THE EFFECT OF POTATOES' COMPRESSIVE MECHANICAL PROPERTIES UNDER DIFFERENT MOISTURE CONTENTS: AN EXPERIMENTAL STUDY

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不同含水率下马铃薯压缩力学特性影响的试验研究

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ABSTRACT

Based on the viewpoint and theory of the integration between agricultural machinery and agronomy, by taking five early-maturing varieties of potato widely planted in western Liaoning Province as the research object, this paper applies the universal material testing machines and electric drum drying ovens etc. in the experiment and obtains the change law of moisture content of potatoes after harvest within 0-5 months, the compressive mechanical properties of potato with different moisture content were tested. The variation of breaking force, maximum deformation and elastic modulus of potato with different moisture content were obtained. Therefore, the experimental results can provide necessary mechanical parameters and theoretical references for the harvesting, storage, the design research on processing/transportation equipment, and the placement method of early-maturing potato in western Liaoning.

摘要

基于农机与农艺结合的观点与理论，本文以辽西地区广泛种植的五个早熟品种马铃薯为试验对象，应用万能材料试验机和电热鼓分干燥箱等仪器设备，测试得到马铃薯收获后 0-5 个月之内含水率的变化规律，并进行了以含水率为单因素的压缩力学特性试验，得到了不同含水率下马铃薯的破裂力、最大变形量和弹性模量的变化规律。试验结果可为辽西地区早熟马铃薯的收获、贮藏及加工运输设备的设计研究和摆放方式提供必要的力学参数和理论参考。

INTRODUCTION

Potato is the world's fourth largest food crop after rice, wheat and corn. With its production advancement as staple food, the potato will surely achieve regionalization of cultivation, mechanization of production, industrialization of operations, refinement of processing and diversification of staple food varieties, further leading to its great growth of grading, transportation and storage capacity, and wide distribution in the market *(Chen, 2014; People's Daily, 2015; Tian et al., 2015)*. During the process of harvesting, transporting, grading and storage, potatoes are subjected to external loads, which are likely to cause mechanical damage. This will not only damage the epidermis tissue of the potato, affect its appearance, but also easily cause internal decay and deformation, reduce its quality and economic value; it can even affect their germination rate if these potatoes are used as seeding material next year *(Lu, 2016; Wang et al., 2014)*. In the potato tuber, the moisture occupies a large proportion and the degree of moisture content greatly affects the compression mechanics of the potato; only with enough hardness and strength will it not be damaged. Currently, the research on the moisture content is mostly concentrated on items such as soybeans, corn, walnuts and fruits, and it has been demonstrated that the degree of moisture content has a significant influence on the mechanical properties of fruits *(Shen et al., 2016; Gao et al., 2012; Li et al., 2018)*. Therefore, it is very necessary to understand the compressive mechanical properties of potato with different moisture content and to further study the compressive mechanical indexes such as rupture force, elastic modulus and maximum deformation of the potato under pressure, aiming to provide the basis and reference for reducing the damage in storage and transportation, guiding the relevant agricultural machinery design, making assessment and detection of potato quality.

At present, scholars in China and abroad have conducted relevant researches on the mechanical properties of potatoes. MG Scanlon et al. performed the compression and stretching tests on potatoes, and demonstrated that the moisture content of potato has an effect on the mechanical properties (*Scanlon et al.,* *1996*); *Bentini et al.* (*2009*) carried on the quasi-static compression tests on two potato varieties harvested for two years and identified that Young's Modulus and Poisson's ratio are related to storage time. The domestic scholars, *Wu Yali and Guo Yuming* (*2011*) conducted experiments on general mechanics of potatoes and then obtained mechanical property indexes such as compressive strength and shear strength of potatoes; *Shi Linyi and Zhang Fengwei et al*. determined the significant effects of loading direction and loading rate on the potato rupture force through the compression mechanical test of the whole potato tubers (*Shi and Wu, 2014; Zhang et al., 2014*); *Wang Yumei et al. (2015)* achieved the main factors affecting the mechanical properties of potato by compressive mechanical properties test of potato. However, among the existing research results, there have been no relevant reports on the different early-maturing potato varieties planted in western Liaoning and there are also relatively few researches on the moisture content test and its effect on compressive mechanical properties under different storage time after harvest.

