Mechanical properties and microstructure of Fuji apple peel and pulp
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ABSTRACT
The mechanical characteristics of apples are crucial to the mechanization of apple production. In this study, the mechanical characteristics of the Fuji apple with the largest crop yield were studied by testing the tensile strength, compression strength, shear strength, bending strength, hardness, friction coefficient, and microstructure. The obtained minimum values of the elastic modulus, yield strength, shear strength, bending strength, and compressive strength were 5.0 ± 0.52, 2.2 ± 0.15, 0.45 ± 0.02, 0.062, and 2.4 ± 0.21 MPa, respectively, all located at the maximum radial radius of the pulp. The hardness decreased gradually with storage time: the hardness of the pulp after 28 days was 0.16 ± 0.02 MPa. The static friction coefficients against TPU (Thermoplastic Urethane) rubber and aluminum alloy materials were 0.88 ± 0.03 and 0.14 ± 0.003, respectively. The microstructure of the peel and pulp changed significantly after damage. The regular shape was destroyed, and the cells deformed and ruptured. The changes in the microstructure were consistent with the changes in the macromechanical properties, so the reliability of the test data could be verified.

Introduction
Mechanical damage is a key problem in the mechanized harvesting, grading, packaging, and transportation of apples, which becomes a bottleneck for large-scale mechanized production. Apple loss caused by mechanical damage has affected 25%–30% of the crop every year in China\textsuperscript{[1]} which seriously impacted the output and the economic benefits. Mechanical damage included both peel damage, which is easy to find, and pulp damage, which is difficult to find\textsuperscript{[2]} The size and location of the damage were closely related to the mechanical properties of the peel and pulp. Therefore, it is necessary to accurately understand the mechanical characteristics of the peel and pulp to reduce or avoid mechanical damage.

Research on the mechanical characteristics of apples has increased globally in recent years, and a lot of effective work has been done. Many studies focused on the whole apple. Li et al.\textsuperscript{[3]} have measured the properties of the whole apple in different storage time, obtained the hardness after 28 days was 0.13 ± 0.75 Mpa. Feng et al.\textsuperscript{[4]} have conducted a puncture test and obtained mechanical properties, including the yield force, the rupture force, and the average hardness of pulp under different test forms and loading rates. Li\textsuperscript{[5]} have conducted compression tests on mature red Fuji apples using an electronic testing machine and determined that the compressive elastic modulus was 2.091 MPa and the yield limit was 0.125 MPa. When the stress exceeded this value, the apple was damaged. Lu and Wang\textsuperscript{[6]} have conducted drop impact tests on Fuji apples from different heights. The results showed that the higher the drop height, the lower the drop elastic recovery; with increased drop times, the
impact force on the apple gradually increased. Yang et al.\textsuperscript{[7]} have conducted a compression test on apple pears, which showed that the loading rate impacted the biological yield and failure limits: the greater the fruit hardness, the greater the biological yield limit of the apple pear. Furthermore, anisotropy in the compression of different parts of the fruit was observed. Yang et al.\textsuperscript{[8]} has measured the surface friction coefficient of apples using a test bed and obtained the static and dynamic friction coefficients between apples and plexiglass or kraft paper, respectively.

In recent years, there have also been studies on the local properties of apples. Zhang et al.\textsuperscript{[9]} have measured the mechanical properties of different parts of the pulp under different compression rates, showing that the elastic modulus (E) increased continuously when the compression rate increased from 20 mm min\textsuperscript{−1} to 40 mm min\textsuperscript{−1}. Ji et al.\textsuperscript{[10]} have simulated the contact process between an apple and flat or curved fingers using the ANSYS software. They found that the stress on the peel was the greatest, followed by the stress on the pulp; however, the stress causing damage to the pulp was smaller, so the pulp was most vulnerable to damage. Grimm et al.\textsuperscript{[11]} have executed a tensile test on apple peel with and without skin spots after the apples were held in refrigerated storage for a minimum period of 14 days. The results showed that the maximum tensile load and elastic modulus of the browning spotted peel were greater than those of the intact peel. Juxia et al.\textsuperscript{[12–14]} have tested the mechanical properties of several varieties of apple peel, and the microstructure of the apple peel was simulated and analyzed. Oey et al.\textsuperscript{[15]} have tested the mechanical properties of apple pulp to explore the effect of cell deformation on cell swelling during tension and compression. The results showed that the size of a single cell changed greatly; in particular, the length-to-width ratio of the cell significantly impacted the cell turgor. Alamar et al.\textsuperscript{[16]} have conducted tensile and compression tests on the pulp tissue of two varieties of Jonathan and Braeburn apples and found that the mechanical properties of different varieties of apple were different.

