

## Experimental study on compression fracture characteristics of wheat grains with different moisture content

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### Abstract

Wheat grains are subjected to various external mechanical forces that lead to deformation or even fracture during sowing, harvesting, storage, and processing. Wheat grains with different moisture content exhibit different mechanical properties. Therefore, compressive mechanical properties of wheat grains with different moisture contents at different directions were conducted by TMS-Pro physical properties analyzer in the present paper. Results show that geometric dimensional size of wheat grains increase with moisture content. When compressed at different directions, deformation of wheat grains increase while mechanical properties decrease with moisture content. A crack through endosperm is formed on the back of grains, and finally throughout the whole ventral groove when wheat grains are compressed at the L-axis and H-axis directions. And, cracks form on the contact area between grains and compression plates when grains are compressed at the B-axis direction. Number, length, and width of cracks in wheat grains decrease with moisture content. The gap between starch particles of wheat grains with high moisture content is smaller, combination of internal particles is much tighter, and viscoelasticity is increased. Therefore, mechanical properties of wheat grains should be higher with lesser moisture content during sowing, harvesting, and storage, while it should be lower with bigger moisture content during the processing of grains.

**Keywords:** Compression test, crack propagation, fracture characteristics, moisture content, wheat grains

### Introduction

Globally, wheat is one of the most important food crops, and it has been extensively cultivated and consumed worldwide. At present, integrity of wheat grains is regarded as an important indicator to evaluate wheat quality both nationally and internationally. Sowing, harvesting, storage, and processing of wheat are becoming increasingly mechanized with rapid development

of modern mechanical manufacturing industry. Wheat grains will suffer various external mechanical forces during sowing, harvesting, storage, and processing of wheat, which can result in deformation or even fracture of grains. The failure grains can be easily invaded by microorganisms, which can shorten the storage life of grains and reduce the processing quality and food safety of wheat (Chen and Li, 2024; Fu *et al.*, 2018). Therefore, studying mechanical properties of wheat grains under

different moisture content is of great significance to optimize parameters of the processing equipment and improve utilization value of wheat grains (Ponce-García *et al.*, 2016; Wang *et al.*, 2023).

The mechanical properties of wheat grains are mainly influenced by physical and chemical properties such as moisture content, protein, starch, etc., in which moisture content of grains is the most important parameter during harvesting, and storage is up to 18% (Bian and Liu, 2024; Li *et al.*, 2024). Mechanical properties of wheat grains have been studied by many scholars (Chen *et al.*, 2020; Gao *et al.*, 2024). Kaliniewicz *et al.* (2022), Ficco *et al.* (2020), and Babić *et al.* (2011) studied the basic physical parameters of different varieties soft wheat and hard wheat, and found that the grain size increased with moisture content and the grains were of ellipsoid shape with sphericity of 60%–80%. Zhao *et al.* (2018), Dufour *et al.* (2024), and Acar *et al.* (2019) found that grain hardness decreased with increase in grain size, the content of protein and starch increased with grain size, and the contact area between starch and protein particles was larger when the moisture content was high. Uniaxial compression tests of grains with strain of 3% and 5% by Escalante-Aburto *et al.* (2023) and Ponce-García *et al.* (2013) found that viscoelasticity of grain decreased with 1000-grain weight and height of grains and was greatly influenced by the maximum force during compression tests. Barrera *et al.* (2019), Canay *et al.* (2022), and Kubik *et al.* (2021) found that mechanical properties of wheat peel are similar to that of the whole wheat, and peel of soft wheat exhibited higher ductility, while endosperm of hard wheat exhibited higher hardness. Jia *et al.* (2015), Voicu *et al.* (2013), Omarov *et al.* (2012), and Ponce-García *et al.* (2008) found that hard wheat with low moisture content showed higher elasticity, soft wheat with high moisture content showed higher plasticity, and wheat with elliptical shape was much easier to show elastic–plastic deformation behavior than that with spherical shape under external force.