The western part of Liaoning Province is the well-known home of potato in China, where the potato planting area is about 13% of the total planting area, and the potato planting area in Jianping County is up to 150,000 ha *(Xiao, 2013; Zhang and Lu, 2015)*. Mainly by taking the five early-maturing varieties planted in Jianping County of western Liaoning Province as the research objects, this paper carries out the moisture content test at various time periods within five months after harvest and finally conducts the single factor compression mechanics test for different moisture contents. It aims to study the variation rule of moisture content in different potato varieties under natural conditions and the effect of different moisture contents on the compression mechanical properties of potato, in order to provide the theoretical basis for potato harvest, storage and design of processing equipment in western Liaoning, as well as for the selection of reasonable placement methods, transport time and related parameters of deep processing machinery for these potato varieties in transportation and storage etc.

MATERIALS AND METHODS

Test materials

In our experiment, the research objects were selected from the potato experimental field jointly built by Shenyang Agricultural University and Jianping Agricultural Technology Promotion Centre, and the experimentally related early-maturing potato varieties were planted, mainly including the Netherland 15#, Fujin, Youjin, Favorita and Zaodabai. They were artificially harvested on July 20, 2017, where 50 were selected from each variety, and 4-6 pest-free, non-porous and non-injurious fresh potatoes were selected for each plant. After harvest, they were stored at room temperature for about two weeks. The Vernier caliper was used to measure the three-dimensional size of fresh potatoes of each variety so as to select the potatoes with similar size and shape for about 100 g, label and store them; then the whole tuber compression test was performed, as shown in Fig.1. To determine the moisture content of potatoes in different storage time periods, the potatoes for the experiment were stored in the agricultural product processing and storage laboratories and cellars at Shenyang Agricultural University at the temperature of 2-8°C and humidity of 80%-85%. The storage lasted from August 1, 2017 to January 1, 2018, for 5 months in total.

Fig. 1 - Potato samples used for the test

Test equipment and instruments

The test equipment includes Instron 3344-series universal material physical testing machine (American Instron Corporation) and Model 101 electric drum drying oven (Beijing Yongguangming Medical Instrument Co., Ltd.), electronic balance (accuracy 0.01g), Vernier caliper (measurement Range 0-300mm, resolution 0.01mm), fresh-keeping bags and paper labels. The universal material physical testing machine was used to test the mechanical properties of potato static loading. It mainly consists of the data acquisition system and test bench (Fig. 2) which can display the compression load, displacement, velocity and test curve in real time; electronic balance and 101 electric drum drying oven were adopted to measure the moisture content of the potato; the Vernier caliper measured the three-dimensional size of the potato sample.

Fig. 2 - Universal material physical testing machine

1-Rack and Rail; 2-Indenter; 3-Base; 4-Computer

Test design and method

(1) Determination of potato moisture content

In order to study the effects of different moisture contents on the compression mechanical property of potato, the test method of moisture content based on the storage time was adopted in this experiment. After one day from harvesting (fresh potatoes 6), the first moisture content determination and compressive mechanical test were conducted; after 15 days, the second test was conducted; after 30 days, the third trial; after 45 days, the fourth trial; after 60 days, the fifth trial; in this way the moisture content was tested once every 15 days, and only the last test was conducted every 30 days, 150 days in total. So, it's expected to obtain the variation of moisture content with the change of storage time and find out its impact on compression mechanics.

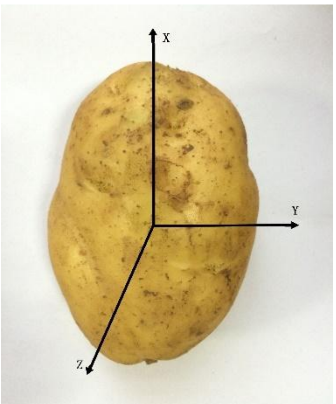
There are lots of methods for moisture determination, where the internationally accepted methods are vacuum drying and air blast drying currently *(Ma and Gu, 2003; Sun et al., 2018)*. Based on the existing conditions in the laboratory, the moisture content of potatoes was measured using the blast drying method and the mass weighing method according to GB/T12078-2008. Firstly, the selected potato was subjected to the compression mechanics test. Immediately after the test, the moisture content was tested: ten samples for each potato variety were firstly prepared, which were cut into the thin slices with similar thickness (weight: over 2g), and numbered separately; afterwards, the weight of samples was measured and the initial weight was recorded; then, they were uniformly placed on the tray and in the blast drying box at the temperature of 85^{o}C, and dried for 0h, 1h, 2h, 3h, 3.5h and 4h respectively; in the drying process, at the specified time, the related varieties were taken out of the box for weighing and data recording. Those that didn't reach the specified drying data shall be put back into the blast box for continuous drying; but if the weight no longer changed, it meant the end of drying. The moisture content of potato samples was calculated as:

