EXPERIMENTAL STUDY AND ANALYSIS ON MECHANICAL PROPERTIES OF CASSAVA ROOTS AT HARVESTING STAGE

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收获期木薯块根力学特性试验研究与分析

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ABSTRACT

During mechanized harvesting operations, including excavation, root–soil separation, collection, and transportation, cassava roots are susceptible to multiple mechanical loads such as shear, compression, and impact, which easily induce mechanical damage and seriously deteriorate the processing quality and storage performance of cassava roots. To reveal the mechanical variation characteristics and damage thresholds of cassava roots under primary mechanical damage modes during harvesting and transportation, this study took harvest-stage cassava roots as the research object and conducted systematic mechanical property tests. Three typical mechanical tests, including compression, shear, and bending tests, were performed to explore the mechanical response rules of cassava roots under typical loads, obtain key mechanical parameters and damage thresholds, and clarify the failure characteristics and mechanical mechanisms under different loading modes. The research results clarify the internal relationship between mechanical properties and mechanical damage of cassava roots at the harvesting stage. This study provides reliable basic data and theoretical support for the parameter optimization of key working components, operational parameter matching of specialized cassava harvesters, and the optimal selection of tool edge angles for cassava slicing machinery, and possesses practical engineering significance for reducing mechanical harvesting damage and improving the post-harvest commodity rate and processing performance of cassava roots.

摘要

木薯块根在机械化收获的挖掘、薯土分离、收集及转运作业中，易受到剪切、挤压、撞击等多种机械载荷作用而产生损伤，严重影响块根加工品质与存储期。为揭示收获与运输过程中木薯块根主要机械损伤形式下的受力变化特性及阈值，本研究以收获期木薯块根为研究对象，系统开展了力学特性试验研究。通过开展压缩、剪切、弯曲三项力学性能试验，测定收获期木薯块根在典型载荷作用下的力学响应规律，获取其关键力学参数与损伤阈值，明确不同受力形式下的破坏特征与力学机制。研究结果阐明了收获期木薯块根的力学特性与机械损伤的内在关联，为专用木薯收获机关键工作部件参数优化、作业参数匹配以及木薯切片机械刀具刃角的合理选取提供可靠的基础数据与理论支撑。在降低木薯机械化收获损伤、提升产后商品率与加工性能方面具有重要的应用价值。

INTRODUCTION

Cassava, a species of the genus Manihot in the *Euphorbiaceae* family, is ranked among the world's three major tuber crops together with potato and sweet potato *(FAO., 2001)*. Having a cultivation history of more than 200 years in China, cassava is mainly grown in tropical and subtropical provinces including Guangxi, Guangdong, Hainan, Yunnan, Fujian, Hunan and Jiangxi *(Fu et al., 2018; Li et al., 2024; Xu et al., 2025)*. Notably, Guangxi Zhuang Autonomous Region accounts for over 60% of China's total cassava planting area and fresh tuber yield *(Feng et al., 2022)*.

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Restricted by the limited area of tropical and subtropical zones in China, as well as the high labor intensity and low mechanization level of cassava cultivation, domestic cassava output has long failed to meet the demand of national industrial production *(Liang et al., 2016; Li et al., 2025)*.

According to the latest statistics released by the Food and Agriculture Organization of the United Nations (FAO), China's cassava planting area reached approximately 3.42×10^5 hectares and the fresh tuber yield was about 7.92×10^6 tons in 2024 *(FAO., 2026)*. Since 2009, China's imports of dried cassava chips have consistently made up more than 80% of the global trade volume of this product *(Tan et al., 2018; FAO., 2026)*.

During mechanized harvesting, cassava roots sustain various types of mechanical damage in the processes of digging, root-soil separation, collection and transportation *(Yang et al., 2026)*. Common damage forms include shearing by the cutting edge of digging blades, compression from digging and separating components, and impact between roots or between roots and container walls during collection and conveying. Such mechanical damage severely impairs the subsequent processing quality and thus reduces the commercial value of cassava roots *(Li et al., 2023; Dankwa et al., 2025; Sreekumar et al., 2026)*.