Tavakoli *et al.* (2009) and Gorji *et al.* (2010) studied fracture resistance of grains by compression tests at horizontal and vertical directions and found that fracture force was smaller when moisture content and loading rate were higher, and fracture energy at the horizontal direction was bigger than that at the vertical direction. Shear characteristics studied by Li *et al.* (2018) and Ramaj *et al.* (2024) showed that shear deformation increased and shear force decreased with moisture content, shear energy changed significantly, and shear force of hard wheat was higher than that of soft wheat. Wang and Jeronimidis (2008) conducted three-point bending tests on soft and hard wheat grains and showed that endosperms of both soft and hard wheat grains were isotropic

composite materials. Study by Chen *et al.* (2021) showed that wear failure of wheat grains can be neglected while compression and impact failure of wheat grains were of great importance. Zhang *et al.* (2024), Başlar *et al.* (2012), Kasraei *et al.* (2015), and Zhao *et al.* (2018) studied the relationship between protein content and mechanical properties for different varieties of wheat and showed that mechanical properties were influenced by wheat variety, and wheat with high protein content was harder and the broken force was higher. Zhou *et al.* (2024), Lu *et al.* (2023), and Topin *et al.* (2009) verified that effective stiffness in compression tests was greater than that in tension tests by discrete element simulation. Jia *et al.* (2014) simulated stress distribution of wheat grain during storage process by finite element method, and results showed that side deformation of wheat was higher than the abdomen deformation.

In summary, mechanical properties of wheat grains with different moisture content at single compression directions were analyzed by domestic and foreign researchers, and deformation, fracture force, and energy were studied. However, there are few reports on importance parameters such as contact elastic modulus, maximum contact stress, and generation and propagation mechanism of microcracks in wheat grains. Therefore, this study assessed compressive mechanical properties of wheat grains with different moisture content tested at three directions, and effects of moisture content and compression directions on geometry dimensional size and compressive mechanical properties of wheat grains were studied. Formation and propagation of crushing cracks in wheat grains at different compression directions were observed. The present study will provide reference for the design and optimization of technical parameters for sowing, harvesting, storage, processing, and other related machinery.

## Materials and Methods

### Preparation of tested samples

Fengde Cunmai 21 wheat grains from the Henan Province were selected for testing, and the initial moisture content was 8.7%. As moisture content of wheat grains during sowing, harvesting, storage, and processing are different, the moisture content during sowing and storage is less than 14%, the moisture content during processing is 14%–18%, and that during harvesting is 20%–25% (Yang *et al.*, 2022). Therefore, five groups of wheat grains with different moisture contents were prepared, and they were moistened by adding moisture several times according to the standard of NY/T 1094.1–2006 (2006) until moisture contents were  $9.3\% \pm 0.14\%$ ,  $12.4\% \pm 0.05\%$ ,  $14.7\% \pm 0.10\%$ ,  $17.9\% \pm 0.17\%$ , and  $21.6\% \pm 0.31\%$ , respectively.

Mass of distilled moisture required for different samples was calculated by Equation (1),

$$M = \frac{x_1 - x_0}{100 - x_1} \cdot m \quad (1)$$

In which,  $x_0$  is the initial moisture content of wheat grains, %;  $x_1$  is the required moisture content of wheat grains, %;  $m$  is the mass of the grain sample, g;  $M$  is the mass of distilled moisture required for each sample, g. The moistened grain samples were cold-stored in a sealed bag. Before the compression tests, the samples should be placed at room temperature for 1 h so that the samples thaw to room temperature.

### Measurement of geometry dimensional size

A complete wheat grain was randomly selected from the sealed bag, and then geometry dimensional size of the wheat grain at three-axis directions was measured using the PD-151 electronic vernier caliper. The measurement diagram is shown in Figure 1. Samples with different moisture contents were repeatedly measured 100 times, and the average was taken as dimensional size of each sample. Three-axis arithmetic average diameter, geometric average diameter, and sphericity of wheat grains were calculated according to the following equations:

$$d_a = \frac{l + b + h}{3} \quad (2)$$

$$d_g = (l \cdot b \cdot h)^{1/3} \quad (3)$$

$$s = \frac{(l \cdot b \cdot h)^{1/3}}{l} \times 100\% \quad (4)$$

In which,  $l$ ,  $b$ , and  $h$  are the length, width, height of wheat grain, respectively, mm;  $d_a$  is the arithmetic average diameter of wheat grain, mm;  $d_g$  is the geometric average

diameter of wheat grain, mm; and  $s$  is the sphericity of wheat grain, %.

