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TEST AND ANALYSIS ON THE MECHANICAL PROPERTIES OF CASSAVA STALKS

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ABSTRACT

The mechanical properties of the cassava stalk play an important role in the design of cassava harvesting and cassava stalk recycling machines. Axial and radial compression tests with different loading rates were conducted on 3 groups of cassava stalks with 5 moisture contents in 3 stalk levels at the harvest time. Sliding cutting tests as well as cutting tests with different loading rates and cutting angles were conducted on 5 groups of root samples of cassava stalks having 5 moisture contents at harvest time. The overall failure loads and the strengths of the cassava stalks were analyzed with respect to the different factors under investigation in this study using SAS software. The following results were obtained: in the axial compression of the stalks, the average values of the failure load and compressive strength were respectively for different levels 2187.28N and 10.65MPa (the upper), 3867.63N and 11.97MPa (the middle) and 5892.03N and 12.81MPa (the lower); in the radial compression of the stalks, the average values of the failure load and compressive strength were respectively for different levels 345.40N and 1.24MPa (the upper), 542.90N and 1.19MPa (the middle) as well as 662.97N and 1.09MPa (the lower). For the sliding cutting, the range of the failure load was between 241.22~1150.32 N with an average value of 662.30 N and the range of the strength was between 1.55~7.51MPa with an average value of 4.20MPa. For the cutting, the range of failure load was between 261.84~1235.64 N with an average value of 649.24N and the range of the strength was between 1.12~4.99MPa with an average value of 2.17MPa. The ANOVA results showed that the impacts of the moisture content and the stalk levels on the axial compressive strength were significant ($P<0.05$). As well, the moisture content and the choice of stalk levels, whether low, medium, or high stalk, had no significant impact on the radial compressive strength ($P>0.05$). The sliding cutting angle and loading rates respectively had a significant and a highly significant impact on the sliding cutting strength ($P<0.05$), as well as the moisture content, cutting angle and loading rate were significant to the cutting strength ($P<0.05$).

Key words: Cassava Stalks; Mechanical Properties; Compression; Shearing;

INTRODUCTION

The trend of bioethanol technology development is to develop non-grain bioethanol (Li *et al.*, 2008). As compared with other non-grain based crops, cassava can bring significant economic and social benefits as well as a poverty-relief effect when it is used to produce bioethanol (Jiang *et al.,* 2012, and Feng *et al.,* 2011). Ministry of Agriculture, China has planned to increase the cultivated area of cassava to 1 Mhm^2 in 2015(Qin *et al.*, 2011).

However, cassava stalk harvesting is a bottleneck of the cassava industry, and a shortage of agricultural workers is the main motivation behind the search for mechanical solutions (Akhir, *et al.* 2002). From a mechanical viewpoint, the crop characteristics must be observed, which are necessary to develop profitable and efficient alternatives to manual harvesting techniques. For an example, Lungkapin, measured the mechanical properties of cassava to lay the foundation for the design of mechanical cassava planting (. Lungkapin, *et al.* 2007). Many cassava stalks will be produced after cassava harvest. It was reported that China's yield of cassava (fresh) in 2009 was nearly 7.2711 million tons (Xie G.H. *et al.* 2011), which means that 12.7563 million tons of stalks were produced as calculated by a cassava stalks coefficient 0.57 (Li *et al.*2011). Currently, only a small proportion of the domestic cassava stalks were preserved as provenance and some were used in edible mushroom base, straw gasification, field compost, and breaking and mulching (Li *et al.*2009, Luo *et al.*2008, Qin *et al.*2013). Most of the stalks were not used in a utilitarian manner but stacked and discarded or burned in fields, which polluted the environment and was a huge waste of resources (Tao *et al.*2011).