After harvesting, cassava roots are first sliced, followed by natural or mechanical drying to reduce the moisture content of slices for the production of dried cassava chips *(Simo-Tagne et al., 2021; Gao et al., 2022; Krishnakumar et al., 2022)*. Therefore, investigating the mechanical properties of fresh cassava roots at the harvesting stage is of great significance for the structural design, parameter optimization and operational parameter selection of cassava harvesters and dedicated cassava slicers. To date, numerous experimental studies have been conducted worldwide on the mechanical properties of common crop materials, mainly focusing on crop rhizomes, fruits, stems and leaves *(Fan et al., 2022; Hostetler et al., 2022; Jin et al., 2024; Zhang et al., 2025)*.

Yang Wang et al. prepared cylindrical and polyhedral specimens from cassava roots and measured their tensile, compressive and shear strengths as well as elastic modulus via physical tests *(Yang et al., 2011)*.

Yan Mei et al. adopted cuboid specimens of cassava roots to investigate their compressive and shear mechanical characteristics *(Yan et al., 2013; Yan et al., 2013)*. Nevertheless, these studies only tested partial tissues of cassava roots rather than the whole root. Cassava roots at the harvesting stage have a complex structure, with distinct mechanical performances among the outer cortex, inner cortex, parenchyma and pith. Mechanical parameters obtained from partial tissues fail to reflect the actual mechanical properties of intact cassava roots.

In this study, intact fresh cassava roots at the harvesting stage were selected as test materials. Combined with the main damage characteristics during harvesting and the subsequent slicing process, physical experiments were carried out to investigate the effects of major test factors on the compressive, shear and bending mechanical properties of cassava roots. Based on the analysis of experimental results, the variation laws of mechanical properties affected by each factor were summarized. The findings can provide fundamental data and theoretical support for the structural design of key components and the selection of operational parameters of low-damage and high-efficiency cassava harvesters and slicers.

MATERIALS AND METHODS

Compression mechanical property test

Preparation of compression specimens

The test materials were collected from the full mechanization demonstration base for cassava and pineapple production at the Agricultural Machinery Research Institute, Chinese Academy of Tropical Agricultural Sciences, Zhanjiang City, Guangdong Province.

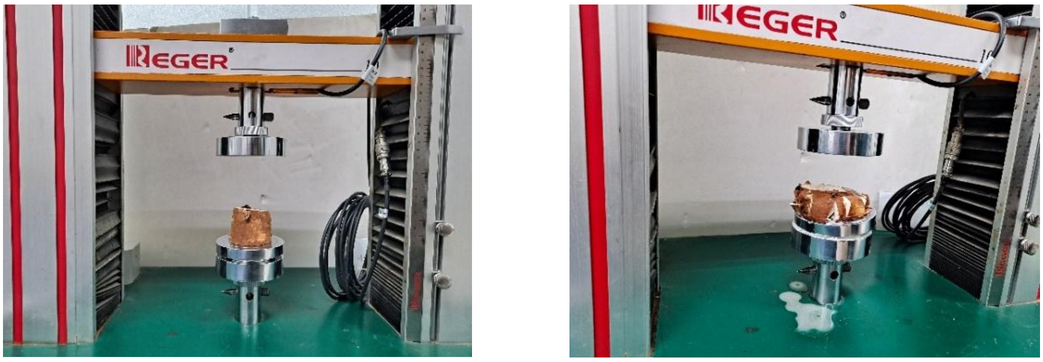
The cassava variety used was *Nanzhi 199*. Intact cassava roots with uniform shape, free from diseases, pests and mechanical damage were selected and cleaned to remove surface soil for standby.

Shear specimens with a length of 50 mm were prepared from the head, middle and tail parts of the cassava roots, and the average diameter at the middle of each specimen was recorded. Both cut ends of the finished specimens were immediately sealed with paraffin to mitigate test errors caused by water loss.