### Compression crushing test of wheat grains

Compression tests of wheat grains were carried out using the TMS-Pro physical property analyzer at the direction of the L-axis (length), B-axis (width), and H-axis (height), respectively. And square bottom plate and cylindrical probe were selected as the compression device, as shown in Figure 2. The induction force range is set as 500 N, the initial force is set as 0.75 N, and the compression speed is set as 6 mm/min, with specific parameter settings listed in Table 1. Both ends of wheat grains were polished to about 1 mm<sup>2</sup> with sandpaper to better place the grains during the L-axis compression test. Twenty sets of wheat grains with different moisture contents were tested at three compression directions, and the average of mechanical parameters was taken as the test results.

Displacement and failure force of wheat grain during compression test can be directly obtained from the force-displacement curve of the compression test results. The failure energy of wheat grain during

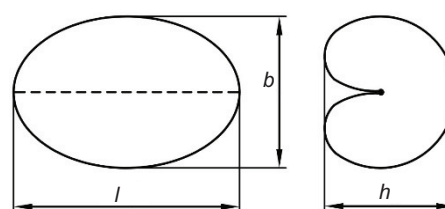


Figure 1. Measurement diagram of geometry dimensional size at three-axis directions for wheat grains,  $l$ ,  $b$ , and  $h$  are the length, width, height of wheat grain, respectively, mm. The dotted line is the ventral groove of the wheat grain, placed horizontally backward.

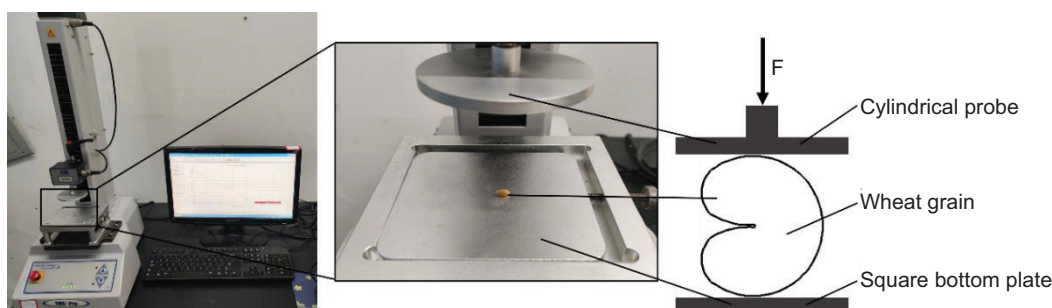


Figure 2. Wheat grain compression test device and schematic diagram (Taking the B-axis as an example).

**Table 1. Compression parameter settings for physical property analyzer.**

Experimental parameters	Numerical value
Inductive force range	500 N
Initial force	0.75 N
Distance between compression probe and base plate	10 mm
Compression probe movement speed	60 mm/min
Compression speed	6 mm/min

compression test can be calculated by Equation (5) (Voicu *et al.*, 2013),

$$W = \frac{F \times D}{2} \quad (5)$$

In which,  $W$  is the compression failure energy of the wheat grain, mJ;  $F$  is the compression failure force of the wheat grain, N; and  $D$  is the compression displacement of wheat grain, mm.