In addition, many researchers\textsuperscript{[17–20]} have obtained others characteristic parameters of apple, such as strain energy, rubber strain energy, elastic strain energy, peak force, impact energy, and compression slope of entire apples, by impact, loading, and unloading, and puncture tests. A regression equation has been constructed using the test data, which relates the mechanical damage and fruit loading conditions, loading mode, self-mechanical parameters, and the physical parameters used. This equation has been used to predict the mechanical damage to the fruit.

The research on mechanical properties and damage to the apples has mostly focused on the whole fruit and peel, and rarely considered the pulp. Compared with the peel, the tissue of the pulp is softer and more vulnerable to damage, in many cases, there is no obvious damage to the peel, but the internal pulp has been damaged. This internal damage is difficult to find quickly by eye, intensifying the eventual degree of decay, causing damage to healthy fruit, intensifying economic losses, and constituting a hidden danger to food safety. Therefore, the mechanical properties of peels and pulp must be researched. In this paper, Fuji apples were subjected to tensile strength, compression, shear, bending, hardness, friction coefficient, and microstructure tests on both the peel and the pulp. The mechanical characteristic parameters of peel and pulp were obtained, such as the elastic modulus, tensile strength, compressive strength, yield strength, shear strength, bending strength, friction coefficient, and microstructure, which provided basic data for research and development of apple harvesting, grading, packaging, and transportation machinery and equipment.

**Materials and methods**

**Sample preparation**

The test materials were red Fuji apples produced by Qixia, Yantai, Shandong, the hometown of red Fuji apples in China, as shown in Figure 1. The apples used had a good appearance: no pests, no mechanical damage, relatively uniform size, 85–90 mm diameter, and an axial length of 72–76 mm. The apples were picked as they ripened and then stored at 20 ± 2°C and 60% ± 5% humidity.
Since most apples grow upward, the angle between the central axis and gravity ranges from −45° to 45°. During the harvesting process, the contact position between the harvesting machine and the apple is generally at the maximum radial circular surface, where the grasping ability of the harvesting machine is the strongest. That is, the grasping force is maximized in this position. Therefore, test sampling occurred mainly along the radial direction of the apple, as shown in Figure 2(a). At the same time, to verify the anisotropy of the apple, some sampling was done along the axis, as shown in Figure 2(b).

In order to ensure measured mechanical properties were consistent with the actual situation of apples, when sampling, the ratio between the length and width of the sample was in agreement with the radial and axial dimension ratio of the whole apple as far as possible. For example, for an apple with a diameter of 89 mm, the radial and axial dimensions are 89 mm and 75 mm, respectively. The ratio was 1:1.18, so the sample ratio was set to 1:1.18. The number of samples in the same part of the same direction per test was 10.

**Peel sample**

Following the test conditions for filming and slicing in part 3 of this document, peel samples were taken along the radial and axial directions of the apple. The peel was removed with a blade and placed on a flat smooth rubber pad, the pulp was gently scraped off the peel under magnification to

![Figure 1. Photo of a sample Fuji apple.](image)

**Figure 2.** Area of sample specimens in radial and axial directions. a. Radial direction b. Axial direction
ensure that the peel sample was not damaged, and a rectangular sample of $40 \times 15 \times t$ mm ($t$ is the peel thickness) was cut. The sample thickness ($t$) was measured with a grating thickness gauge. The peel thickness of a Fuji apple is $0.213–0.224$ mm. The peel samples are shown in Figure 3.

**Pulp sample**

In order to ensure the proportions of the pulp sample are similar to that of the whole apple, the radial sample was $31 \times 31 \times 26$ mm, and the axial sample was $26 \times 26 \times 31$ mm. The pulp sample is shown in Figure 4.