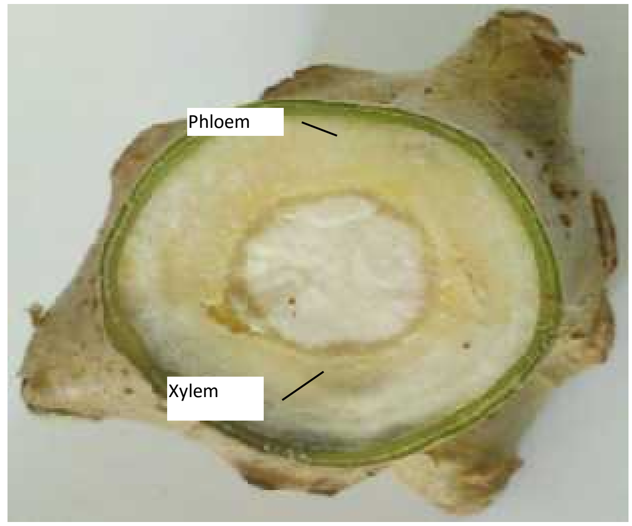
The mechanized treatment of the stalks is an important part of the rational utilization of cassava. A knowledge of the physical and mechanical properties of cassava stalks can provide theoretical basis and basic technical parameters for the mechanized treatment. Gakwaya had conducted mechanical properties tests of the compression and bending strength on cassava stalks and studied the impact of the sampling position and the loading rate on the compressive strength as well as the impact of the sampling length on the bending strength (Gakwaya . *et. al.*, 1990). Xue . measured the radial compressive strength, axial compressive strength, radial tangent strength, axial tangent strength, and the three-point bending strength of cassava stalks with a moisture content of 68.86% and a loading rate of 50mm/minute and results were respectively 0.76MPa, 1.51MPa, 2.23MPa, 0.32MPa and 5.94MPa (Xue Z. *et. al.*2014). Yang *et al*. measured the compressive strength, shearing strength, tensile strength, and elasticity modulus of the cassava stalk, and supported the assertion that it was a type of anisotropic material (Yang *et al.*2011). Yan M. developed instruments and conducted bending and shearing tests on 4 varieties of cassava. Their results showed that as the moisture content was reduced, the cutting force increased and then reduced (Yan *et al.*2013).

Currently, there are many researches about dig the cassava roots (Odigboh *et al.* 1982 and 1991, Peipp *et al.*1991 Sukra , *et al.*1986 and 1994 and 1996. Agbetoye *et al.* 1998 and 2000), but not much research about the mechanical properties of cassava stalks has been seen in the world. This study attempts to explore the changes in the stalks' mechanical properties under different factors such as moisture content, loading rate, sampling position and cutting angle, and the significance of each factor on the index relates to the mechanical properties of the cassava stalks. In this article, the mechanical properties tests of compression and shearing were conducted to discover the impact of different factors and the number of the factors on the compressive strength and shearing strength on cassava stalks.

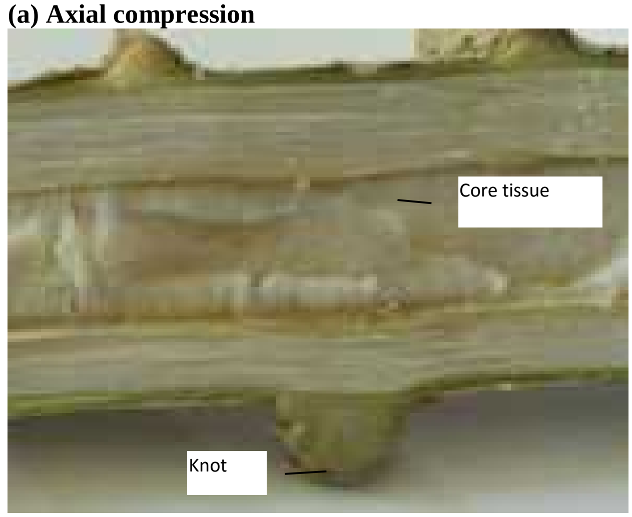
MATERIALS AND METHODS

The stalks of cassava SC 205, which were widely cultivated in Guangdong Province and in the Guangxi Autonomous Region were selected as the test subjects. The stalks were sampled in Mazhang District of Zhanjiang, Guangdong Province on 20th of December 2013. The cassava stalks selection grows good, straight, no worm and no defects. The branches of the samples were removed and the surface of the stalks were cleaned manually.

A cassava stalk mainly consists of the core tissure, the xylem, the phloem, and the knot. The core tissue, which delivers and stores water during the growth of the cassava stalk, is analogous to a sponge. Preliminary compression tests on the core tissue and the xylem showed that the strength of the core tissue was negligible compared with the strength of the xylem. The knot was simply a succulent structure with moisture content of 98%, the strength of which was also negligible compared with the strength of the xylem. So, the cassava stalk was regarded as loop material in this study.