According to ASAE S3684 DEC2000 (R2008) (2008) standard, the apparent contact elastic modulus of wheat grains was calculated by the Hertz equation,

$$E = \frac{0.338K_U^{3/2}F(1-\mu^2)}{d^{3/2}} \left( \frac{1}{R_U} + \frac{1}{R_U'} \right)^{1/2} \quad (6)$$

In which,  $E$  is the apparent contact elastic modulus of the wheat grain, MPa;  $K_U$  is the coefficient of geometric characteristics of the wheat grain, which is obtained by calculating  $\cos\theta$  look-up table,  $\cos\theta = (1/R - 1/R_U)/(1/R_U + 1/R)$ ;  $F$  is the failure force, N;  $\mu$  is the Poisson's ratio of wheat, with a value of 0.3;  $d$  is the compression deformation of the wheat grain (the value is equal to half of the compression displacement), mm;  $R_U$  and  $R$  are the large and small contact curvature radii of wheat grain and the rigid plate during compression process, mm. The curvature radius is expressed by the following equations for compression at the B-axis direction,

$$R_U = \frac{b^2 + \frac{l^2}{4}}{2b} \quad (7)$$

$$R_U' = \frac{b^2 + \frac{h^2}{4}}{2b} \quad (8)$$

The maximum contact stress between wheat grain and the compression plate is located at the center of the

contact elliptical area, which is 1.5 times of the average contact stress. It can be calculated by Equation (9),

$$S_{\max} = \frac{1.5F}{\pi ab} \quad (9)$$

In which,  $S_{\max}$  is the maximum contact stress of wheat grain, MPa;  $a$  and  $b$  are the semi-major axis and semi-minor axis of the contact elliptical area during compression process, mm, which are calculated as follows:

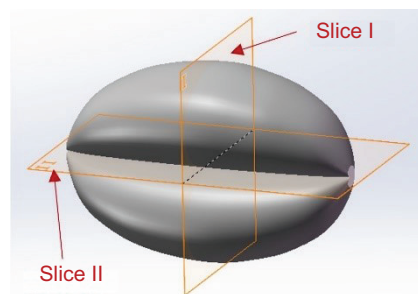
$$a = c_1 \left[ \frac{3Fk}{2} \left( \frac{1}{R_U} + \frac{1}{R_U'} \right)^{-1} \right]^{1/3} \quad (10)$$

$$b = c_2 \left[ \frac{3Fk}{2} \left( \frac{1}{R_U} + \frac{1}{R_U'} \right)^{-1} \right]^{1/3} \quad (11)$$

In which,  $c_1$  and  $c_2$  are coefficients of elliptical eccentricity, which are obtained by the table look-up method;  $k = (1 - \mu^2)/E$ .

### Observation of wheat grain crushing crack

Based on the mechanical compression tests of wheat grains, formation and propagation of external cracks inside the wheat grains compressed under different loads at different compression directions were observed by ultra-depth three-dimensional microscope system (UDM, Keyence VHX-5000). The compressed wheat grains were sliced, and then the internal microstructure and crack distribution of wheat grains were observed by Phenom XL desktop scanning electron microscope. The slice direction of compressed wheat grains is shown in Figure 3, and slice I is at the semi-minor axis of wheat grains while slice II is at semi-major axis of wheat grains.



**Figure 3. Slice diagram of compressed wheat grains.**

## Experiment Results and Analysis

### Effect of moisture content on geometry dimensional size of wheat grains

The geometry dimensional size of wheat grains at three-axis directions under different moisture contents were measured by the digital vernier caliper. The arithmetic average diameter, geometric average diameter, and sphericity of the grains were calculated according to Equations (2), (3), and (4). The effect of moisture content on the geometric dimensional size of wheat grains was analyzed at a significance level of  $\alpha = 0.05$ , and the results are shown in Table 2.

It can be seen from Table 2 that the length, width, height, arithmetic average diameter, geometric average diameter, and sphericity of wheat grains exhibit a certain increase trend with moisture content. Among them, the length, width, height, and sphericity of wheat grains are significantly affected by moisture content ( $P < 0.01$ ), while arithmetic average diameter and geometric average diameter of wheat grains are highly significantly affected by moisture content ( $P < 0.001$ ). Sphericity of wheat grains with different moisture contents is more than 66%, and therefore, wheat grains can be assumed as an ellipsoid model with a transverse groove when analyzing wheat grains by numerical simulation methods.