**Experimental and analytical procedures**

Apples are subjected to compression, shear, bending, and friction during production. In order to fully understand the mechanical characteristics of apple, tensile, shear, hardness, friction coefficient, and microstructure tests were conducted on the peel, and the compression, shear, bending, hardness, and microstructure tests were performed on the pulp. These tests occurred in the material laboratory of College of Mechanical and Electrical Engineering, Qingdao Agricultural University, China. The tensile, compression, shear, and bending tests were performed by a model E44 304 micro-control electronic universal testing machine produced by MTS Industrial System Co., Ltd., China. Its

![Figure 3. Example peel samples. a. The front of the peel sample b. The back of the peel sample](image1)

![Figure 4. A prepared pulp sample.](image2)
maximum rated force is 30 kN, the indication error is 1%, the span is 300 mm, and the stroke is 1000 mm. The hardness test was conducted with a Shaoshi model GS-709 N hardness tester produced by the High-Speed Railway Testing Instrument Co., Ltd. (Dongguan, China) with a measurement range of 0–100 HA and an accuracy of 0.2 HA. The microstructure test was conducted using a DM4000M optical microscope (Leica, Germany), which has a measuring range of 5.00–10.00 μm with an indication error of ±0.5 μm). The length, width, and height of the sample were measured with a digital vernier caliper (Harbin Measuring and Cutting Tools Group Co., Ltd.), which has a measurement range of 0–150 mm, and a resolution of 0.01 mm). In order to prevent the loss of water from the sample, the peel and pulp samples were installed on the fixture of the testing machine immediately after preparation. Each test was repeated 10 times, and the average test data was used as the final results.

**Tensile test**

The upper end of the peel sample was clamped on the upper collet of the micro-control electronic universal testing machine, the force was cleared to eliminate the self-weight of the sample, and then the lower end of the sample was clamped on the lower collet (as shown in Figure 5). The peel length after clamping was 20 mm. The compression test standard (ASABE S368.4(R 2012)) suggests the biological yield point can be observed well at a loading speed lower than 10 mm min⁻¹. Accordingly, the tensile speed was set to 1 mm min⁻¹ until the sample broke and the test stopped, and the stress and strain data were recorded. The test was considered valid if the sample ruptured in the middle.

According to the stress–strain curve of the peel, the elastic modulus, yield strength, and tensile strength of the peel were calculated. The elastic modulus was obtained by calculating the slope of the elastic stage in the curve using the formula:

\[ E = \frac{F_u l}{A_0 \Delta l} \]  

Figure 5. Peel tensile test.
where $E$ is elastic modulus (MPa); $F_a$ is the force (N); $A_0$ is the original cross-sectional area of the sample ($m^2$); $l$ is the original length of the sample (m); and $\Delta l$ is the elongation of the specimen (m). The yield strength is very important for judging the mechanical damage to the pulp. When the stress on the apple is greater than the yield strength, the apple has been damaged. This value is obtained according to the yield stress and strain from the stress–strain curve using the following formula:

$$\delta = \frac{F_d}{A_0}$$  \hspace{1cm} (2)

where $F_d$ is the force at which the sample yields (N); and $\delta$ is the yield strength (MPa). The tensile strength is an important index for evaluating peel fracture failure, it is obtained according to the fracture stress and strain of the stress–strain curve and is calculated as:

$$\sigma = \frac{F_b}{A_0}$$  \hspace{1cm} (3)

where $F_b$ is the force at which the sample breaks (N); and $\sigma$ is the tensile strength (MPa).

**Compression test**

During the compression test, the pulp sample was placed vertically between the two metal plates of the testing machine, and the gap between the metal plate and the sample was adjusted. Next, the loading force and displacement after eliminating the gap were reset (as shown in Figure 6), and the loading speed was set to 1 mm min$^{-1}$. The compression stress and strain were recorded, and the test was considered valid if the sample was crushed in the middle. The compressive stress–strain curve of the pulp was obtained, and the elastic modulus, yield strength, and compressive strength of the pulp were calculated following the calculation methods shown in equations (1), (2), and (3).

![Figure 6. Pulp compression test.](image)
Shear test

The sample was fixed on the workbench of the testing machine; the cylinder punch was fixed in the collet of the testing machine (Figure 7(a, b)), and the loading speed was set to 1 mm min⁻¹. During the test, the shear stress and strain data were recorded. The shear strength of the peel and pulp was calculated according to the maximum shear force, using the formula:

\[
\tau = \frac{F_j}{A}
\]  

(4)

where \(F_j\) is the force at the shear point of the sample (N); \(\tau\) is shear strength (MPa); and \(A\) is the shear area \((mm^2)\).

