rate increased within the range of 5.00–10.00 mm·min^{-1} and ages 1.00–2.00 years.

(*ii*) The toughness of the tuber was observed to increase as the tuber age increased, but decreased as the loading orientations reduced when loading in the transverse direction while in the longitudinal direction, a direct linear relationship exists between the properties with the loading rate and the ages of tuber. Also, the firmness of the tuber was found to be higher in the transverse direction than in the longitudinal direction.

(*iii*) The moduli of stiffness and toughness were observed to be more in the longitudinal direction than in the transverse direction as the loading rate increases across the ages of the tuber

Hence, for engineering design, there is need to consider the conclusions stated above for an efficient system.

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Received: July 31, 2020
Accepted: November 23, 2020
Published online: March 29, 2021