### Effect of moisture content on compression mechanical properties of wheat grains

Compression tests of wheat grains with different moisture contents at three-axis directions were carried out by the physical property analyzer. Deformation and failure force of wheat grains with different moisture contents were obtained according to the force-displacement curve. Failure energy, apparent contact elastic modulus, and maximum contact stress of wheat grains were calculated by a combination of Equation (5) to Equation (11). The results are listed in Table 3.

### Relationship between deformation and moisture content

Compression deformation at different directions of wheat grains with different moisture contents is shown in Figure 4. Results show that deformations of wheat grains at three-axis directions increase with moisture content. Deformations of wheat grains with the same moisture content are different at different compressed directions, and deformation at the L-axis direction is the largest, that at the B-axis direction is medium, while that at the H-axis direction is the smallest. When wheat grains were compressed at the L-axis direction, deformation of wheat grains with moisture content of 9.3% is 0.591 mm, deformation of wheat grains with moisture content of 17.9% is slightly increased to 0.672 mm, which is increased by 13.7% compared with wheat grains with moisture content of 9.3%. However, deformation of wheat grains is increased to 0.788 mm by increasing moisture content to 21.6%, which is greatly increased by 33.3% compared with wheat grains with moisture content of 9.3%. When wheat grains were compressed at the B-axis direction, deformation of wheat grains with moisture content smaller than 14.7% is slightly increased, and deformation is rapidly increased for wheat grains with moisture content higher than 14.7%. Deformation of wheat grains is increased from 0.536 mm to 0.616 mm by increasing moisture content of wheat grains from 14.7% to 17.9%, which is increased by 3.5% and 18.9% compared with wheat grains with moisture content of 9.3%. When wheat grains were compressed at the H-axis direction, deformation of wheat grains with moisture content of 14.7% is 0.504 mm, while that of wheat grains with moisture content increased to 17.9% is 0.569 mm, which is increased by 4.3% and 17.8% compared with wheat grains with moisture content of 9.3%.

As stated in 'Effect of moisture content on geometric dimensional size of wheat grains' section, geometry dimensional size of wheat grains with lower moisture content is much smaller; therefore, the hardness of the internal structure is much larger, and the deformation resistance is much higher. However, wheat grains with higher moisture content can absorb more moisture

**Table 2. Geometry dimensional size of wheat grains with different moisture contents (n = 100).**

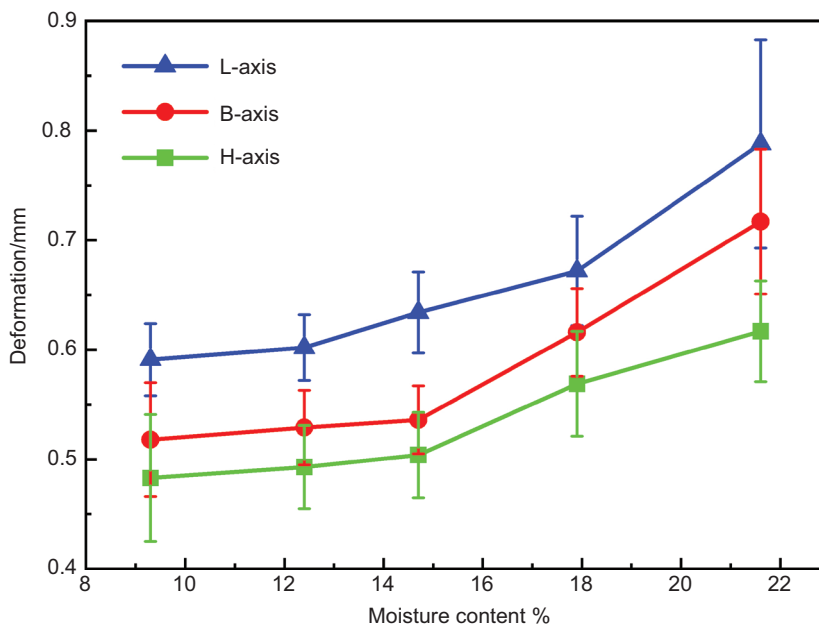
Moisture content (%)	<i>l</i> (mm)	<i>w</i> (mm)	<i>h</i> (mm)	<i>d<sub>a</sub></i> (mm)	<i>d<sub>g</sub></i> (mm)	<i>s</i> (%)
9.3 ± 0.14	6.062 ± 0.333	3.494 ± 0.218	3.154 ± 0.184	4.236 ± 0.205	4.057 ± 0.200	66.93 ± 2.36
12.4 ± 0.05	6.086 ± 0.253	3.521 ± 0.176	3.190 ± 0.170	4.266 ± 0.166	4.089 ± 0.164	67.18 ± 1.68
14.7 ± 0.10	6.124 ± 0.260	3.563 ± 0.212	3.211 ± 0.201	4.299 ± 0.193	4.123 ± 0.196	67.31 ± 1.97
17.9 ± 0.17	6.177 ± 0.265	3.608 ± 0.192	3.273 ± 0.193	4.353 ± 0.177	4.178 ± 0.179	67.65 ± 2.19
21.6 ± 0.31	6.212 ± 0.260	3.678 ± 0.147	3.308 ± 0.157	4.399 ± 0.138	4.228 ± 0.136	68.06 ± 2.34
LSD	0.001	0.001	0.001	< 0.001	< 0.001	0.001