(a) Axial compression



(b) Radial compression

Fig. 1 The layered structure and arrangement of the inner stalk of the cassava plant

(a) Before Compression

(b) After Compression
Fig. 2 Compression of cassava's core tissue

The conventional drying method was used to measure the moisture content of the sample. The experimental instrument were 101-1 digital drying oven (a similar instrument can be purchased from Shanghai Yetuo Instrument Co., Ltd.), electronic scale (accuracy 0.01g), glass dehydrator, and carpenter's saw. The measuring method is shown as follows: selected 2 cassava stalks randomly in each test; took samples (length= 60 mm) from 3 levels (upper, middle, lower) of the stalks; weighed the 6 samples to get the weight M1; put the samples into the drying oven to dry them at the temperature of 100 ℃ for 24 h and weight of all samples were taken. simultaneously, weighed the samples at every 3 h interval until the difference between two adjacent results were less than 0.01, and then samples were considered to be fully dry. The samples were kept in the glass dehydrator to cool them to the ambient temperature; weighed the samples to get the weight M2. The calculation formula of the moisture content is shown as below:

$$\text{Moisture content (wb)} = \frac{M1 - M2}{M1} \times 100\% \quad (1)$$

Compression test method: The compression test of the stalks was conducted based on the moisture content. The test was carried out in 3 repeats, in each of which 3 levels (upper, middle and lower) of the samples were tested individually and 5 loading rates(20 mm/min,40 mm/min, 60 mm/min, 80 mm/min and 100 mm/min) were considered. according to the length. For each stalk section, 2 adjacent smaller sections with a length of 40 mm were taken from each section, one for axial compression and the other for radial compression. The Universal Material Tester JS-805 (Dong Guan Jits Tech Co., Ltd.) was used for the compression test. During the axial compression, abrasive paper was used to polish the two ends of the sample to prevent inclination as well as to ensure that even pressure is applied during the testing process. The compression test is shown below in Fig. 3.

(a) Axial compression

(b) Radial compression
Fig. 3 Method for compression test

The compressive strength of the cassava stalk was calculated using the following formula (Liu H.W..1992)

$$\pm = F/S \quad (2)$$

Where, F refers to the maximum load during compression, A refers to the average sectional area of the stalk,

Average sectional area of the axial compression was calculated with the following formula

$$\overline{D} = (D1 + D2 + D3)/3$$

$$\overline{d} = (d1 + d2 + d3)/3$$

$$S = ® \frac{\overline{D}^2 - \overline{d}^2}{4} \quad (3)$$

where, D_1, D_2 and D_3 refer to the outer diameter of the stalk in 3 times of measurements, and d_1, d_2 and d_3 refer to the inner diameter of the stalk in 3 times of measurement.

The sectional area of the radial compression was calculated with the following formula

$$S = (\overline{D} - \overline{d}) \times l \qquad (4)$$

where, *l* refers to the length of the sample in the radial compression.

Shearing test method: The shearing tests included sliding cutting and cutting tests. The sliding cutting tests were conducted with 5 factors of moisture content(68.85%, 67.15%, 64.65%, 62.14% and 60.44%), 5 loading rates (30mm/min, 60mm/min, 90mm/min, 120mm/min and 150mm/min), 5 blade angles (0°, 15°, 30°, 45° and 60°) and 5 blade sliding cutting angles (0°, 12°, 24°, 36° and 48°). The cutting tests were conducted with 5 factors of moisture content, 5 loading rates (30mm/min, 60mm/min, 90mm/min, 120mm/min and 150mm/min) and 5 cutting angles (0°, 10°, 20°, 30° and 40°). The L25(5^4) orthogonal test was adopted in the sliding cutting tests as well as cutting tests in this study due to the various factors and stalk levels in the shearing test.

In order to conduct the shearing test conveniently and effectively, the tools and support implements shown in Fig.4 were manufactured. 25 combinations of sliding cutting angle and blade angle could be realized through 5 combinations of the blade and handle. 5 shearing angles could be realized with the supporter in the shearing test. The tools and the supporter were granted by the National Utility Model Patent (Patent No. of the tool: ZL201420098930.0, Patent No. of the supporter: ZL201420098917.5). The blade was made of mild steel treated by quenching and the edge angle was 2.2°.