Fig. 1 - Compressive specimens

Test apparatus

The testing device adopted was the RGM-4005 microcomputer-controlled fully digital electronic universal material testing machine manufactured by Reger Instruments. This equipment is mainly used to determine the mechanical properties and related physical parameters of various materials under tension, compression, bending and shear conditions. Equipped with different fixtures, it can also perform tests such as tearing, peeling and puncture. A disc-type compression fixture was used in this experiment. The structural appearance and technical parameters of the testing machine are presented below. Other auxiliary tools included a vernier caliper, paraffin, utility knife and steel ruler.



a. Universal material testing machine **b. Post-compression state of samples**

Fig. 2 - Reer RGM-4005 electronic universal testing machine

Table 1

Nameplate parameters of electronic universal testing machine

Item	Parameter value
Tester model	RGM-4005
Maximum load capacity	5 kN
Test speed range	0.001–500 mm/min
Relative error of test force	Within ±1% of indicated value
Relative error of speed	Within ±1% of indicated value
Relative error of displacement	Within ±1% of indicated value
Tensile test stroke	800 mm
Effective test width	400 mm
Motor power	0.4 kW
Overall dimension of main machine	975 × 460 × 2170 mm
Weight of main machine	Approx. 200 kg

Experimental design and methods

Cassava roots are generally quasi-cylindrical, conical, or spindle-shaped, and their compressive mechanical properties differ among the head, middle, and tail regions *(Yang et al., 2011)*. Based on the structural characteristics of cassava roots and previous literature *(Yang et al., 2022; Dai et al., 2026)*, three experimental factors were selected for this study, namely loading direction, loading speed, and root position. The experimental factors and corresponding levels are listed in Table 2.

Table 2

Factors and levels for compression test

Level	Loading direction (A)	Loading speed (B) / (mm/min)	Root position (C)
1	Axial	50	Head
2	Major radial	100	Middle
3	Minor radial	150	Tail

According to the selected experimental factors and levels, an $L_9(3^4)$ orthogonal array was adopted for the compression mechanical property test of cassava tuberous roots. A total of 9 groups of tests were conducted in each run, and all tests were repeated once, resulting in 18 test groups in total. The compression fixture was correctly mounted on the electronic universal testing machine. A cassava tuberous root sample was placed at the center of the lower platen of the compression fixture, and the upper platen was adjusted until its bottom surface just contacted the sample. After setting the operating parameters of the testing machine, the test was initiated by clicking the "Run" button. The compressive load increased gradually. When the compression deformation reached the maximum value, the cassava tuberous root fractured, accompanied by a sharp drop in load reading, and the test was terminated. All experimental data were automatically recorded by the computer.

The compressive stress calculation formula for cassava roots is expressed as:

$$\sigma_y = \frac{F_y}{A} \tag{1}$$

In equation:

σ_y- Maximum compressive stress of specimen, [MPa];

F_y- Maximum compressive load in compression test, [N];

A - Cross-sectional area of specimen, [mm^2].

The calculation formula for the cross-sectional area under axial compression is expressed as:

$$A_y = \pi \left(\frac{D_b + D_s}{4}\right)^2 \tag{2}$$

In equation:

A_y- Axial cross-sectional area of specimen, [mm^2];

D_b- Maximum outer diameter at the middle of specimen, [mm];

D_s- Minimum outer diameter at the middle of specimen, [mm].

The calculation formula for cross-sectional area under radial compression is expressed as:

$$A_{y1} = 50D_b \tag{3}$$

$$A_{y2} = 50D_s \tag{4}$$

In equation:

A_{y1}- Cross-sectional area of specimen at major diameter, [mm^2];

A_{y2}- Cross-sectional area of specimen at minor diameter, [mm^2].

Shear mechanical property test

Preparation of shear specimens

Test materials were sourced from the same batch used in the compressive mechanical property test. Specimens with a length of 50 mm were prepared from the head, middle and tail portions of cassava roots, and the average diameter at the middle position of each specimen was recorded. After preparation, the cut ends of specimens were immediately sealed with paraffin to minimize experimental errors induced by moisture loss.

Test apparatus

A computer-controlled fully digital universal material testing machine (Model RGM-4005, Reger Instrument, Shenzhen, China) was adopted for the test. A self-designed shear fixture dedicated to cassava roots was equipped in this experiment. The fixture consists of two components: a blade clamping seat and a specimen supporting base, wherein the supporting base enables adjustment of the angle between the blade and the axial line of cassava root specimens. Additional experimental accessories include shear blades, vernier calipers, paraffin, utility knives and steel rulers. The operation mode of shear test and fixture structure are shown in figure 3.