Bending test

The pulp samples were placed firmly on the support such that the sample was equidistant from both ends. Next, the position of the indenter was adjusted to slightly contact the surface of the sample, the pressure sensor was set to zero, the testing machine was started, and the indenter pressed slowly until the sample broke, which stopped the test (Figure 8(a, b)). The changes in the stress and strain were recorded during the bending test. The test was considered valid if the center of the pulp fractured.

The bending stress–strain curve of the pulp was obtained. Based on this curve, the bending elastic modulus of the pulp was calculated as follows:

\[
G = \frac{F_W l}{48 I \gamma}
\]  

(5)

where \(G\) is the bending elastic modulus (MPa); \(F_W\) is the force acting on the middle of the pulp (N); \(l\) is the width of the support (mm); \(I\) is the moment of inertia of the sample\((mm^4)\); \(d\) is the average value of the diameters \(d_1, d_2\) at each end of the sample (mm); and \(\gamma\) is the deflection in the middle of the sample (mm). The bending strength of the pulp can be calculated according to the rupture bending force and displacement of the bending stress–strain curve using the following formula:
\[ \sigma = \frac{64FwI}{\pi d^3} \] (6)

where \( \sigma \) is the bending strength (MPa).

**Hardness test**

Hardness is an important quality of fruit, which is usually used as an index of mechanical damage resistance. During the hardness test, the indenter of the hardness tester was aligned vertically with the peel and pulp samples, the pressure was evenly applied, and stopped when the cylindrical indenter with a diameter of 10 mm pressed into the peel by 0.11 mm and the pulp by 10 mm. The apple hardness is directly read from the display screen (shown in Figure 9(a, b)). The average value was taken as the final result.

**Friction coefficient test**

During harvesting, the frictional force between the harvesting device and the apple mainly acts on the peel; therefore, the friction coefficient between the peel and the harvesting device was measured. Figure 10. shows a schematic of the test platform[17]: the support platform is fixed, the mobile platform...
moves freely on the support platform, the digital tension meter is fixed on the support platform, and the friction material moves with the electric mobile platform. The apple was connected to the digital tension meter through a tension rope, and its tension value, which is the frictional force between the friction material and the apple, was displayed on the PC. According to the formula for the frictional force, the friction coefficient is:

\[ \mu = \frac{F_m}{mg} \]

where \( F_m \) is the frictional force (N); \( \mu \) is the friction coefficient; when \( f \) is the maximum static frictional force, \( \mu \) is the static friction coefficient, when \( f \) is the dynamic friction, \( \mu \) is the dynamic friction coefficient; \( m \) is the mass of the apple (kg); and \( g \) is the acceleration of gravity, 9.8 N kg\(^{-1}\).

The experimental steps were as follows: (1) the friction material was embedded into the electric mobile table, and the apple was placed on the friction material. (2) The electric mobile station was slowly moved at 1.5 mm s\(^{-1}\) to generate a frictional force between the apple and the friction material, and the value was displayed in real-time on the computer from the digital tension meter. (3) When a relative motion was produced between the apple and its friction material, the tensile force was the maximum static frictional force; (4) The electric mobile station continued to move, which caused relative sliding between the apple and the friction material. After moving smoothly for a while, the tension obtained at this time is the dynamic frictional force; (5) The average value of tests was the friction coefficient between the apple and the different friction materials.

As the apple harvesting machine is mainly made of an aluminum alloy and rubber, tests were conducted using friction plates made from these two materials. The aluminum alloy plates with thickness of 8 mm and a smooth surface without rust were made from 6063 aluminum, while the rubber (TPU) plates were 8-mm thick and had a smooth surface without burrs, scratches or concave-convex structures.

**Microstructure test**

As a complex biomass, the mechanical properties of apple peel and pulp are closely related to their microstructure; therefore, establishing the relationship between the microstructure and macrostructure of the apple peel and pulp helps model an apple and analyze its response behavior under load. Before the test, the peel and pulp were sampled by hand slicing. The sample was 5 × 5 × 3 mm\(^{1,2}\) and the microstructure tests of the peel and pulp are shown in Figure 11(a, b), respectively. The sample was stained with 0.1% methylene blue solution for 10s and then washed with deionized water (Sterling, 1968; Lewicki et al., 2005; Mayor et al., 2005; Alamar et al., 2008) to remove bacteria, dust, and other foreign matter from the surface of the peel. Next, the slide and coverslip were cleaned and dried, and
the processed materials were placed on the slide, covered with the cover slip, and fixed. The finished slide was placed under the microscope for observation (Figure 11(a, b)), and the observed tissue structure was photographed and saved.