(a) Sliding cutting tools and support (b) Cutting tools and support
Fig. 4 Tools and support for shearing test

The shearing strength in the sliding cutting test was calculated using the formula below:

$$_{2} = \frac{F\cos}{S} \qquad (5)$$

where, F refers to the maximum load during compression, S refers to the sectional area of the sample, the calculation method was the same as that in the axial compression test. refers to the blade angle of sliding cutting.

The shearing strength in the cutting test was:

$$_{2} = \frac{F\sin}{S} \qquad (6)$$

where, F and S remain the same as in (5). refers to the blade angle of cutting.

In the sliding cutting test, the lower supporter of the instrument was replaced by the homemade supporter and the tools shown in Fig.5. According to the orthogonal test table, 5 cutter handles were selected. Each handle has 5 pairs of installation holes and could be used to realize 5 different sliding cutting angles fixing the blade onto different holes as illustrated in Fig.5. In the cutting test, the handle (cutting angle 0°) and blade (installing hole with sliding cutting angle 0°) were mounted in advance, and the 5 cutting angles were achieved by means of adjusting the supporting beam on the supporter to different supporting holes.

Fig. 5 Sliding cutting test

Fig .6 Cutting test

RESULT AND ANALYSIS

Result and analysis of compression test

(1) Result and analysis of axial compression test

As shown in the 3 curves of the load-displacement for the axial compression test (Fig.7), after the test started, the load increased linearly as the displacement increased, and the sample was damaged when the load was increased to the maximum. The load reduced with steady increase in displacement. Depending on different positions, the max load ranges between 505.53~6253.24 N. It was observed on the testing site that there was no crisp sound when the sample was damaged and liquid flowed from the sample during the compression.

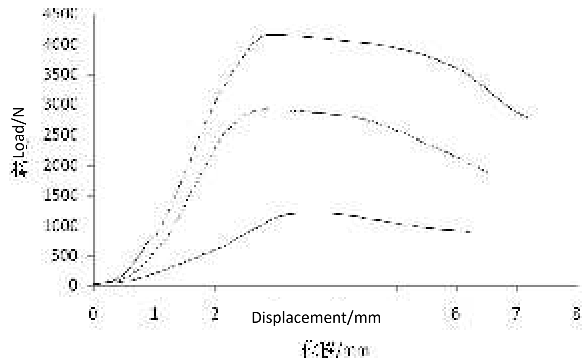


Fig.7. The curve of load-displacement for the axial compression test

In Fig. 8, the effect of moisture content and growth on the maximum load of the stalk in the axial compression, with the same moisture content, the maximum load of the cassava stalk in the axial compression reduced as the sampling height increased. With the moisture content between 68.85% and 64.65%, the maximum load of the middle and lower stalk levels reduced and then increased as the moisture content reduced. The maximum load tolerated by the upper section was reduced as the moisture content decreasing.

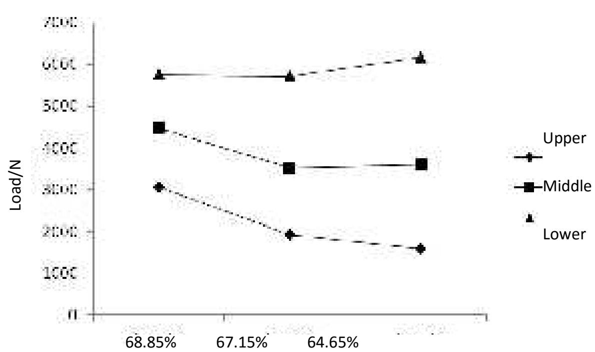


Fig. 8. Effect of factors on maximum load of cassava stalks during axial compression

As shown in the effect of the moisture content and the growth part on the axial compressive strength of the stalk (Fig. 9), with the same moisture content, the axial compressive strength of the cassava stalk reduced as the sampling height increased. As seen in fig. 9 with the moisture content between 68.85% and 64.65%, the axial compressive strength of each part of the stalk increased and then reduced as the moisture content reduced.

