MECHANICAL PROPERTIES AND MICROSTRUCTURE ANALYSIS OF TPA IN APPLE PULP BASED ON DIFFERENT LOADING SPEEDS

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基于不同加载速度的苹果果肉TPA力学特性与微观结构分析

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ABSTRACT

In order to enrich the apple quality evaluation system, TPA mechanical tests were carried out on Fuji, Guoguang and Golden delicious apple pulp at 10 loading speeds of 0.01, 0.1, 0.5, 1, 2, 5, 9, 13 and 17 mm/s, and the mechanical characteristic parameters of pulp were obtained. The effects of loading speed on pulp hardness, elasticity, cohesiveness, chewiness and resilience were analysed. The microstructure of pulp of different varieties pulp was observed by laser confocal microscope. Based on the Voronoi model of pulp tissue structure, the compression test was simulated to construct the relationship between microstructure and mechanical properties. The results showed that the loading speeds had a certain effect on the cohesiveness and chewiness, and had a linear relationship with the cohesiveness of Guoguang variety and the chewiness of Golden delicious. The microstructure of pulp directly determines its mechanical properties, the smaller the roundness of cells and pores, the greater the hardness, cohesiveness, chewiness and resilience. Using Abaqus for compression test simulation, the maximum deviation of stress is 4.3%, which proves that the model is effective and the accuracy is improved. The results provide technical parameters for mechanical system improvements for apple during harvesting, storing and transporting and perfect evaluation system of apple texture.

摘要

为了丰富苹果品质评价体系，选用 0.01, 0.1, 0.5, 1, 2. 5, 9, 13, 17 mm/s 10个加载速度，对富士、国光、金冠苹果果肉进行了TPA力学试验，获得果肉力学特性参数，分析加载速度对果肉硬度、弹性、内聚性、咀嚼度、回复性的影响；采用激光共聚焦显微镜对不同品种果肉微观结构进行观测，得到不同品种组织结构差异；基于果肉组织结构的Voronoi模型模拟仿真压缩试验，构建微观结构与力学特性的联系。结果表明，加载速度对内聚性、咀嚼度有一定影响，与国光品种内聚性、金冠品种内聚性、咀嚼度成线性关系；果肉微观结构直接决定了其力学特性，细胞及孔隙圆形率越小，硬度、内聚性、咀嚼度、回复性越大；运用Abaqus软件进行压缩试验仿真，应力最大值偏差度为4.3%，证明模型有效，且精确度提升。研究结果为苹果采收、贮藏、运输等相关机械系统的改善提供数据支持，完善苹果贮运品质评价体系。

INTRODUCTION

Apple has rich nutritional value and is the second largest fruit species in China, with an annual output of one million tons *(Li et al., 2021)*. The evaluation of apple quality mostly adopts sensory evaluation, instrumental analysis and other methods to realize the difference comparison of characteristic parameters such as fruit hardness, brittleness, chewiness and moisture content *(Yogesh et al., 2017).* Many studies have shown that the difference in fruit quality is closely related to its microstructure. For example, Hou *(Hou et al., 2016)* analysed the mechanical properties of apple on the basis of puncture and compression experiments, combined with the observation of laser confocal microscope to obtain the pulp cell structure, and realized the prediction of the quality of fruit pulp. Yang *(Yang, 2019)* constructed the macro and micro models of dried apple pulp slice, carried out experimental verification, and analysed the drying characteristics of apple pulp slice under different conditions. Fan *(Fan, 2017)* observed the cell structure of 'Ruiyang' and 'Ruixue' by scanning electron microscope, obtained the content changes of pulp cell wall materials and components,

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which provided a reference for apple quality evaluation and genetic breeding from the perspective of cytology. Wang *(Wang et al., 2020)* studied the quality of freeze-dried apple pulp slices, analysed the effects of polysaccharide and its concentration on the quality and microstructure of freeze-dried apple slices. Wang *(Wang et al., 2020)* observed the microstructure of apple peel and studied the relationship between its mechanical properties and microstructure. Bu *(Bu et al., 2020)* constructed the model of apple, constructed the plastic damage model of apple pulp through the test data, carried out the simulation test, which proved that the model was reasonable and accurate. To sum up, the parameters such as peel breaking force, pulp hardness and brittleness can evaluate the texture of apple, the microstructure of pulp tissue is closely related to the texture of apple. At present, there are few studies on the simulation of tissue microstructure based on geometric parameters *(Bu et al., 2020)*, which still stay in obtaining the relevant parameters of peel and pulp through experiments and the stage of simulation *(Hou et al., 2016)*. The purpose of this study is to: (1) Measure the TPA mechanical parameters of the same variety of apple pulp under different loading speeds, study the effect of loading speeds on the mechanical parameters, so as to provide data support for the improvement of the harvest, transportation and storage of apple. (2) The effect of pulp tissue on fruit substantive parameters was studied through the analysis of TPA mechanical parameters of different varieties of pulp, so as to provide reference for consumers' selection. (3) The microstructure of different apple varieties was observed, the Voronoi model of microstructure was constructed, the mesh was divided based on the Voronoi model in the Abaqus simulation analysis, the three-dimensional model of pulp tissue was established, and the relationship between the mechanical properties of TPA and its microstructure was analysed to verify the effectiveness of the model.