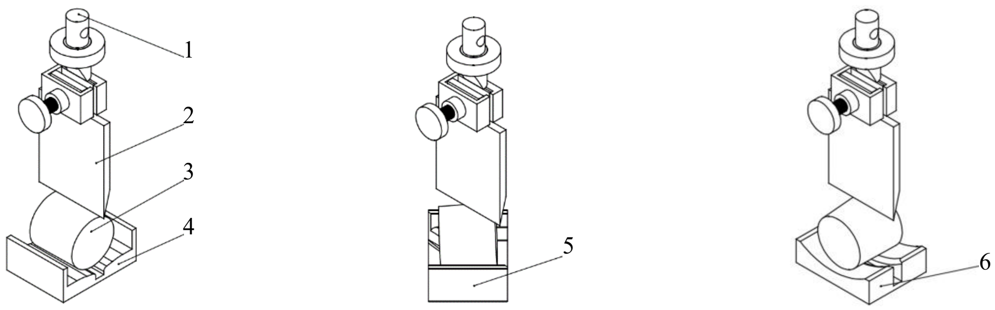


Fig. 3 - Shear mode and fixture

1. Blade clamping seat; 2. Shear blade; 3. Shear specimen; 4. Axial shear supporting base; 5. Lateral 45° shear supporting base; 6. Radial shear supporting base

Experimental design and methods

Based on previous studies on shear mechanical properties of rhizome crops and the actual slicing operation of cassava roots *(Yan et al., 2013; Chen et al., 2024)*, four experimental factors including shear angle (D), blade cutting edge angle (E), root position (F) and loading speed (G) were selected to investigate the shear mechanical characteristics of cassava roots. The shear angle is defined as the included angle between the cutting edge of the blade and the central axis of specimens, with three levels of 0°, 45° and 90°. A single-edge cutter was adopted in this test, and the blade cutting edge angles were set as 15°, 30° and 45°. Three root positions (head, middle and tail of cassava roots) were chosen, and loading speeds were designed at 50 mm/min, 100 mm/min and 150 mm/min. The experimental factors and corresponding levels are listed in Table 3.

Table 3

Factors and levels for shear test

Level	Shear angle (D)	Blade cutting edge angle (E)	Root position (F)	Loading speed (G) / (mm/min)
1	0°	15°	Head	50
2	45°	30°	Middle	100
3	90°	45°	Tail	150

According to the selected experimental factors and levels, an orthogonal array test $L_9(3^4)$ was adopted for the shear mechanical property test of cassava roots. Nine groups of tests were conducted per trial, and each test was replicated once, resulting in a total of 18 experimental groups. A tension-compression load cell was mounted on the sensor holder of the universal material testing machine. Subsequently, the blade fixture and specimen supporting base of the self-made cassava root shear fixture were connected to the upper and lower fixture joints of the testing machine, respectively, to complete the assembly of the load cell, fixture and testing equipment. The shear specimen was placed on the specimen supporting base. The moving crosshead of the universal testing machine was adjusted to make the cutting edge tangent to the outer cylindrical surface of the specimen. The specimen base of the fixture was further adjusted to set a specified included angle between the central axis of cassava root and the blade cutting edge. After parameter configuration on the testing machine, the test was initiated by clicking the “Run” button and terminated once the specimen was completely cut off by the blade. All test data were automatically recorded by the supporting software of the universal material testing system.

The shear stress calculation formula of cassava roots is expressed as:

$$\sigma_j = \frac{F_j}{A_j} \tag{5}$$

where:

σ_j- Maximum shear stress of specimen, [MPa];

F_j- Maximum shear load during shear test, [N];

A_j- Shear cross-sectional area of specimen, [mm^2].

The calculation formula for cross-sectional area under axial shear is given as:

$$A_j = 50D_j \tag{6}$$

where:

D_j- Average outer diameter of specimen, [mm].

The calculation formula for cross-sectional area under both axial 45° and 90° shear is defined as:

$$A_j = \pi \left(\frac{D_j}{2}\right)^2 \Big/ \sin\alpha \tag{7}$$

where: α- Included angle between blade cutting edge and specimen central axis, [rad].