Results and discussion

Tensile properties

Figure 12(a, b) show the stress–strain curve of the radial and axial samples of the peel. A nonlinear relationship exists without an obvious yield point between the stress and the strain. The curves were S-shaped, and larger deformation occurred at the fracture point b, where the strain was 11.6%. The whole curve is composed of two segments. The first segment is oa, which is a straight line. At this stage, the deformation characteristics complied with Hooke’s law: the strain increased faster than the stress. The unstretched peel was in a state of microbuckling, which resulted in a larger tensile strain and uneven stress distribution. The second segment is dc, which is a curved segment. The relationship between the peel stress and strain is nonlinear at this stage. With increased stress and strain, the stress reaches a maximum at point b. After that, the peel sample gradually fractured, but the stress did not rapidly decrease to zero. Instead, it decreased gradually, and the curve had a smaller extension.

According to Figures 12(a, b), and formulas (1), (2), and (3), the elastic modulus, yield strength, and tensile strength of the radial and axial peel samples can be calculated. The resulting values are shown in Table 1. As shown in Table 1, the range of mean values of elastic modulus was 19.3–23.82, the elastic...
moduli of the axial and radial peels have significant differences, and the axial elastic modulus is 23.42% higher than the radial elastic modulus, indicating that the axial peel is more resistant to elastic deformation than the radial peel. The range of the mean values of the yield strength was 0.25–0.3, and the axial yield strength was 20% higher than the radial yield strength. The range of mean values of tensile strength was 1.2–1.22. The axial tensile strength and the radial tensile strength differ. When the sample length is small, the difference is small. Consistent with previous research results,[3,10,26] the radial peel is easier to damage than the axial peel.

As shown in Figure 12, their tensile curve characteristics were the same and tended to coincide for the radial and axial peel samples. However, the mechanical parameters of elastic modulus, yield strength, and tensile strength for the radial and axial peels were different, as listed in Table 1. The peel can be considered an anisotropic material. The mechanical characteristics of the radial peel were lower than those of the axial peel, which presented smaller resistance to deformation than the axial peel and was more susceptible to damage. Therefore, the mechanical characteristics of the radial peel should be key factors when designing mechanical equipment for harvesting, grading, packaging, and transportation of apples.

**Compression properties**

Figure 13(a, b) show the stress–strain curve of the radial and axial pulp samples. The whole curve is nonlinear for both samples without an obvious yield point. The maximum stress is 2.4 ± 0.21 MPa, located at point b, which is the crushing stress of the pulp. The whole curve is composed of two segments, the first segment is the segment that has obvious linear characteristics; however, after point a, nonlinear characteristics occurred. When observed under a microscope, destruction of the microstructure of pulp cells had begun, some cells deformed (Figure 20(b)), the pulp ruptured at point b, the curve decreased, and the stress decreased, but it did not drop to zero immediately. There was a certain extension, which showed the creep and viscosity of the pulp.

![Stress-strain curves of compression test of pulp](image_url)

**Figure 13.** Stress–strain curves of compression test of pulp. a. Compressive stress–strain curve of radial pulp b. Compressive stress–strain curve of axial pulp

| Parts  | Tensile elastic modulus (MPa) | Yield strength (MPa) | Tensile strength (MPa) |
|--------|-------------------------------|----------------------|------------------------|
| Radial | $19.3 \pm 2.26$              | $0.25 \pm 0.04$      | $1.22 \pm 0.23$        |
| Axial  | $23.82 \pm 2.21$             | $0.3 \pm 0.05$       | $1.2 \pm 0.29$         |
At the beginning of the curve (the curve segment before point o), the unstretched pulp was in a state of microbuckling, resulting in larger strain and smaller stress. Moreover, due to the existence of interstitial cells, tissue cells are reoriented at the beginning of stretching. According to Figures 13(a, b) and formulas (1), (2) and (3), the elastic modulus, yield strength, and tensile strengths of the radial and axial peel can be calculated. All values are given in Table 2.