MATERIALS AND METHODS

Test materials

Fuji, Golden delicious and Guoguang apples were selected from Fruit Tree Research Institute of Shanxi Academy of Agricultural Sciences in October 2019. The apples with regular shape, similar size, no diseases and pests and no obvious defects were selected. The electronic balance hc31 produced by Huachao High Tech Institute was used to measure the single apple quality, and the digital vernier caliper produced by Dongguan Sanliang measuring tools Co., Ltd. was used to measure the transverse and longitudinal diameter of apple. Measure the circumference of the equator with a tape measure to obtain various parameters of the fruit, as shown in Table 1.

Quality and geometric dimensions of different varieties of apples **Table 1**

Varieties	Mass	Transverse diameter	Longitudinal diameter	Circumference at equator
	[kg]	[mm]	[mm]	[mm]
Fuji	195.6±31.3a	75.7±5.0a	62.0±5.5a	249.5±12.4a
Guoguang	120.0±24.2b	67.0±4.8b	51.4±4.1b	218.8±15.4b
Golden delicious	161.0±16.9c	72.4±2.5c	62.7±3.3a	236.0±7.7c

It can be seen from Table 1 that there are significant differences in the quality and geometric dimensions of different apple varieties. Fuji varieties have the largest parameters, followed by Golden delicious varieties and Guoguang varieties, indicating that Fuji varieties have the largest fruit and Guoguang varieties have the smallest size.

TPA mechanical test instruments and methods

Cut an apple into two halves along the radial direction, take samples at the equator of the apple with a cylindrical mold with a diameter of 1 cm. Take two samples on each half. Select two sharp blades, fix them at an interval of 1 cm, keep the two blades parallel to each other, cut the sample, and obtain a cylindrical sample with regular shape and 1 cm height for subsequent test.

TPA mechanical tests were conducted on the prepared cylindrical sample using TA-XT plus texture analyser (SMSTA.XTPlus, UK) which can measure load 0.001 to 295 mm and show the kinematic course of the force size, the sample deformation amount, and a test curve real-time. During the test, P50 probe is selected. The speed before measurement is 3 mm/s and the speed after measurement is 3 mm/s. The loading speeds are 0.01, 0.1, 0.5, 1, 2, 5, 9, 13 and 17 mm/s. For one loading speed, 10 samples from five apples are selected for repeated test. Analyse the test data and obtain the force time curve, as shown in Fig.1.

According to the force time curve, five parameters of hardness, elasticity, cohesiveness, chewiness and resilience can be calculated. Hardness is the maximum force in the first compression process on the curve. Elasticity is the ratio of the time difference between anchor 4 and anchor 5 to the time difference between anchor 1 and anchor 2. Cohesiveness is the ratio of the area under the curve of anchor 4 and anchor 6 to the area under the curve of anchor 1 and anchor 3. Chewiness is the product of hardness, cohesiveness and elasticity. Resilience is the ratio of the area under the curve of anchor 2 and anchor 3 to the area under the curve of anchor 1 and anchor 2.

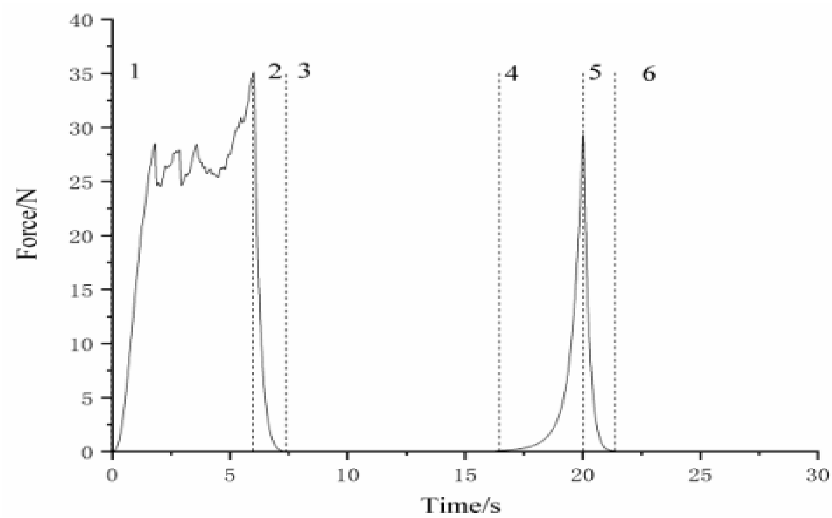


Fig. 1 - Force time curve

Instruments and methods for observing the microstructure of apple pulp

Cut out as thin as possible disc-shaped pulp tissue on the prepared cylindrical sample with a blade *(Li et al., 2020)*, soak it in Congo red dye with a concentration of 5% for 20 minutes, take it out after discoloration, wash it in deionized water, place it on the slide, absorb excess water, cover the slide, and observe the microstructure with a laser confocal microscope, 488 nm argon ion laser irradiation is selected to excite fluorescence, and the observation time shall not exceed 5 minutes to avoid the influence of tissue dehydration curl on the results *(Pipintakos et al., 2021)*. 10 apples were selected from each variety, and 10 disc-shaped tissues were taken from each apple for analysis *(Sheppard, 2021)*.