Through the least significant difference (LSD) test ( $P < 0.05$ ). *l*: Grain length; *b*: Grain width; *h*: Grain height; *d<sub>a</sub>*: Arithmetic average diameter; *d<sub>g</sub>*: Geometric average diameter; *s*: Sphericity. Note: The test values in the table are "average ± standard deviation".

**Table 3.** Triaxial compression mechanical test results of wheat grain (n = 20).

Compression direction	Moisture content (%)	d (mm)	F (N)	W (mJ)	E (MPa)	S <sub>max</sub> (MPa)
L-axis (Length)	9.3 ± 0.14	0.591 ± 0.033	149.922 ± 18.740	88.436 ± 11.451	125.703 ± 20.283	36.700 ± 1.553
	12.4 ± 0.05	0.602 ± 0.030	141.868 ± 10.123	85.447 ± 7.720	114.905 ± 11.774	33.877 ± 0.819
	14.7 ± 0.10	0.634 ± 0.037	132.107 ± 10.762	83.760 ± 8.563	98.927 ± 12.487	29.789 ± 0.800
	17.9 ± 0.17	0.672 ± 0.050	110.657 ± 4.763	74.415 ± 6.696	75.807 ± 9.235	23.386 ± 0.335
	21.6 ± 0.31	0.788 ± 0.095	75.221 ± 11.714	58.884 ± 8.789	41.502 ± 11.308	13.654 ± 0.688
B-axis (Width)	9.3 ± 0.14	0.518 ± 0.052	156.441 ± 12.589	81.089 ± 10.607	182.865 ± 27.892	47.357 ± 1.277
	12.4 ± 0.05	0.529 ± 0.034	148.490 ± 13.956	78.794 ± 11.293	165.431 ± 14.354	43.418 ± 1.357
	14.7 ± 0.10	0.536 ± 0.031	141.979 ± 10.796	76.066 ± 7.197	154.950 ± 17.403	40.786 ± 1.010
	17.9 ± 0.17	0.616 ± 0.040	116.915 ± 8.559	72.112 ± 8.239	102.887 ± 10.559	28.941 ± 0.704
	21.6 ± 0.31	0.717 ± 0.066	81.043 ± 10.833	58.132 ± 9.877	57.057 ± 11.666	17.196 ± 0.740
H-axis (Height)	9.3 ± 0.14	0.483 ± 0.058	139.407 ± 12.541	67.108 ± 8.665	185.039 ± 40.841	46.144 ± 1.370
	12.4 ± 0.05	0.493 ± 0.038	133.814 ± 8.492	66.026 ± 7.597	167.985 ± 18.312	42.604 ± 0.901
	14.7 ± 0.10	0.504 ± 0.039	123.849 ± 19.295	62.792 ± 13.340	148.680 ± 18.192	38.047 ± 1.935
	17.9 ± 0.17	0.569 ± 0.048	102.223 ± 7.580	58.426 ± 8.750	102.119 ± 7.378	27.693 ± 0.693
	21.6 ± 0.31	0.617 ± 0.046	70.893 ± 6.195	43.706 ± 4.763	62.790 ± 10.398	17.671 ± 0.513