$$X = \frac{m_1 - m_2}{m_1} \% \tag{1}$$

where X is the moisture content of the potato, %; m_1 is the mass of the sample, g; m_2 is the mass of the sample after drying to constant weight, g.

(2) Compressive mechanical properties test

In the harvesting, storage and transportation process, potatoes are generally subjected to external loads under natural placement conditions. Therefore, it is very valuable to test the mechanical properties of whole potato tubers in natural states *(Guo et al, 2014)*. The test steps of potato compression characteristics are: the fixed loading speed is 15 mm/min and the loading directions are Z directions. (X is placed upright, Y is placed lateral, Z is flatwise) as shown in Fig.3a and 3b. The single-factor determination test of moisture content was conducted. The potato tubers of five varieties were selected respectively. They were subjected to Z-direction compression under the moisture content of the natural storage at different time periods, so as to obtain the epidermis rupture force, elastic modulus and maximum deformation of the potato. Then the study was conducted for the effect of moisture content on the compressive mechanics property through the static loading mechanical properties. For each variety, five repeated tests were carried out at the same moisture content. The data were statistically analysed to take the average and variance. During the test, the rigid plate was used as the loading device. The whole tuber of the potato was placed in the centre of the indenter, and the upper indenter was adjusted to just not touch the potato. Then, the test program control interface was entered and the control setting parameters were selected in the method interface, including loading rate 15 mm/min, upper limit load 2000 N, upper limit displacement 50 mm, the upper limit load-descending percentage 20%, and the upper limit load-descending 10N. In the test interface, the steps were followed by clicking Load Zero, Reset Gage, Start and Finish. In order to reduce the experimental/test error, each test was repeated 5 times under the same conditions and finally averaged.



a) b)

Fig. 3 - Diagram of potato compression loading device

a) Z-direction loading device b) Diagram of potato directions

(3) Experimental factors and indexes

In this paper, potato moisture contents are selected as the experimental factors. The maximum load received when the potato tuber breaks, deformation and elastic modulus under compression were used as test indexes.

RESULTS

Variation rule of moisture content for different varieties

The measurement results of moisture content for the five varieties within 0 to 5 months after harvest were collected and analysed (Fig.4). It can be seen that the fresh potato's moisture content of the five varieties reached 80%-84% at harvest, but with storage time increasing, the moisture content of the five varieties showed a downward trend: in the first 0-30 days of storage the moisture content decreased more rapidly; at about 45 days, the decline of moisture content tends to decrease more slowly, reaching about 75%-80%. At the 60 days of storage, the moisture content of Zaodabai was the lowest and also tended to be stabilized. From the 75th day onwards, the moisture content of potatoes in the four varieties of Fujin, Youjin, Favorita, and the Netherlands 15# also increased slightly. Taking Favorita as example, the moisture content of its fresh potatoes reached 83.8% at the beginning; after 30 days, it dropped to 80.5%, which was a drop of 3% or so. The moisture content at the 60th day was 78.2% and the data became stable. After about 120 days, the data was further increased. For different potato varieties, their moisture contents also vary, esp., Favorita had a significant drop in moisture content at the beginning of storage (0-60d). But the other four varieties did not change so dramatically. In general, despite the different varieties, the variation rules of the potato tubers' moisture content are similar.