Bending mechanical property test

Preparation of bending specimens

Test materials were consistent with those used for the compression mechanical property test. Referring to relevant literatures *(Yan et al., 2013; Chen et al., 2024)*, ten bending specimens with a length of 200 mm were prepared. In the preparation process, the head and tail of cassava roots were cut off and only the middle nearly cylindrical part was reserved. The outer diameters at the front, middle and rear positions of each specimen were measured and recorded by a vernier caliper, and the average value was regarded as the specimen diameter. After specimen fabrication, both end cross-sections were sealed with paraffin wax, and the bending test was conducted immediately.

Test apparatus

A computer-controlled fully digital universal material testing machine (Model RGM-4005, Reger Instrument, Shenzhen, China) was adopted for the test. The fixture consisted of the original indenter matched with the tester and self-fabricated lower supports, as shown in Figure 4. Other experimental tools included a vernier caliper, paraffin wax, utility knife and steel ruler.

Fig. 4 - Bending test of cassava roots

1. Upper indenter; 2. Compression specimen; 3. Left lower support; 4. Right lower support

Experimental design and methods

The three-point bending method was adopted for the bending mechanical property test. The span of the three-point bending fixture on the universal testing machine was adjusted to 100 mm, with the midpoint of the span set as the indentation position of the upper indenter. The prepared cassava root specimen was placed on the supports, and the test was performed at a loading speed of 2 mm/min until complete fracture of the specimen. The double-layer peel of cassava root is approximately 2 mm thick and tightly bonded to the flesh; thus, cassava roots are simplified as cylindrical materials. Based on the load data recorded by the testing machine, the flexural modulus of elasticity and flexural strength of cassava roots can be calculated.

The bending moment equation for three-point bending test of cylindrical specimens is given as *(Liu., 2004)*:

$$M_w = \frac{F_w L}{4} \tag{8}$$

In equation:

M_w- Bending moment of specimen, [N·mm];

F_w - Maximum bending load of specimen, [N];

L - Bending span of specimen, [mm].

The moment of inertia and flexural section modulus of cylindrical specimens are expressed as *(Liu., 2004)*:

$$I_w = \frac{\pi d_w^4}{64} \tag{9}$$

$$W_w = \frac{\pi d_w^3}{4} \tag{10}$$

where:

I_w- Moment of inertia of specimen, [mm^4];
d_w- Diameter of specimen, [mm];
W_w- Flexural section modulus of specimen, [mm^3].

The calculation formula for flexural elastic modulus of the specimen is as follows:

$$E_w = \frac{F_w L^3}{48 y_w I_w} \tag{11}$$

where:

E_w- Flexural elastic modulus of specimen, [MPa];
y_w- Bending deflection of specimen, [mm].

The calculation formula for flexural strength of the specimen is as follows *(Liu., 2004)*:

$$\sigma_w = \frac{M_w}{W_w} \tag{12}$$

where: σ_w- Flexural strength of specimen, [MPa].

RESULTS AND ANALYSIS

Compression mechanical property test results and analysis

Test results

Loading direction, loading speed and root position were selected as influencing factors for compression tests of cassava roots at harvest stage, while compressive stress and compression deformation were taken as evaluation indices. After data calculation and screening, the measured values of compressive stress and compression deformation are listed in Table 4.

Table 4

Compression test results of harvest-stage cassava roots

Test No.	Level combination	Compressive stress (MPa)		Compression deformation (mm)	
		I	II	I	II
1	$A_1B_1C_1$	1.12	1.00	15.94	12.42
2	$A_1B_2C_2$	1.09	1.73	15.05	15.18
3	$A_1B_3C_3$	1.28	1.56	14.38	13.98
4	$A_2B_1C_2$	0.32	0.30	8.29	7.66
5	$A_2B_2C_3$	0.45	0.56	5.79	11.85
6	$A_2B_3C_1$	0.40	0.21	7.29	9.49
7	$A_3B_1C_3$	0.70	0.34	15.84	8.99
8	$A_3B_2C_1$	0.40	0.35	10.25	6.66
9	$A_3B_3C_2$	0.26	0.38	10.69	7.99

Results analysis

ANOVA of compression test data for cassava roots was conducted with SPSS, and the results are shown in Tables 5 and 6.