Compression test simulation

The first compression process in TPA mechanical test is used for data analysis and simulation. The stress and strain obtained from the test are nominal stress and nominal strain *(Jiang et al., 2021)*. In order to accurately describe the change of the sample in the process, it is necessary to calculate its real stress and real strain. The calculation formula is as follows *(Zhan et al., 2021)*:

$$\varepsilon_{true} = \ln(1+\varepsilon_{nom}) \tag{1}$$

$$\sigma_{true} = \sigma_{nom}(1+\varepsilon_{nom}) \tag{2}$$

Where: ε_{nom} is the nominal strain, %; ε_{true} is the true strain, %; σ_{nom} is the nominal stress, MPa; σ_{true} is the true stress, MPa.

In order to characterize the damage of the sample, a plastic damage model is constructed, and the relevant parameters of the plastic stage required for the simulation are calculated by using Sidoroff's energy equivalence principle. The calculation formula is as follows *(İynen et al., 2021)*:

$$\varepsilon^{in} = \varepsilon - \varepsilon_0^{el} \tag{3}$$

$$\varepsilon_0^{el} = \frac{\sigma}{E_0} \tag{4}$$

$$\varepsilon^{pl} = \varepsilon^{in} - \frac{d}{1-d}\varepsilon_0^{el} \tag{5}$$

$$d = 1 - \sqrt{\frac{\sigma}{E_0 \varepsilon}} \tag{6}$$

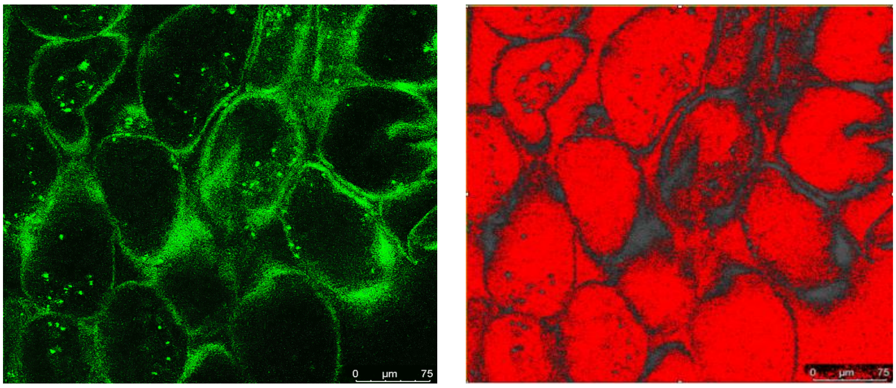
Where: ε^{in} is inelastic strain, %; ε_0^{el} is Elastic strain under the initial stiffness E_0, %; ε^{pl} is plastic strain; d is the damage factor.

The Voronoi model is constructed by MATLAB, the Voronoi model is imported into AutoCAD as a template for meshing, and the three-dimensional model of pulp is established. Then the three-dimensional model is imported into Abaqus for compression test simulation. According to authors *(Lv et al., 2017)*, combined with the test data, the apple pulp density is 8.4E-10 tonne/mm3, the elastic modulus is 5 MPa, the initial elastic modulus is 3.5 MPa, and the Poisson's ratio is 0.35. Through the simulated compression test, the maximum stress is obtained by outputting the stress-strain curve. Compared with the parameters obtained from the test, the accuracy of the model is analysed.

Data and image processing

Origin2017 is used to draw the force time curve, locate the anchor and calculate the area under the curve, using SPSS13.0 carries out difference analysis on mechanical characteristic parameters of pulp, linear fitting with loading speed and difference analysis on Euclidean geometric structural parameters of pulp tissue, taking 95% confidence interval *(Jiang, 2021)*.

Image J is used to process the image and extract the geometric parameters of cells. As shown in Fig.2, convert the image into 8-bit gray image, adjust the threshold to make the red fill the cells and pores, keep the contour clear, and extract the geometric parameters *(Sun et al., 2020)*.



(a) (b)

Fig. 2 - (a) Fuji pulp laser confocal image; (b) Fuji pulp laser confocal image after image J processing

RESULTS

Analysis of TPA mechanical characteristic parameters of pulp

With the increase of loading speed, the impact of the indenter on the pulp increases and the resistance increases, resulting in the increase of three parameters related to the tightness of pulp tissue: hardness, cohesiveness and chewiness, which is consistent with the situation shown in Fig. 3. Among them, Fuji variety has close pulp tissue, the greatest resistance, hardness, cohesiveness and chewiness, and Guoguang variety has the opposite. There was no significant difference in elasticity among different varieties, indicating that they had the same elasticity under small shape variables. The resilience is related to the tightness of pulp tissue binding and the size of intracellular turgor. Among different varieties, Fuji variety has the largest resilience while Guoguang has the smallest, reflecting that the resilience is less affected by the tightness of pulp tissue binding than the parameters of hardness, cohesiveness and chewiness.