As shown in Table 2, the range of the mean values of the elastic modulus was 5.0–5.32, the range of the mean values of yield strength was 2.2–2.3, and the range of mean values of fracture strength was 2.4–2.6. By comparing radial and axial mechanical parameters of the pulp, it has obvious anisotropy. The radial elastic modulus of pulp is 10.6% lower than the axial elastic modulus, so the ability of the radial pulp to resist elastic deformation is lower than that of the axial pulp. The radial yield strength is 4.5% lower than the axial yield strength; that is, the radial pulp is easier to damage than the axial pulp under the same force.\(^\text{12}\) The mechanical characteristics of the radial pulp should be considered when designing mechanical equipment for harvesting, grading, packaging, and transportation.

**Shear properties**

**Shear test of peel:** The shear strength–strain curve of the peel is shown in Figure 14. The shear curve of the peel can be divided into four stages: The strain range of the first stage is 0–0.9, its shear strength is almost unchanged with the increase in the strain. Because the peel sample is buckling at the beginning of the test, and the buckled peel tissue cells gradually expand, the strain range of the second stage is 0.9–2.2. The buckling state of the peel gradually disappeared in this stage, and the tissue cells of the peel begins to deform under the shear force, so the gap between cells becomes smaller and smaller. The expansion pressure of the cell itself increased; therefore, shear strength increased gradually with increase of displacement at this stage. The strain range of the third stage is 2.2–2.7. With the further action of the perforator on the peel, shear strength increases. Further, the swelling pressure of the peel tissue cells increases sharply, and finally, the cells rupture. The load at this stage also increases sharply; after reaching the maximum value of point b, the peel is cut, and the stress and strain values at point b are shown in Table 3.

According to Figure 14, there is only one peak in the shear curve of the peel, indicating that the mode of shear rupture of the peel sample is to simultaneously rupture the peel tissue cells, which can be seen from the fractured sample of peel in Figure 15, which has also been observed by Juxia et al.\(^\text{12}\)

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**Table 2.** Mean value and standard error of mechanical properties of Fuji apple pulps under compression loading.

| Parts  | Compression elastic modulus (MPa) | Yield strength (MPa) | Fracture strength (MPa) |
|--------|----------------------------------|----------------------|-------------------------|
| Radial | 5.0 ± 0.52                       | 2.2 ± 0.15           | 2.4 ± 0.21 MPa          |
| Axial  | 5.32 ± 0.43                      | 2.3 ± 0.18           | 2.6 ± 0.32 MPa          |

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![Figure 14](image-url). Shear strength–strain curve of peel.
Shear test of Pulp: The shear strength–strain curve of the pulp is shown in Figure 16. The shear deformation of the pulp experienced two stages. The first stage is the elastic deformation segment oa; the relationship between the stress and the strain conformed to Hooke’s law. The second stage is the segment ab, where the pulp deformation enters plastic deformation, and the relationship between the stress and strain is no longer linear. The shear strength further increases, and finally, the cells rupture. The load at this stage also increases sharply. The pulp was cut off after reaching the maximum value of point b; as the cutting point, the strength of point b is the shear strength of the peel. After the pulp was cut, the strain increased rapidly, and the stress decreased gradually until it was close to zero. These
curves extend for some time, and their extension length was larger than that of the peel, and the creep of the pulp was larger. The values of the shear elastic modulus, shear strength, and failure strain are shown in Table 3.

By comparing the mechanical parameters of the peel and pulp, the shear elastic modulus of the peel was greater than that of the pulp, the shear strength of the peel was greater than that of the pulp, and the failure strain of the peel was also greater than that of the pulp, showing that the pulp presented less resistance to deformation than the peel when bearing shear force and torsion force. The pulp was more easily damaged than the peel under the same force. During apple harvesting, handling, storage, and transportation, the likely damage to the apple pulp is the first factor to be considered.

**Bending properties**

The bending stress–strain curve of the pulp is shown in Figure 17(a): the curves were S-shaped, the bending deflection (abscissa) was very small, and the bending stress (ordinate) was not very large, which indicated that the bending strength and bending deformation of the pulp were small, which is consistent with the fracture diagram of the test (Figure 17(b)).

As shown in Figure 17, at the beginning of bending, the strain increases greatly, the stress remains unchanged due to the buckling of the peel, and the curvature of the eo curve is very small. With increased stress, the pulp entered the elastic deformation stage (oa) until point d, where the pulp began to yield, and the sample broke. The mechanical bending parameters of the pulp are shown in Table 4.