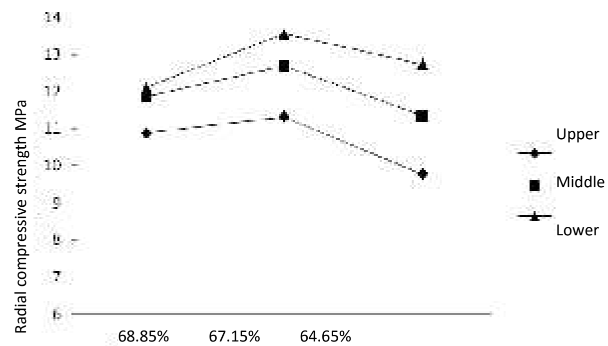


Fig. 9. Effect of factors on axial compressive strength of cassava stalks

As demonstrated in (table 1) ANOVA results of axial compressive strength (Table 1), the loading rate was found not to have any significant impact on the axial compressive strength, while the moisture content and the growth factors respectively had a significant impact ($P<0.05$) on the compressive strength of the stalks.

(2) Result and analysis of radial compression test

As shown in the 3 curves of load-displacement for radial compression test (Fig. 10). After beginning the test, the load approximately increased linearly as the displacement increased and the sample was cracked when the load increased to the maximum, and that is when the load reduced sharply. The load increased when the displacement increased continuously. It was observed that there was crisp sound when the sample was cracked and the crack in the section of the stalk extended radially from the center and liquid flowed from the stalk during the compression, since as indicated previously the cassava stalks were fresh and green.

Table. 1 ANOVA table of axial compressive strength

Source	Quadratic sum	DF	Mean square	F value	significance
Loading rate	14.322	4	3.581	2.098	0.101
Moisture content	12.253	2	6.126	3.589	0.038
Growth part	35.467	2	17.733	10.389	0.000
Error	61.451	36	1.707		
Total	123.493	44			

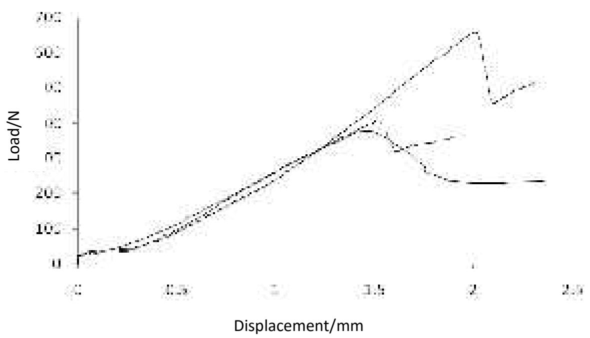


Fig. 10 The curve of load-displacement for radial compression test

As shown relative to the effect of the moisture content and growth factors on the maximum load of the stalk in radial compression (Fig. 11). With the same moisture content, the maximum load of the cassava stalk in radial compression reduced as the sampling height increased. Additionally, with the moisture content between 68.85% and 64.65%, the maximum load of the middle and lower stalk levels first reduced and then slightly increased as the moisture content reduced. The maximum load of the upper part reduced as the moisture content reduced. Therefore, as the stalk dried out the maximum load tolerated and supported was lowered.

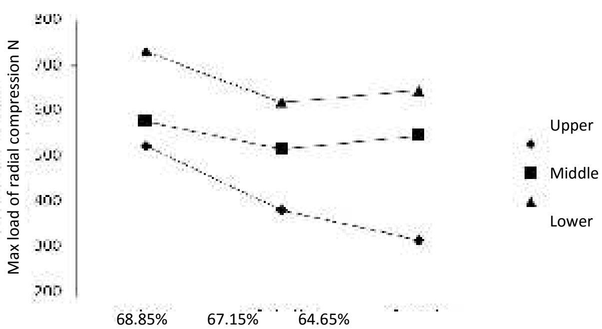


Fig. 11 Effect of factors on maximum load of cassava stalks in radial compression

As shown in the effect of the moisture content and growth part on radial compressive strength of the stalk (Fig. 12), with the same moisture content, radial compressive strength of the cassava stalk increased as the sampling height increased. With the moisture content between 68.85% and 64.65%, the radial compressive strength of each part of the stalk increased and then reduced as the moisture content reduced.

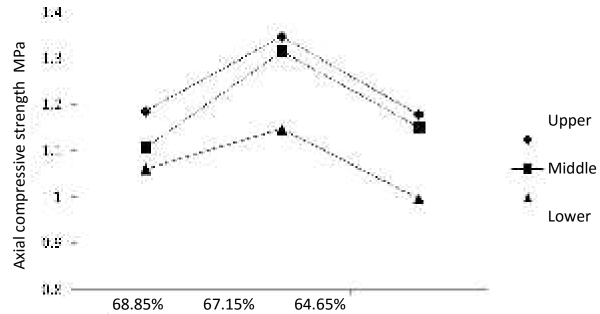


Fig.12 Effect of factors on radial compressive strength of cassava stalks

As shown in the ANOVA results of radial compressive strength (Table 2), the loading rate, moisture content and the growth part had no significant impact on the radial compressive strength of the stalk (P>0.05).