Analysis of TPA mechanical characteristic parameters of pulp under different loading speeds. The differences of the mechanical characteristic parameters of the pulp of the same variety of apple under different loading speeds are analysed, and the ratio between the cases with significant differences and all cases is set. The result is the influence rate of loading speeds on the mechanical characteristic parameters of the pulp *(Zhang et al., 2018)*, and the results are shown in Table 2. It can be seen from Table 2 that different loading speeds have a great impact on the pulp cohesiveness of the three varieties of apple, with an average value of 0.578, which has a certain impact on the hardness, chewiness and resilience, with an average value of 0.4, 0.385 and 0.326 respectively, which basically has no impact on the pulp elasticity, indicating that the change of loading speeds have a certain impact on the degree of pulp tissue binding. Fuji varieties are closely combined with tissues and have the strongest ability to resist the change of loading speed, so the change of loading speed has the least influence on various mechanical characteristic parameters of Fuji varieties. The tight degree of tissue binding of Golden delicious varieties is between Fuji varieties and Guoguang varieties, but the change of loading speed has the greatest impact on the mechanical properties of Golden delicious varieties, indicating that the mechanical properties of Golden delicious varieties pulp are more vulnerable to the influence of different loading speeds during storage and transportation, and its tissue binding mode may be more vulnerable to the change of loading speed.

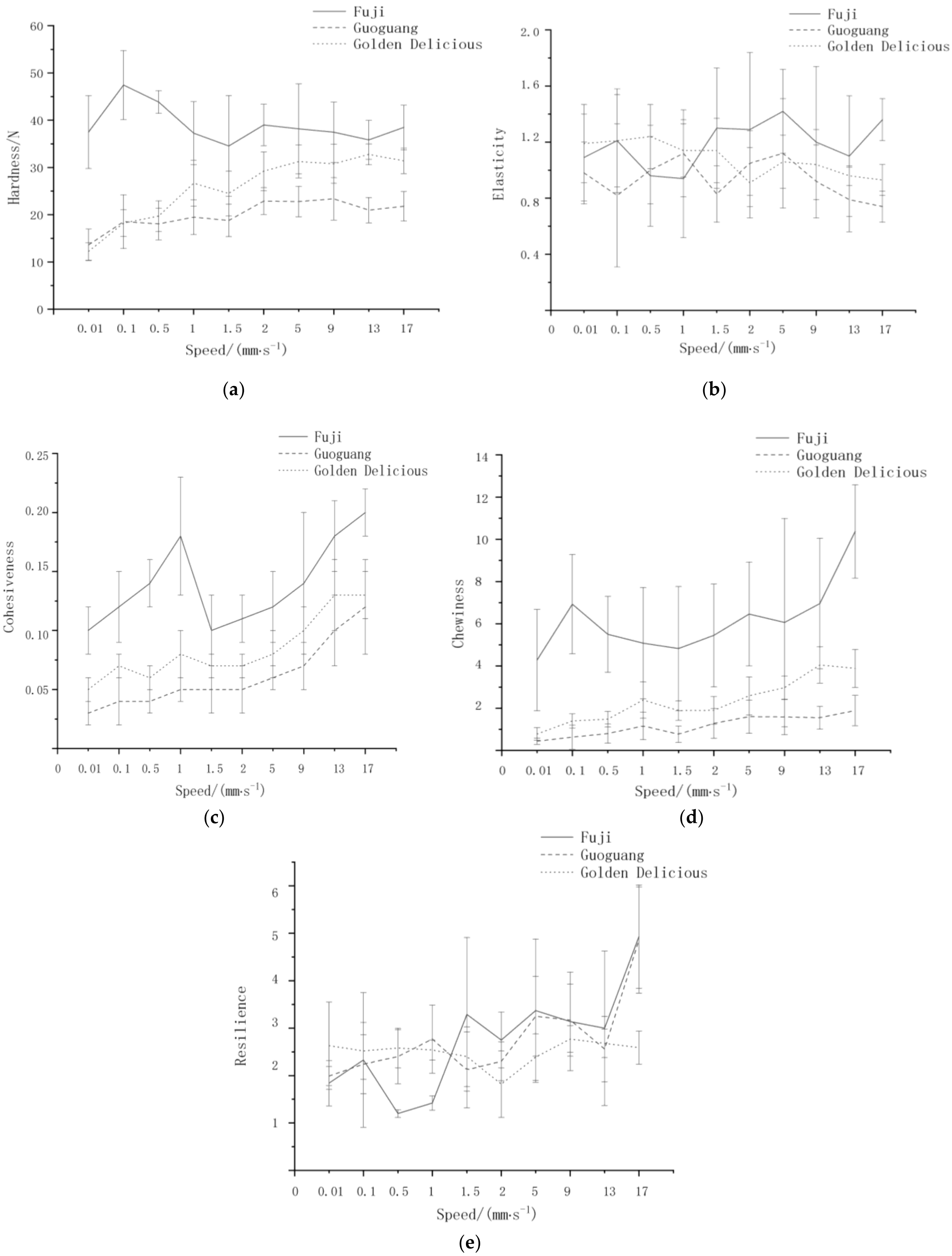


Fig. 3 - (a) Hardness; (b) Elasticity; (c) Cohesiveness; (d) Chewiness; (e) Resilience