Through the reason analysis, it's found that: after harvesting, although the photosynthesis stops immediately, the potato is still a living organism. Its life metabolism is still being carried out in an orderly manner. The potato epidermis has not been completely corked and the respiration inside the potato block is strong, so the moisture evaporates actively and the water is easily lost, causing it to lose weight and lose freshness. With the increase of storage time, the potato will go into dormancy, followed by the reduced metabolism, the decreased water transpiration, and the weakened respiration. Therefore, the relevant moisture content will decline slowly and tends to be stable. Considering that the potato contains starch, sugar and other carbohydrates in addition to water, it is certain that potato tubers are not fully mature with the tender epidermis within 0-20 days from the beginning of potato harvest, and the cork layer isn't formed with high moisture content and easy peeling. But it can be used for processing food such as mashed potatoes. However, fresh potatoes with high moisture content are not suitable for long-distance transportation. Thus, it can be concluded that after two months from potato harvest, the water loss rate of the above five varieties of potatoes is between 4% and 6%, and the relevant energy is converted into other dry matter.

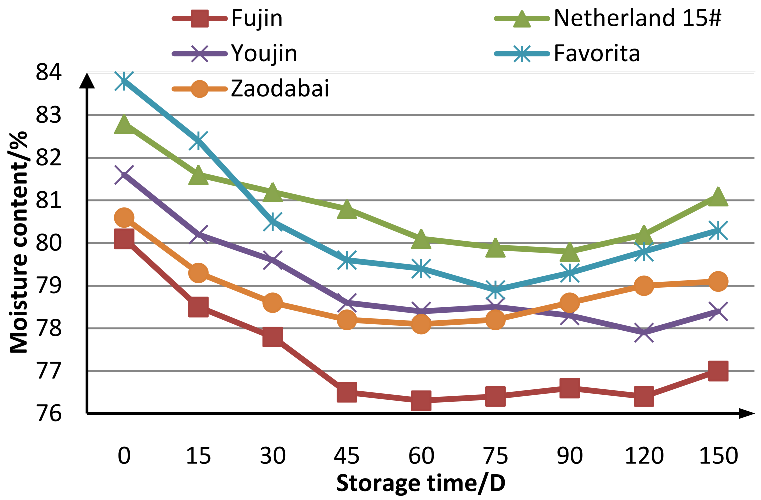


Fig. 4 - Variation of potatoes with storage time

Compressive mechanical properties of potato under different moisture contents

Due to the fact that most tubers are placed in piles during the transport and storage of potatoes, the most common interaction between tubers is mutual extrusion. So, this paper focuses on the mechanical experiment of uniaxial compression of potato under natural flat state. Through the stress test, the mechanical properties of different varieties of potato under different moisture contents were obtained (Table 1).

(1) Relationship between moisture content and rupture force. The rupture force of potato mainly refers to the maximum value of the external load when the potato breaks. In Table 3, it can be seen that as the moisture content decreased, the compressive load that the potato can withstand increased and the moisture content of the potatoes of each variety at the early harvesting stage was more than 80%; after the natural storage for 30 days, moisture content declined rapidly, e.g., for the Zaodabai, the relevant compressive force rose from 1,196.19N to 1,424.53N; then, after 45-day storage, the change of compressive force tended to be stable; with the increase of storage time, at about 120 days of storage, when the moisture content decreased, the rupture force further decreased.

The main reason of analysing the effect of moisture content on potato rupture strength is that potato is the viscoelastic solid agricultural material, and the different moisture contents lead to the difference in its internal structure and mechanical strength. The higher the moisture content, the softer the internal tissue of the potato, the lower the resistance to rupture; when subjected to external loads, the fluid inside the cell can cause the internal pressure to act on the cell wall. This allows the cells to be in a state of elastic pressure, showing elastic properties, thus, the potato is easily deformed and its pressure capacity decreases. As the moisture content decreases, the cellular pressure in the inner tissue of the potato decreases, showing an increase in the rigidity and elasticity of the inner cell wall, besides, the inner tissue is tightly bound, the hardness of the potato fruit increases, and the loading capacity is improved accordingly. Based on the MATLAB software, the relational graph of storage time, moisture content and rupture force of each variety was fitted in the diagram. Due to the limited space, in this paper, only the relational graph of Fujin potato variety is given in Fig.5.