In which, d: Deformation; F: Failure force; W: Failure energy; E: Elastic modulus; S<sub>max</sub>: Maximum contact stress. The test values in the table are "average ± standard deviation".



**Figure 4.** Changes in the deformation of wheat grain in compression fracture for different moisture content (9.3% ± 0.14%, 12.4% ± 0.05%, 14.7% ± 0.10%, 17.9% ± 0.17%, 21.6% ± 0.31%). L-axis, B-axis, and H-axis are the compression of length, width, and height orientation, respectively. Results are expressed as mean ± standard deviation (n = 20).

and expand to bigger size; therefore, wheat grains with much higher moisture content will get much softer, with the viscoelasticity being increased and the deformation resistance being decreased. So, wheat grains with moisture content exceeding a certain value will become soft,

and the deformation of wheat grains will be increased rapidly during compression. Therefore, the connection between germ and endosperm of wheat grains with moisture content exceeding 17.9% will become soft when the grains are compressed at the L-axis direction, and

the endosperm of wheat grains with moisture content exceeding 14.7% will become softer when the grains are compressed at the B-axis direction and H-axis direction. Wheat grains with high moisture content are relatively round, and it is easy to produce large deformation under external force; therefore, the grains will pile with high density and small porosity which is harmful for the ventilation effect and will lead to dampness and mildew of wheat grains. Therefore, it is better to keep the moisture content of wheat grains smaller than 14% when storing wheat grains.

#### Relationship between failure force and moisture content

Figure 5 shows compressive failure force at different directions of wheat grains with different moisture contents. Results show that failure force of wheat grains at three-axis directions decrease with moisture content. When moisture content of wheat grains is increased from 9.3% to 21.6%, failure force of wheat grains compressed at the L-axis direction is decreased from 149.922 N to 75.221 N, failure force at the B-axis direction decreases from 156.441 N to 81.043 N, and failure force at the H-axis direction decreases from 139.407 N to 70.893 N. In addition, failure force of wheat grains with lower moisture content decreases much slower than that of wheat grains with higher moisture content. The reason is that wheat grains with low moisture content are relatively dry, and toughness of wheat grains is much lower. Volume of internal cells inside wheat grains with low moisture content is much smaller, and hardness is much higher. Consequently, fracture resistance of wheat grains with

low moisture content is relatively high, and the grains are hard to be fractured. Wheat grains with much higher moisture content exhibit much higher plasticity, and toughness of seed coat and endosperm decreases with moisture content, which can decrease compression fracture resistance of grains and therefore the grains are easier to be fractured. Therefore, moisture content of wheat grains should be as low as possible to increase breakage resistance and ensure their integrity and activity in the sowing and harvesting process of wheat.

When the moisture content of raw materials is too low during the flour grinding process of wheat grains, the grain skin is brittle, the toughness is poor, and the fragmentation of grains is high. The skin and endosperm cannot be better separated and small bran particles will mix into the flour during grinding, and lead to decrease in the color and quality of the flour, thereby resulting in economic losses. After adjusting moisture content of wheat grains to about 15% with appropriate amount of moisture, toughness of the epidermis increases, the bran formed during grinding decreases, the internal tissues of endosperm become softer, the strength of grains decreases, and a slight displacement between the epidermis and endosperm is generated, resulting in a decrease in the binding force. Therefore, the grains can be well separated during the grinding process, which is beneficial for improving grinding performance and reducing force consumption, thereby resulting in cost savings. However, when the moisture content of wheat grains is too high, the endosperm on the surface is difficult to be peeled