Table 2

Effects of different loading speeds on TPA mechanical parameters of apple pulp

Varieties	Hardness	Elasticity	Cohesiveness	Chewiness	Resilience
Fuji	0.267	0.089	0.444	0.222	0.4
Guoguang	0.333	0.156	0.667	0.333	0.289
Golden delicious	0.6	0.156	0.622	0.6	0.289

Note: The closer the influence rate is to 1, the greater the influence of loading speed on the mechanical parameters of TPA in apple pulp.

Prediction ability of loading speed on mechanical parameters of apple pulp. In order to analyse the prediction ability of different loading speeds on the mechanical characteristic parameters of apple pulp, the univariate linear model is used to fit them, and the fitting equation is:

$$y = \beta x + k \tag{7}$$

Where: y is the mechanical characteristic parameter of apple pulp including cohesiveness, chewiness, resilience; β is the fitting coefficient; x is the loading speed, mm/s; k is the intercept.

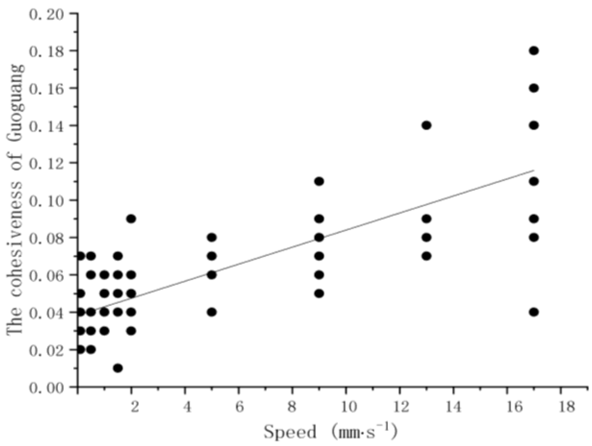
The determination coefficients of univariate linear regression model with different loading speeds and pulp mechanical characteristic parameters are shown in Table 3.

Table 3

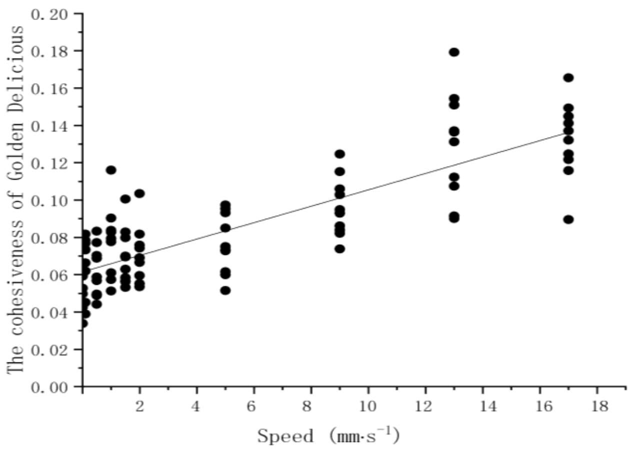
Determination coefficients of univariate linear regression model between loading speed and mechanical characteristic parameters of pulp

Varieties	Hardness	Elasticity	Cohesiveness	Chewiness	Resilience
Fuji	0.059	0.025	0.097	0.122	0.216
Guoguang	0.264	0.021	0.521	0.325	0.127
Golden delicious	0.386	0.147	0.557	0.619	0.001

Note: The closer the influence rate is to 1, the greater the influence of loading speed on the mechanical parameters of TPA in apple pulp.



(a)



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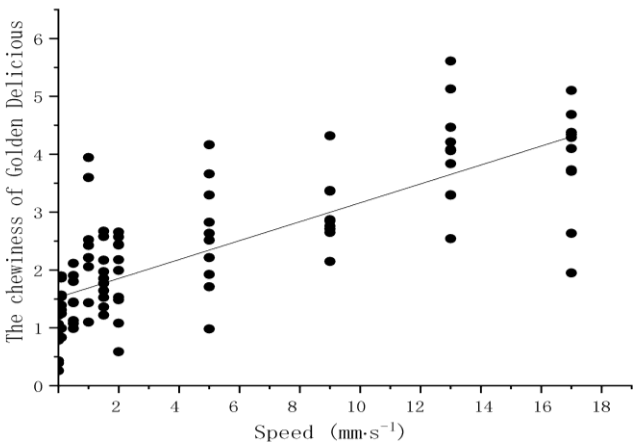


(c)

Fig. 4 - (a) Guoguang cohesiveness; (b) Golden delicious cohesiveness; (c) Golden delicious chewing