According to the test data and the MATLAB fitting graph of various varieties, it can be seen that the compressive loads of Fujin, Youjin, and Zaodabai potatoes did not change much at the beginning of storage; after 45 days or so, the maximum compressive force increased sharply, which was 1.5 times the initial value, indicating that these three varieties have become more solid at this time, besides, from the perspective of storage and transportation, the external load pressure does less damage to the potato, so it's the best time for transport. For the other two varieties Netherlands 15# and Favorita, their changes were relatively small, and the overall upward trend was relatively slow; at the 60th day of storage, these two varieties bear a greater load. This is related to the change of their internal moisture content: the effect of different moisture contents on the potato is still relatively large, and the compressive force of the potato among different varieties also varies, which mainly depends on their different internal structure.

The single-factor relational expression between potato rupture force and moisture content of five different varieties was fitted by MATLAB software, which was approximated by the cubic function relation, with the determination coefficient above 0.98. The related formula is expressed in Table 2.

Table 1

Compressive mechanical property values under different moisture contents

Variety	Moisture content %	Max. rupture force/N	Max. compression deformation/mm	Elastic modulus/MPa
Favorita	83.8	997.63	12.27	16.01
	82.4	1073.81	13.21	17.86
	80.5	1125.39	14.54	21.68
	79.1	1203.48	15.05	24.93
	78.2	1341.03	16.45	26.88
	78.3	1318.97	16.49	26.95
	78.6	1287.91	15.96	25.82
	79.3	1165.32	14.61	25.26
	79.8	1163.02	14.06	24.22
Netherland 15#	82.8	986.7	13.43	24.34
	81.2	1097.1	14.89	26.93
	80.6	1047.34	15.31	28.21
	80.3	1057.8	15.78	28.70
	79.6	1254.97	16.59	30.66
	79.5	1265.27	16.61	30.99
	79.8	1171.82	15.99	30.24
	80.2	1063.44	15.61	28.52
	81.1	1048.82	14.69	26.91
Zaodabai	81.6	1196.19	17.30	22.84
	79.3	1339.57	16.06	26.39
	78.6	1424.53	15.65	28.67
	77.8	1418.84	14.56	30.49
	78.1	1592.44	15.18	28.68
	78.2	1390.78	15.11	28.54
	78.8	1342.9	15.36	28.17
	79.2	1322.43	15.59	26.44
	79.5	1311.73	15.84	26.17
Youjin	81.8	958.4	16.03	21.25
	80.2	974.48	15.41	23.65
	79.6	1059.1	14.53	25.13
	78.3	1180.85	12.63	27.72
	78.4	1178.27	12.96	27.97
	78.5	1170.34	13.01	27.95
	78.8	1129.2	12.83	25.95
	79.4	1049.24	13.34	24.36
	79.9	1062.44	13.06	21.11
Fujin	80.1	846.91	15.79	16.03
	78.5	1054.77	13.59	18.54
	77.8	1148.61	12.66	19.56
	76.5	1267.51	11.42	21.23
	76.3	1286.23	11.88	21.75
	76.4	1269.78	11.89	21.31
	76.6	1243.37	11.56	21.38
	76.4	12633.2	11.53	21.67
	77	1120.93	12.19	19.12