By comparing the bending elastic modulus, the bending strength in Table 4, the compression elastic modulus, and the fracture strength in Table 2, the bending elastic modulus and bending strength are smaller than the compression elastic modulus and the fracture strength, which showed that the pulp had a weak resistance to bending, but had strong resistance to compression. Therefore, in the mechanized operation of an apple, try to avoid bending force.

**Hardness properties**

The hardness of the peel and pulp and the change rule during storage are shown in Figure 18 (a), b), and Table 5. Figure 18 depicts the hardness change trend of peel and pulp. Table 5 gave the hardness values with storage times of 0, 14, and 21 days.

![Figure 17](image_url)

**Figure 17.** Bending stress–strain curve and test breaking diagram of the pulp. a. Bending stress–strain curve of pulp b. Test breaking diagram
Table 4. Mean value and standard error of mechanical properties of Fuji apple pulps under bending loading.

| Parts | Bending elastic modulus (MPa) | Yield strength (MPa) | Bending strength (MPa) |
|-------|-------------------------------|----------------------|------------------------|
| Pulp  | 2.41 ± 0.19                   | 0.062                | 0.14                   |

Figure 18. Hardness changes of peel and pulp with storage period. a. Hardness changes of peel with storage period b. Hardness changes of pulp with storage period.

Table 5. Hardness values of peel and pulp with storage period.

| Parts | Storage time (days) | Hardness (kg cm⁻²) |
|-------|---------------------|--------------------|
| Peel  | 0                   | 8                  |
|       | 14                  | 7                  |
|       | 21                  | 6.18               |
| Pulp  | 0                   | 2.29               |
|       | 14                  | 1.9                |
|       | 21                  | 1.74               |

As shown in Figure 18, the hardness of the apple peel and pulp decreased with extended storage time, the hardness decreased greatly within 14 days of storage, and the decreasing trend of hardness slowed down. The lower the hardness of the fruit, the weaker the compressive capacity, and the more prone it is to damage. The hardness of the apple is closely related to the size of the pulp cells, cell density, and pectin content in the cell walls.

As shown in Table 5, the hardness of the apple peel and its pulp is the greatest when freshly picked. Over 14 days, the hardness of peel and pulp was reduced by 12.5% and 17%; in 21 days, the hardness of the peel and pulp was reduced by 22.75% and 24%. The hardness of the pulp decreased faster than that of the peel. With increased storage time, the hardness of the peel and pulp decreased gradually.

For the whole apple, the cells at the top of the apple were smaller, and density was higher in general because the cells at the middle of the apple surface were larger and had a lower density, so the hardness at the middle was small. Therefore, the middle part of the apple is vulnerable during storage and transportation.

Microstructure

The microstructure of an intact apple is shown in Figure 19, the microstructure of a peel is shown in Figure 19(a), and the microstructure of the pulp is shown in Figure 19(b). Microstructures of apples after yield damage are shown in Figure 20, the microstructure of peel is shown in Figure 20(a) and microstructure of pulp is shown in Figure 20(b).

In Figure 19, the peel cells and the pulp cells of the intact apple are full; the cell shape is dense, square, and similar to the particle structure, and there are no microcracks. The cell spacing of the peel is small and closely arranged, the cell spacing of the pulp is large, the cell fluid is smooth and viscous,
and there is no accumulation or pits. The peel and pulp cells have a tip structure: when the peel was stretched, the relative sliding between cells became larger, the stress was concentrated, and the tensile performance of the apple was poor.

Figure 20 shows that the microstructure of the apple changes after damage: some cells of peel and pulp were deformed, and their regular shape was destroyed. If the pressure continues to increase, the cells have permanent deformation and damage: slip, deformation, and rupture; the cell fluid has obvious viscous flow along the rupture surfaces of peel and pulp, which was relatively irregular, at both ends of the fracture. Part of the stratum corneum was extracted and stripped, that is, when the peel broke, the failure mode involved peeling between cells due to the crack extension at the incision.\footnote{23} The structural changes to the microstructure of the apple before and after the damage were consistent with the changes in tensile and compressive properties, which reflected that the macro-mechanical properties of the apple were closely related to its microstructure.