It can be seen from Table 3 that the loading speed is used to predict the cohesiveness of Guoguang varieties, and the determination coefficient of linear regression model R^2=0.521 (p<0.05). The loading speed is used to predict the cohesiveness and chewiness of Golden delicious varieties. The determination coefficients of linear regression model R^2=0.557 (p<0.05) and R^2=0.619 (p<0.05), indicate that the loading speed has a certain impact on the cohesiveness, cohesiveness and chewiness of Guoguang varieties and has the ability of prediction *(Fu, 2021)*. The results are basically the same as the effects of different loading speeds on the mechanical parameters of apple pulp. The image of linear regression equation between loading speeds and Guoguang variety cohesiveness, Golden delicious variety cohesiveness and chewiness is shown in Fig. 4. The linear regression equation between different loading speed and Guoguang variety cohesiveness is $y = 0.0046x + 0.038$, with Golden delicious variety cohesiveness is $y = 0.0044x + 0.062$, and with Golden delicious variety chewiness is $y = 0.163x + 1.572$.

Analysis of mechanical characteristic parameters of pulp of different varieties. The differences of pulp mechanical characteristic parameters of different varieties of apples under the same loading speed are analysed. The influence rate of varieties on pulp mechanical characteristic parameters is shown in Table 4. It can be seen from Table 4 that different varieties have a great impact on pulp hardness, cohesiveness and chewiness, and basically have no impact on elasticity and resilience, indicating that there are great differences in the tightness of pulp tissue and cells between varieties. Combined with the changes of TPA mechanical parameters of pulp, the image analysis results show that, compared with the three parameters of hardness, cohesiveness and chewiness which are affected by the combination degree of pulp tissue, the difference of resilience among varieties is small, which is less affected by the tightness of pulp tissue and varieties.

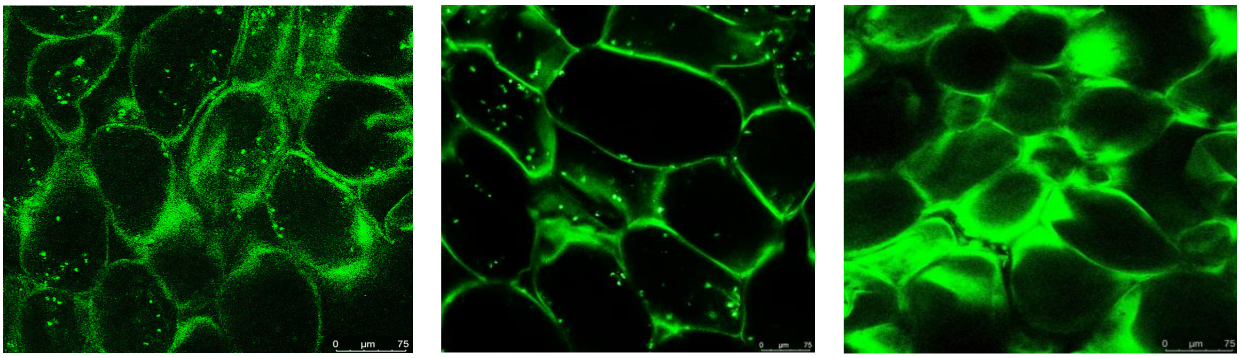
Table 4

Influence rate of different varieties on mechanical parameters of apple pulp

Varieties	Hardness	Elasticity	Cohesiveness	Chewiness	Resilience
0.01	0.667	0	1	1	0
0.1	0.333	0	1	0.667	0
0.5	1	0.333	0.333	1	0.667
1	1	0	0	1	0.667
1.5	1	0.667	1	1	0
2	0.667	0	1	0.667	0
5	1	0.333	1	1	0
9	0.667	0	1	1	0
13	1	0	1	0.667	0
17	0.667	1	0.667	1	0.333

Note: The closer the influence rate is to 1, the greater the influence of loading speed on the mechanical parameters of TPA in apple pulp.

Morphological analysis of apple pulp



(a) (b) (c)

Fig. 5 - (a) Laser confocal image of Fuji pulp tissue; (b) Laser confocal image of Fuji pulp tissue; (c) Laser confocal image of Fuji pulp tissue

Microstructure of pulp of different varieties. Fig. 5 is a laser confocal image of apple pulp tissue. It can be seen from Fig. 5 that the apple pulp tissue cells are connected by the cell wall, which is mixed with irregular polygonal areas. The pulp tissue cells and pores of Guoguang apple are larger than those of Fuji and golden delicious varieties. In Fig. 5 (a), the pulp cells of Fuji varieties are mostly oval, one end is sharp, and the cells are closely connected. Fig. 5 (b) the area and perimeter of pulp cells of Guoguang varieties are large, and the binding length between cells is short. In Fig. 5 (c), there are many round cells in the pulp of golden delicious varieties, and the cells are closely bound, but the connection length is small and the pores are less. The connection modes of tissue cells of the three varieties are different, and the histomorphological parameters are also different.

Euclidean geometric morphological parameter analysis of pulp cells and pores. Image J is used to calculate the area, perimeter, equivalent diameter and circularity of cells and pores, ignoring the characteristics of cells and pores with straight lines at the edge of the picture. The roundness rate is a shape parameter. The smaller it is, the rounder the cell is. The calculation formula is as follows:

$$\gamma = \frac{C^2}{4\pi S} \tag{8}$$

Where: γ is circularity; C is the perimeter, μm; S is the area of cells or pores, μm^2.