Table 5

ANOVA of compressive stress results

Source	Type III Sum of Squares	df	Mean Square	f	Sig.
Corrected Model	1.831[a]	8	0.229	7.953	0.003
Intercept	5.422	1	5.422	188.38	<0.001
Loading direction (A)	1.427	2	0.713	24.79	<0.001
Loading speed (B)	0.251	2	0.126	4.38	0.047
Root position (C)	0.153	2	0.077	2.67	0.122
Error	0.259	9	0.029	—	—
Total	7.512	18	—	—	—
Corrected Total	2.090	17	—	—	—

Note: R^2 = 0.876 (Adjusted R^2 = 0.765)

Table 6

ANOVA for compression deformation results

Source	Type III Sum of Squares	df	Mean Square	f	Sig.
Corrected Model	168.720[a]	8	21.090	3.757	0.032
Intercept	2215.920	1	2215.920	394.70	<0.001
Loading direction (A)	135.611	2	67.806	12.07	0.003
Loading speed (B)	21.352	2	10.676	1.900	0.202
Root position (C)	11.757	2	5.879	1.046	0.389
Error	50.530	9	5.614	—	—
Total	2435.170	18	—	—	—
Corrected Total	219.250	17	—	—	—

Note: R^2 = 0.770 (Adjusted R^2 = 0.565)

Loading direction (A) exerted an extremely significant effect on both compressive stress and compression deformation of cassava roots (P < 0.001 and P = 0.003, respectively). Loading speed (B) significantly affected compressive stress (P = 0.047) but showed insignificant influence on compression deformation (P > 0.05), while root position (C) had no significant impact on the two indicators (P > 0.05). The factor influence order was loading direction > loading speed > root position, and the determination coefficients indicated satisfactory fitting of the two ANOVA models.

As shown in the experimental data in Table 4, the average axial compressive stress is 3.45 times and 3.24 times the average compressive stress under large radial and small radial compression, respectively. The compressive stress varies from 0.21 MPa to 1.73 MPa with an overall average of 0.69 MPa. Loading direction exerts the most significant influence on the compressive stress of cassava roots, and the axial compressive strength is higher than the radial compressive strength.

Shear mechanical property test results and analysis

Test results

The load-displacement curves automatically recorded by the software of an electronic universal testing machine during shear tests on harvest-stage cassava roots were processed to obtain the maximum shear force of each sample. Combined with the premeasured root diameter of each replicate group, the maximum shear stress was calculated in accordance with the specified data processing method, and the calculated results are listed in Table 7.

Table 7

Shear test results of harvest-stage cassava roots

Test No.	Level combination	Maximum shear stress (kPa)	
		I	**II**
1	$D_1E_1F_1G_1$	37.99	87.86
2	$D_1E_2F_2G_2$	68.78	95.13
3	$D_1E_3F_3G_3$	100.50	97.25
4	$D_2E_1F_2G_3$	99.98	59.24
5	$D_2E_2F_3G_1$	86.48	64.15
6	$D_2E_3F_1G_2$	154.22	128.93
7	$D_3E_1F_3G_2$	77.90	67.75
8	$D_3E_2F_1G_3$	71.07	90.48
9	$D_3E_3F_2G_1$	112.28	78.96

Results analysis

ANOVA of shear test data for cassava roots was conducted with SPSS, and the results are shown in Tables 8.

Table 8

ANOVA for maximum shear stress results

Source	Type III Sum of Squares	df	Mean Square	f	Sig.
Corrected Model	8449.965[a]	8	1056.246	2.508	0.096
Intercept	7919.111	1	7919.111	18.806	0.002

Source	Type III Sum of Squares	df	Mean Square	f	Sig.
Shear angle (D)	1121.622	2	560.811	1.332	0.311
Blade cutting edge angle (E)	5487.648	2	2743.824	6.516	0.018
Root position (F)	523.623	2	261.812	0.622	0.559
Loading speed (G)	1317.072	2	658.536	1.564	0.261
Error	3789.928	9	421.103	—	—
Total	150744.510	18	—	—	—
Corrected Total	12239.893	17	—	—	—