Result and analysis of shearing test: The samples in the test conditions of 5 different sliding cutting angles and 5 different cutting angles are shown respectively in Fig. 13 (a) and (b).

The 3 curves of load-displacement for sliding cutting test are shown in Fig. 14. The test process could be analyzed based on the Fig.14. The load increased linearly as the displacement increased. Then, when the load reached the first peak, the load reduced as the displacement increased, the reason is that the tool cut the xylem of the stalk when the test started, and cut core tissue after the inner wall of the stalk was cut, since the strength of the xylem is much harder than the core tissue. The overall strength of the xylem tissue is very low and, as mentioned previously, the xylem mainly serves the cassava plant a location for water storage, much like a sponge. Therefore, the xylem does not provide the cassava much rigidity or strength. After that, the load changed largely with a general increasing tend as the displacement increased. When the load reached the maximum, the stalk was cut through and then the load reduced sharply and the test finished.

Table.2 ANOVA table of radial compressive strength

Source	Quadratic sum	DF	Mean square	F value	Significance
Loading rate	0.201	4	0.050	0.440	0.779
Moisture content	0.247	2	0.124	1.083	0.349
Growth part	0.229	2	0.115	1.003	0.377
Error	4.113	36	0.114		
Total	4.791	44			

(a) Samples of sliding cutting

(b) Samples of cutting

Fig. 13 The sample after shearing test

During the tests, the second peaks were generally greater than the first peak, this was probably due to the thickness of the blade, which increased gradually as it cut into the stalk. So, the friction between the post-cut cassava stalk and the blade increased gradually as the displacement of the blade increased[28]. The first peak was taken as the failure load of the sliding cutting in the analysis of the test results.

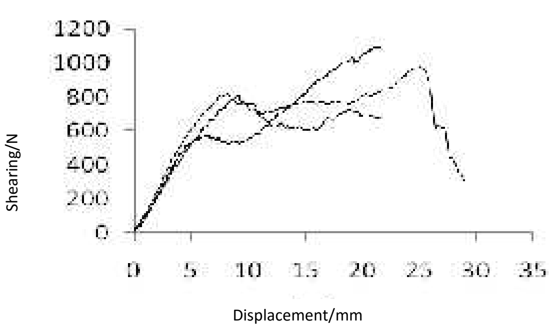


Fig. 14 The curve of load-displacement for sliding cutting test

The 3 curves of load-displacement for orthogonal cutting test of the cassava stalks are shown in Fig. 15. The cutting test process could be analyzed from the figure. The load approximately increased linearly as the displacement increased after the test was started. When the compressive load reached the first peak, the load reduced as the displacement increased. This was because with the load increased to some point, the upper part of the stalk shell was damaged by the cut, and the bearing capacity of the inner tissue was impaired, thus the recline of the curve. As time went by, the lower shell of the stalk started to carry the load, and the friction between the blade and stalk would increase, which caused the curve to ascend. When the stalk reached its maximum load capacity, the stalk would break. After that, the load changed greatly with a general increasing tend as the displacement increased. When the load reached the maximum, the stalk was cut through and then the load reduced and the test finished. The first peak was taken as the failure load of the cutting in the same way as it was during the sliding cutting test.