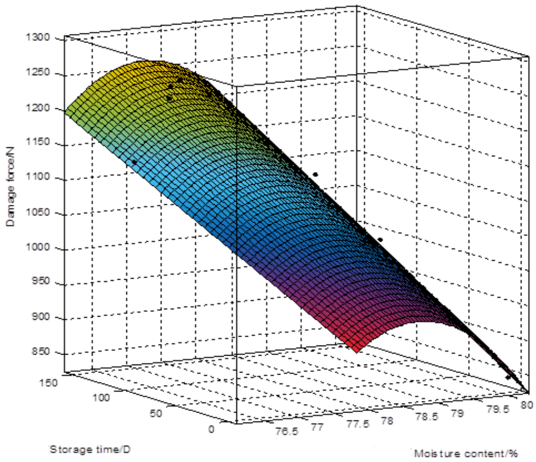


Fig. 5 - Relational graph between rupture force and moisture content

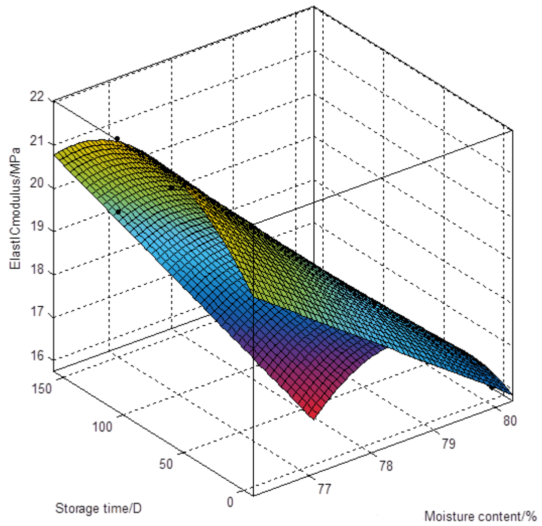


Fig. 6 - Relationship between elastic modulus and moisture content

Table 2

Fitting function of potato rupture force and moisture content

Varieties	Fitting function	R^2 *determination coefficient*
Zaodabai	$F(x) = 4.14x^3 - 992.7x^2 + 79240 - 2105000$	0.979
Favorita	$F(x) = -5.317x^3 + 1300x^2 - 106000x + 2881000$	0.993
Netherland 15#	$F(x) = -62.3x^3 + 15190x^2 - 123500x + 3344000$	0.985
Youjin	$F(x) = 5.578x^3 - 1320x^2 + 10400x - 2729000$	0.987
Fujin	$F(x) = -20.35x^3 + 4769x^2 - 37250x + 9703000$	0.980

where F(x)is the maximum loading force when the potato is placed flat, N; X is the moisture content of the potato.

(2) Relationship between moisture content and elastic modulus. The elastic modulus of potato is a measure of the difficulty degree of deformation. The greater the elastic modulus is, the greater the pressure of the external load is, and the smaller the elastic deformation is. The INSTRON universal material testing machine used in this test has the function of automatically measuring and recording the elastic modulus, and it can measure the elastic modulus of potato under any pressure and deformation.

From the test data in Table 1, it can be seen that the modulus of the five varieties increased with the decrease of moisture content, and the elastic modulus values of Zaodabai and Netherlands 15# were the largest, but after four months, the changes of the elastic modulus for the five varieties were similar, where the modulus value of Favorita potatoes was the maximum, followed by the Zaodabai, Netherlands 15# and Fujin, and Youjin's elastic modulus was the minimum. The higher the elastic modulus value, the better its tuber firmness. The reason analysis shows that after the moisture content is reduced, the elastoviscosity of the potato is reduced and the density of the material is increased. So, the potato is close to the rigid body and is not easily deformed under pressure with a certain load carrying capacity. According to MATLAB software, the relational graph of storage time, moisture content and elastic modulus of each variety was fitted. Due to the limited space, only the relational graph of Fujin potato variety was given in this paper as shown in Fig.6.

The single-factor relational expression between the elastic modulus and moisture content of five different varieties of potato was fitted by Matlab software, which was approximated by the cubic function relation, with the determination coefficient above 0.96. The related formula is expressed in Table 3.

Table 3

Fitting function of potato elastic modulus and moisture content

Varieties	Fitting function	R^2 determination coefficient
Zaodabai	$E(x) = 0.02537x^3 - 5.871x^2 + 450.5x - 11420$	0.975
Favorita	$E(x) = 0.06203x^3 - 15x^2 + 1206x - 32260$	0.986
Netherland 15#	$E(x) = -0.1365x^3 + 33.49x^2 - 2741x + 74580$	0.981
Youjin	$E(x) = -0.2594x^3 + 62.55x^2 - 5029x + 13480$	0.965
Fujin	$E(x) = -0.3418x^3 + 80.2x^2 - 6274x + 16360$	0.992

Note: E(x) in the formula is the elastic modulus of the potato when it is laid flat; X is the moisture content of the potato

(3) Relationship between moisture content and compressive deformation. The compressive deformation of potato refers to the deformation of potato under the action of external compressive load, which is the maximum displacement of potato at the rupture point. From the test data in table 3, it can be seen that as the moisture content decreased, the amount of deformation tended to decrease, and the trend of change among different varieties was the same. E.g., for the variety Fujin, the variation of potato deformation with moisture content is shown in Fig. 8; when the moisture content decreased from 80.1% to 76.5%, the deformation showed a downward trend, but on the whole, the downward trend was relatively slow; after 45-day storage, when the moisture content dropped to approximately 76%, the changes of deformation were small and potato variation in other varieties had their own characteristics; the Netherlands 15#, Favorita and Fujin had less variation, while the Zaodabai and Youjin changed significantly, but the overall trend was the same. According to MATLAB software, the relational graph of storage time, moisture content and deformation amount of each variety was fitted. Due to the limited space, only the relational graph of Fujin potato variety was given in this paper, as shown in Fig.7.