Note: R^2 = 0.690 (Adjusted R^2 = 0.415)

ANOVA results indicated that blade cutting edge angle (E) exerted a significant effect on the maximum shear stress of cassava roots ($P < 0.05$), which was the dominant factor governing the shear mechanical properties of cassava roots. Shear angle (D), root position (F) and loading speed (G) had no statistically significant influence on maximum shear stress ($P > 0.05$). The priority of factor influence followed the order: blade cutting edge angle (E) > loading speed (G) > shear angle (D) > root position (F). The determination coefficient R^2 = 0.690 and adjusted R^2 = 0.415 indicated that the regression model had acceptable fitting performance for experimental analysis.

Cassava roots consist of epidermis, endodermis and flesh, with respective mass proportions of 1.0% – 2.0%, 10.0% – 14.0% and 80.0% – 90.0%, showing relatively uniform internal composition. At the initial cutting stage, shear load increases nearly linearly with rising displacement, and the load-displacement curve approximates a straight line. After the shear load reaches its peak value, further increase of cutting displacement leads to two distinct load-falling patterns: sharp cliff-type drop and fluctuating stepwise decline. The difference originates from specimen dimension, loading speed and blade cutting edge angle. Larger outer diameter, loading speed or blade cutting edge angle causes wedge-induced fracture inside cassava roots during cutting, resulting in abrupt cliff-like load reduction; in contrast, wedge-induced fracture disappears when any of the three parameters is set at a low level. According to shear test data, the maximum shear stress of harvest-stage cassava roots ranges from 37.99 kPa to 154.22 kPa with an average value of 87.72 kPa. ANOVA confirms that blade cutting edge angle imposes a statistically significant effect on the shear strength of cassava roots.

Bending mechanical property test results and analysis

Test results

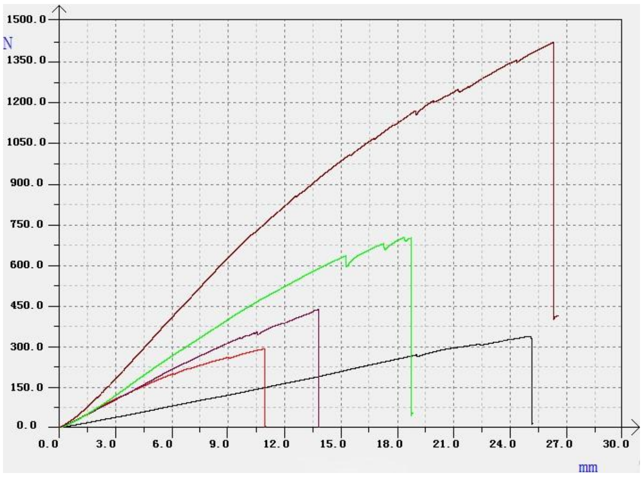
In the bending test of harvest-stage cassava roots, the maximum bending load F_w and bending deflection y_w for each specimen were obtained from load–displacement curves automatically recorded by the electronic universal testing machine. The bending elastic modulus E_w and flexural strength σ_w were calculated according to Eqs. (8) – (12), and the results are summarized in Table 9.

Table 9

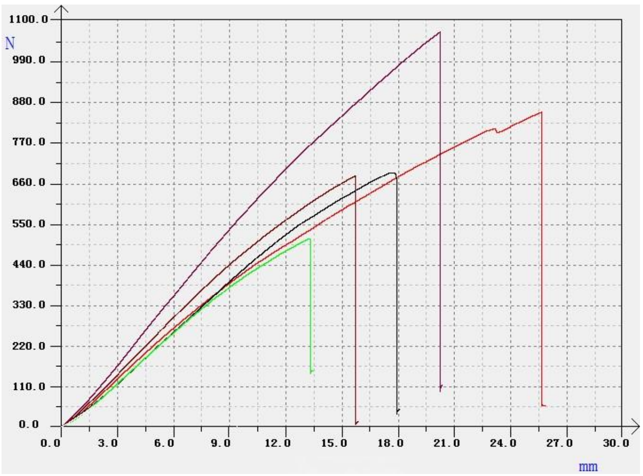
Bending test results of harvest-stage cassava roots