\textbf{Friction coefficient}

In this test, the friction coefficients between the apple and the rubber (TPU), the apple and metal materials (aluminum alloy) were tested. The results are shown in Figure 21, Figure 22, and Figure 23. Figure 21 and Figure 22 depicted the changing trend of friction between apples and different materials. The friction was constantly changing during the friction test. At the beginning of the test, the friction was zero, then it began to rise to the maximum value, and then the tension decreased slightly and tended to be constant. The maximum value of the friction was the maximum static friction; after that, the relative motion between the material and the apple began, and the friction

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{figure19a.png}
\includegraphics[width=0.45\textwidth]{figure19b.png}
\caption{Microstructure of intact apple. a. Microstructure of peel b. Microstructure of pulp.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{figure20a.png}
\includegraphics[width=0.45\textwidth]{figure20b.png}
\caption{Microstructure of apple after damage. a. Microstructure of peel b. Microstructure of pulp.}
\end{figure}
tended to be constant, which indicates dynamic friction. Figure 23 indicates that contacting friction coefficient from five experiments between apple and rubber (TPU) and apple and metal (aluminum alloy), their values are shown in Table 6, respectively.

From Figure 23 and Table 6, the friction coefficient between the rubber and the apple was larger. The average values of the static and dynamic friction coefficients were 0.88 ± 0.03 and 0.80 ± 0.015, respectively. The friction coefficient between the metal and the apple was smaller. The average values of the static and dynamic friction coefficients were 0.14 ± 0.003 and 0.13 ± 0.006, respectively. That is, the friction coefficient between rubber and an apple was larger under the same pressure compared with metal materials, but the contact pressure between rubber and the apple was smaller than with metal under the same frictional force.

Figure 21. Friction between apple and rubber.

Figure 22. Friction between apple and metal.

Figure 23. Friction coefficient between apple and different materials.
Table 6. Friction coefficient between apple and rubber (TPU), apple and metal (Aluminum alloy).

| Materials          | Number of tests | Static friction coefficient | Dynamic friction coefficient |
|--------------------|-----------------|-----------------------------|------------------------------|
| Rubber (TPU)       | 1               | 0.877                       | 0.805                        |
|                    | 2               | 0.852                       | 0.780                        |
|                    | 3               | 0.914                       | 0.789                        |
|                    | 4               | 0.864                       | 0.801                        |
|                    | 5               | 0.865                       | 0.801                        |
| Metal (Aluminum alloy) | 1           | 0.142                       | 0.138                        |
|                    | 2               | 0.138                       | 0.135                        |
|                    | 3               | 0.141                       | 0.136                        |
|                    | 4               | 0.140                       | 0.136                        |
|                    | 5               | 0.148                       | 0.137                        |

Therefore, during apple harvesting, grading, packaging, and transportation, using rubber as the contact material can not only increase friction and improve harvesting stability but also reduce contact pressure and mechanical damage.

Conclusions

In this paper, the mechanical characteristics and damage to the peel and pulp of Fuji apples were studied comprehensively. The minimum values of the elastic modulus, tensile strength, compressive strength, yield strength, shear strength, bending strength, hardness, and friction coefficient were obtained, and the following conclusions were drawn: (i) The stress–strain curve of the peel and pulp presented an approximate S-shape. The mechanical characteristics differed for the radial and axial peel and pulp, indicating that the peel and pulp were nonlinear and anisotropic viscoelastic materials without an obvious bioyield point. These observations provide some references from which to build models of the peel and pulp material. (ii) The mechanical properties of the pulp are lower than those of the peel: its elastic modulus, shear strength, and hardness are 25.9%, 10.2%, and 28.6% of those of the peel, respectively. The macromechanical properties of the peel and pulp were closely related to their microstructure. When subjected to the same force, the pulp is more likely to be damaged. Therefore, the mechanical characteristics of the pulp should be key factors when designing mechanical equipment for harvesting, grading, packaging, and transportation. (iii) The friction coefficient between an apple and rubber materials was larger than between an apple and metal materials, which provided a theoretical basis for reducing mechanical damage to the apple. In addition, during apple harvesting, grading, packaging, and transportation, rubber materials used as contact components not only improved harvesting stability but also reduced contact pressure and mechanical damage. The results of this paper provide basic data for the design of mechanical equipment for apple harvesting, grading, packaging, and transportation and lay a foundation for the mechanization of apple production.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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