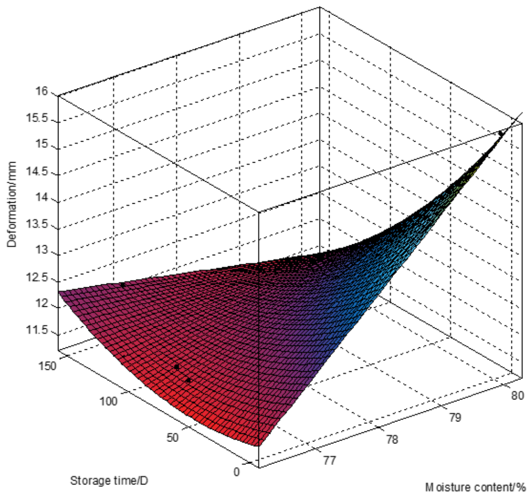


Fig. 7 - Relationship between deformation amount and moisture content

The reason analysis shows that the moisture content of potato is the main factor affecting its tissue cell turgor pressure. The freshly harvested potato with more moisture content shall have a higher internal cell turgor pressure. As the storage time increases, the moisture content gradually decreases, and the potato internal tissue gradually becomes more compact; besides, the degree of maturity increases, the hardness increases, and the ability to resist external loads becomes stronger, so the amount of deformation decreases. In comparison, in order to reduce the potato's compression damage during transportation, it is most reasonable to transport the potato in the minimal-deformation period.

The single-factor relational expression between the deformation and moisture content of five different varieties of potato was fitted by MATLAB software, which approximated by the cubic function relation, with the determination coefficient above 0.97. The related formula is expressed in Table 4.

Table 4

Fitting function of potato deformation and moisture content

Varieties	Fitting function	R^2 determination coefficient
Zaodabai	$S(x) = 0.1261x^3 - 30.14x^2 + 2401x - 63750$	0.976
Favorita	$S(x) = -0.06224x^3 + 15.19x^2 - 1237x + 33580$	0.993
Netherland 15#	$S(x) = -0.06283x^3 + 15.37x^2 - 1254x + 34150$	0.987
Youjin	$S(x) = -0.2852x^3 + 68.23x^2 - 5440x + 14450$	0.991
Fujin	$S(x) = -0.06469x^3 + 15.32x^2 - 1209x + 31750$	0.982

Note: S(x)is the maximum deformation displacement when the potato is placed flat, mm; x is the moisture content of the potato.

CONCLUSIONS

Through experiments on the static mechanical properties of different potato varieties in western Liaoning Province, the mechanical properties of the whole potato tubers and their variations were explored with different moisture contents, and the relations between moisture content and rupture force, elastic modulus, and maximum deformation of all five potato varieties were analysed. The main conclusions are made as follows:

(1) The moisture content of five varieties of potatoes in the period after harvest of 5 months has been studied. The moisture content of different varieties has similar change law. The moisture content of potatoes in the early harvest period is high. At about 60 days, the moisture content decreases to the lowest level, and then increases. Among them, the moisture content of Fujin is lowest.

(2) The moisture content greatly affects the mechanical properties of the potato such as rupture force, elastic modulus and deformation: the elastic modulus and rupture force increase with the decrease of the moisture content, and the deformation decreases with the decrease of the moisture content. The correlation coefficients of polynomial regression fitting are all above 0.95, indicating that the regression equation is well-fitted, and the numerical value changes regularly, which can be used for routine judgment.

(3) Potatoes with low moisture content show better static pressure mechanical property, therefore, from the perspective of reducing potato damage, storage and transportation should be made about 45-60 days after harvesting, when the moisture content drops below 80%, the hardness of potatoes increases, and the ability to resist deformation is improved to avoid damage.

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