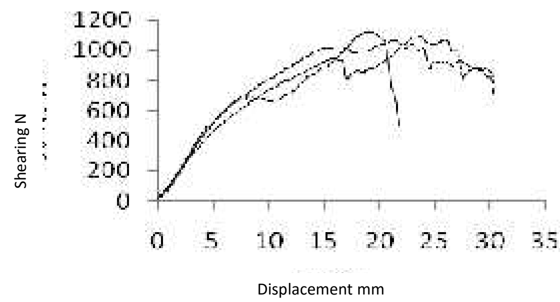


Fig. 15 The curve of load-displacement for cutting test

Mechanical properties analysis of the cassava stalk shearing: The following conclusions were derived from the analysis of the data rendered from the various tests: in the sliding cutting test for the lower stalk levels of the 5 batches of SC 205 cassava with different moisture contents at harvest time. When the moisture content was 68.85%, the maximum shearing force range of the stalks was between 241.22～1053.23N with average value of 584.28N and the range of shearing strength was between 0.78～2.43MPa with an average value of 1.72MPa. When the moisture content was 67.15%, the maximum shearing force range of the stalks was between 326.56～900.25N with an average value of 678.42N and the range of the shearing strength was between 1.32～2.65MPa with an average value of 2.13MPa. When the moisture content was 64.65%, the maximum shearing force range of the stalks was between 305.97～1141.49N with an average value of 714.90N and the range of shearing strength was between 1.26～3.26MPa with an average value of 2.01MPa. When the moisture content was 62.14%, the maximum shearing force range of the stalks was between 397.17～1023.81N with an average value of 710.20N and the range of shearing strength was between 1.54～3.22MPa with an average value 2.29MPa. When the moisture content was 60.44%, the maximum shearing force range of the stalks was between 329.50～1150.32N with an average value of 623.71N and the range of the shearing strength was between 1.46～3.75MPa with an average value of 2.35MPa.

In the cutting test, when the moisture content was 68.85%, the maximum shearing force range of the stalks was between 729.62～1047.35N with an average value of 924.96N and the range of the shearing strength was between 1.94～2.80MPa with an average value of 2.44MPa. When the moisture content was 67.15%, the maximum shearing force range of the stalks was between 420.71～944.38N with an average value of 576.63N and the range of the shearing strength was between 1.12～2.47MPa with an average value of 1.60MPa. When the moisture content was 64.65%, the maximum shearing force range of the stalks was between 294.12～923.79N with an average value of 589.56N and the range of the shearing strength was 1.32～2.87MPa with an average value 2.03MPa. When the moisture content was 62.14%, the maximum shearing force range of the stalks was between 385.40～803.17N with an average value of 538.97N and the range of the shearing strength was between 1.31～2.87MPa with an average value of 1.95MPa. When the moisture content was 60.44%, the maximum shearing force range of the stalks was between 261.84～1235.64N with an average value of 616.05N and the range of the shearing strength was between 1.19～4.99MPa with an average value of 2.85MPa.

As shown in the ANOVA table (Table 3) of sliding cutting test results, the sliding cutting angle and the blade angle respectively had a significant<0.05） impact on the sliding cutting strength, while the moisture content and the load rate had no significant impact on the sliding cutting strength.

As shown in the ANOVA table (Table 4) of cutting test results, the cutting angle and the loading rate had a significant impact on the cutting strength, while the moisture content had no significant impact on the cutting strength.

Table. 3 ANOVA table of sliding cutting strength

Source	Quadratic sum	DF	Mean square	F value	Significance
Moisture content	5.017	4	1.254	2.14	0.167
Sliding cutting angle	10.390	4	2.597	4.44	0.035
Blade angle	24.515	4	6.129	10.47	0.003
Loading rate	3.691	4	0.923	1.58	0.270
Error	4.683	8	0.585		
Total	48.295	24		(R^2=0.903)	

Table. 4 ANOVA table of cutting strength

Source	Quadratic sum	DF	Mean square	F value	Significance
Moisture content	4.743	4	1.186	3.01	0.062
Cutting angle	5.438	4	1.360	3.45	0.043
Loading rate	5.359	4	1.340	3.40	0.044
Error	4.726	12	0.394		
Total	20.265	24		(R^2=0.767)	

Conclusion and Discussion:

(1) Both the axial and radial compressive strength increased and then reduced as the moisture content reduced, as well as when the height of the sampling position increased, the axial compressive strength reduced, while the radial compressive strength increased.

(2) The ranges of the axial compressive strength, the radial compressive strength, the sliding cutting strength, and the cutting strength were respectively 7.49~15.74MPa, 0.61~1.83MPa, 1.55~7.51MPa and 1.12~4.99MPa.

(3) The moisture content and growth part respectively had a significant and a highly significant impact ($P<0.05$) on the axial compressive strength, but neither of them had any significant impact ($P>0.05$) on the radial compressive strength. The sliding cutting angle and the loading rate respectively had a significant and a highly significant impact ($P<0.05$) on the sliding cutting strength; and the moisture content, the cutting angle, and loading rate had significant ($P<0.05$) effect on the cutting strength.

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