The Euclidean geometric morphological parameters of cells and pores of pulp tissues of different apple varieties are shown in Table 5. It can be seen from Table 5 that the area, perimeter and equivalent diameter of pulp tissue cells of different apple varieties are the largest in Guoguang variety, indicating that Guoguang variety has the largest pulp tissue cells. The area, perimeter and equivalent diameter of pulp tissue cells of Guoguang varieties were significantly different from those of the other two varieties (p<0.05). The roundness rate of pulp tissue cells of the three varieties was the smallest in Guoguang variety and the largest in Fuji variety. There was a significant difference in the roundness rate between the three varieties (p<0.05), indicating that the pulp tissue cells of Guoguang variety were round and there were few connections between cells. It can also be seen from Table 5 that the area, perimeter and equivalent diameter of pulp tissue pores of Guoguang varieties are greater than those of Fuji and Golden delicious varieties, indicating that the pulp tissue pores of Guoguang varieties are the largest. The area, perimeter and equivalent diameter of pulp tissue pores of Guoguang varieties were significantly different from those of Golden delicious (p<0.05), but not from Fuji varieties. The round rate of pulp tissue pores of Fuji varieties was higher than that of Guoguang and Golden delicious varieties, which reflected that the round rate of pulp tissue pores of Guoguang varieties was the lowest. There was significant difference between Fuji and the other two varieties in the pore roundness rate of pulp tissue (p< 0.05), indicating that Fuji has longer connecting distance and more contact between pulp tissue cells. In conclusion, Fuji variety has the largest cell and pore roundness rate, long connection distance and tight combination, while Guoguang variety has the smallest cell and pore roundness rate and less cell connection. Hardness, cohesiveness, chewiness and resilience are in direct proportion to the tightness of pulp tissue. Combined with the analysis results of pulp mechanical parameters, the pulp tissue structure directly determines the texture parameters.

Table 5

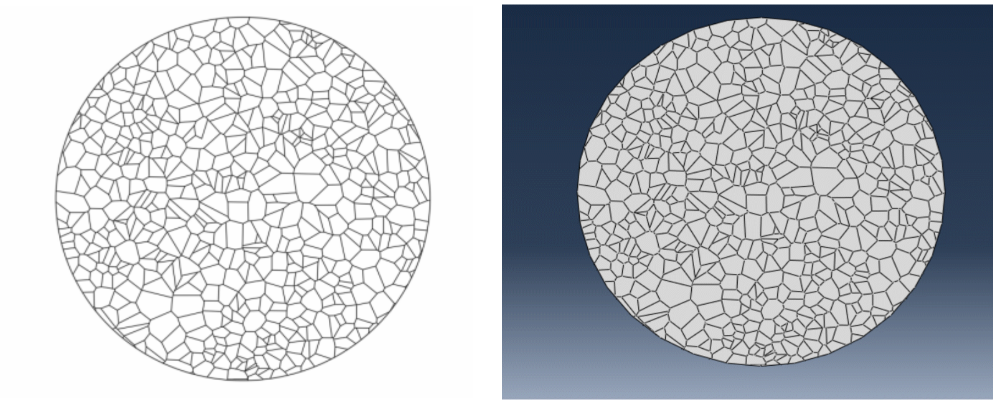
Euclidean geometric morphological parameters of Apple tissue cells and pores

Organization	Varieties	Area [μm^2]	Perimeter [μm]	Equivalent diameter [μm]	Circularity
Cells	Fuji	9374.91±2237.95ab	110.86±14.27a	96.64±18.09a	0.11±0.01a
	Guoguang	36532.54±10730.10b	201.31±59.42b	157.09±24.62b	0.08±0.02c
	Golden delicious	9828.16±2418.73a	111.01±19.11a	94.48±15.10a	0.10±0.02b
Pore	Fuji	4593.77±3047.03a	82.09±20.31a	65.06±26.92a	0.15±0.01a
	Guoguang	9011.71±4293.68b	93.58±28.92a	69.35±20.48a	0.07±0.04b
	Golden delicious	4925.27±2364.63a	84.90±16.23b	67.30±12.30a	0.09±0.11b

Note: Different lowercase letters represent the same Euclidean geometric morphological parameters of cells or pores of different varieties, with significant differences.

Simulation analysis of pulp mechanical test process

Voronoi model of apple pulp tissue. According to the cell area, 7477 Fuji pulp tissue cells, 2737 Guoguang pulp tissue cells and 10175 golden delicious pulp tissue cells can be distributed in a given square area of 10000 μm x10000 μm. The Voronoi model of Fuji pulp tissue cells *(Zheng et al., 2021)* is constructed by MATLAB. In order to facilitate analysis, the cell area is enlarged by 10 times in equal proportion, imported into AutoCAD, and the Voronoi model is adjusted according to the pulp tissue structure of Fuji varieties *(Xing et al., 2021)*. The adjusted model ensures that the pulp tissue structure is similar to the actual observation. The geometric model of pulp tissue structure is shown in Fig. 6 (a). The three-dimensional model of pulp tissue structure is constructed by using AutoCAD and imported into Abaqus. The mesh is divided based on the adjusted Voronoi model. The obtained model is shown in Fig. 6 (b).