Test No.	Specimen diameter d_w (mm)	Bending deflection y_w (mm)	Maximum bending load F_w (N)	Bending elastic modulus E_w (MPa)	Flexural strength σ_w (MPa)
1	37.33	9.40	227.04	5.28	1.11
2	39.35	10.95	290.92	4.70	1.22
3	43.30	25.03	336.58	1.62	1.06
4	46.07	13.81	436.13	2.98	1.14
5	52.99	18.38	700.71	2.05	1.20
6	53.59	17.74	686.50	1.99	1.14
7	54.78	15.73	678.38	2.03	1.05
8	55.70	25.70	850.04	1.46	1.25
9	61.66	20.24	1065.83	1.55	1.16
10	61.78	26.34	1416.46	1.57	1.53

Figure 5 shows the load-displacement curves obtained from three-point bending tests of harvest-stage cassava root specimens.



a. Test 1



b. Test 2

Fig. 5 - Bending load–deformation curves

Results analysis

As listed in Table 9, the maximum bending load of cassava roots specimens increases gradually with rising specimen diameter. Quadratic regression fitting was conducted between measured maximum bending load and specimen diameter, and the fitted equation is expressed as $F_w = 1.56d_w^2 - 112.3d_w + 2311$ with a determination coefficient R^2 = 0.9429, revealing that the ultimate bearing bending load has a positive quadratic correlation with root diameter. The bending elastic modulus generally declines as specimen diameter increases, while bending strength fluctuates slightly within the range of 1.05 - 1.53 MPa with an average value of 1.19 MPa. Owing to the high moisture content inside cassava roots, a great deal of sap exudes from loading and supporting positions during bending test, which imposes a certain influence on the measured bending strength. As illustrated in Figure 5, the whole bending process of harvest-stage cassava roots can be divided into two stages: quasi-elastic deformation stage and brittle fracture stage. At the initial loading phase, bending deformation is approximately proportional to the applied load. Once the load reaches the critical yield point, the specimens rupture instantly without apparent plastic deformation accompanied by crisp cracking sound, meanwhile the bending load drops sharply in cliff-type form, which demonstrates obvious brittle fracture property of cassava roots.

CONCLUSIONS

In this study, mechanical tests including compression, shear and bending were carried out on intact cassava roots at the harvesting stage. Based on systematic experimental analysis, the main research conclusions are summarized as follows:

(1) The compression test results show that the loading direction has a significant influence on the compressive stress of cassava roots, while the loading speed and root position have no significant effect. All three experimental factors (loading direction, loading speed and root position) exhibit insignificant effects on the compressive deformation of cassava roots. The compressive stress of harvest-stage cassava roots ranges from 0.21 MPa to 1.73 MPa, with an average value of 0.69 MPa, and the axial compressive strength is generally higher than the radial compressive strength.

(2) The shear test results indicate that the influencing order of each factor on the maximum shear stress of cassava roots is blade cutting edge angle (E) > loading speed (G) > shear angle (D) > root position (F). Only the blade cutting edge angle presents a significant effect on the shear mechanical properties, while the other factors have no significant influence. The shear stress of harvest-stage cassava roots varies from 37.99 kPa to 154.22 kPa, with an average value of 87.72 kPa.

(3) The bending test results demonstrate that the bending elastic modulus decreases gradually with the increase of cassava root diameter, while the bending strength fluctuates slightly in the range of 1.05–1.53 MPa, with an average of 1.19 MPa. Quadratic regression fitting was conducted between the maximum bending load and root diameter, and the coefficient of determination (R^2) reaches 94.29%, which indicates high fitting accuracy and verifies the reliability of the test data and the applicability of the regression model.

(4) By comparing the average failure stress obtained from compression, shear and bending tests, the damage priority of cassava roots under mechanical load is determined as shear damage, compressive damage and bending damage. This study systematically clarifies the basic mechanical response rules and mechanical damage characteristics of harvest-stage cassava roots. The research results can provide reliable theoretical support and basic test data for the structural parameter optimization of key components of dedicated cassava harvesters, the matching of field operation parameters, and the optimal selection of tool edge angles for cassava slicing machinery.

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