(a) (b)

Fig. 6 - (a) Voronoi model; (b) Mesh generation

Voronoi model of apple pulp tissue. Using Abaqus, set the parameters of the three-dimensional model according to the mechanical properties of Fuji apple pulp, select the elastic, plastic and density parameters to build the plastic damage model, use the adjusted Voronoi model as the basis for grid division, select the loading speed of 1 mm/s, and output the displacement stress curve, as shown in Fig. 7. The simulation results are in good agreement with the test results. In the TPA mechanical test, the maximum stress value at the speed of 1 mm/s is 0.46 ± 0.02 MPa, and in the simulation, the maximum stress value is 0.48 MPa. The relative deviation between the two is 4.3%, which is lower than the deviation of the existing simulation test, indicating that the model can better simulate the damage of apple pulp during compression. Based on the analysis of the first compression in TPA mechanical test, the pulp plastic damage model is constructed, and the simulation test is carried out to ensure the effectiveness of the model. The grid division method is refined. Voronoi model similar to the microstructure of apple pulp is adopted and adjusted according to the microstructure observation results, so as to make the model closer to the real microstructure of apple pulp and effectively improve the accuracy.

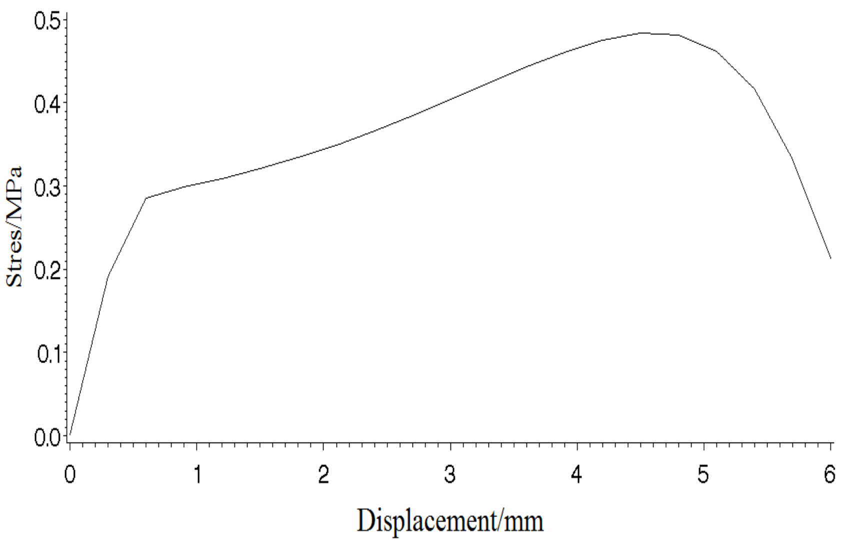


Fig. 7 - Displacement stress curve

CONCLUSIONS

(1) TPA mechanical tests were carried out on the pulp of three apple varieties at different loading speeds, and the differences of mechanical properties of the pulp of the same apple variety under different

loading speeds were analysed. The results showed that there were differences in the mechanical properties parameters of the same apple variety under different loading speeds, and the loading speed had the greatest influence on the cohesiveness, with an average value of 59.1%. Hardness, chewiness and resilience have a certain impact, with an average of 40%, 38.5% and 32.6% respectively, which has no effect on elasticity. Among the three varieties, Fuji variety has the least influence on various mechanical characteristic parameters by the change of loading speed, and has the strongest ability to resist fruit damage caused by the change of loading speed.

(2) The results showed that under the same loading speed, there were differences in the mechanical parameters of different apple varieties. The varieties had a great influence on the chewiness, hardness and cohesiveness, with the average values of 90.01%, 80.01% and 80% respectively. Among the 10 loading speeds, the mechanical parameters of apple at the speeds of 1.5 and 17 mm/s were most affected by the varieties, and the difference of fruit damage was also the largest.

(3) The microstructure of apple pulp was observed by laser confocal microscope. The rounder the pulp cells, the smaller the connection between cells, the looser the structure and the smaller the mechanical characteristic parameters. Among the three varieties of apple, Fuji has the highest rate of pulp tissue cells and pore roundness, the highest hardness, cohesiveness, chewiness and resilience, and Guoguang has the lowest rate of pulp tissue cells and pore roundness, Hardness, cohesiveness, chewiness and resilience were the smallest, and the correlation between Euclidean geometric parameters of pulp tissue and mechanical properties was established.

(4) According to the observation image of Fuji variety pulp microstructure, the Voronoi model of pulp tissue structure is constructed. The plastic damage model is established by using the parameters obtained from the first compression test in TPA mechanical test. The Voronoi model is used for grid division, and Abaqus finite element simulation is carried out. The deviation between the simulation results and the actual test results is 4.3%. The model is effective and has high precision. It can be used for mechanical test analysis of whole apple TPA.

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