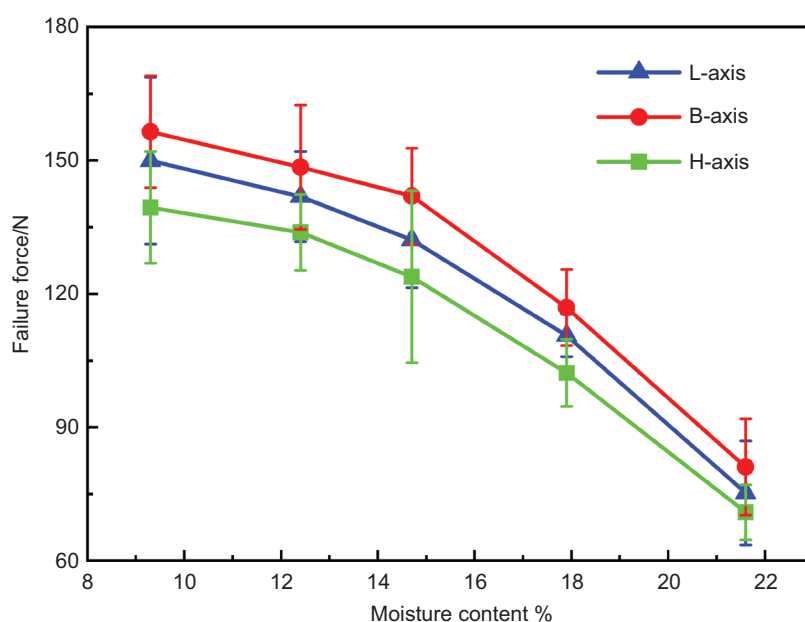


Figure 5. Changes in the failure force of wheat grain in compression fracture for different moisture contents ( $9.3\% \pm 0.14\%$ ,  $12.4\% \pm 0.05\%$ ,  $14.7\% \pm 0.10\%$ ,  $17.9\% \pm 0.17\%$ ,  $21.6\% \pm 0.31\%$ ). L-axis, B-axis, and H-axis are the compression of length, width, and height orientation, respectively. Results are expressed as mean  $\pm$  standard deviation ( $n = 20$ ).

off, and fluidity of the products will also be decreased, which can lead to material blockage, thereby resulting in decrease of the flour yield and factory efficiency. In addition, germ of wheat grains contains abundant protein, fat, and various trace elements necessary for humans. Although they only account for 2% of the whole grain weight, their nutritional value accounts for about 97% of the entire grain. Germ of wheat grains will be screened out along with bran during grinding of wheat grains with lower moisture content, which will result in a significant loss of nutrients. Increasing moisture of wheat grains to a proper content helps to separate germ from epidermis of wheat grains, which can greatly enhance nutritional value of wheat flour. Moreover, adding germ to flour can improve color and chewiness of noodles to a certain extent (Aktaş *et al.*, 2015; Demir *et al.*, 2021). Above all, moisture content of the wheat grains should be adjusted to about 15% during the flour grinding process of wheat grains in order to obtain better flour quality (Yang *et al.*, 2022).

Compressive failure force of wheat grains with the same moisture content is different at different compression directions. Failure force of wheat grains compressed at the B-axis direction is the largest, failure force compressed at the L-axis direction is medium, and failure force compressed at the H-axis direction is the smallest. The hairy end of the wheat grain is known as the top, and the end with the germ is known as the bottom. The side of the wheat grain with the germ is known as the back, which is in a semi-circular shape. The flat opposite side is known as the ventral surface. The middle of the wheat grain is a groove sunken to the center of the grain called the ventral groove, which is almost as long as the whole wheat grain. When wheat grains are compressed at the B-axis direction, the main load-carrying parts are peel and endosperm. The peel cells of wheat grains are closely arranged and relatively hard, and the crushing resistance is much stronger, so the failure force is the largest when wheat grains are compressed at the B-axis direction. When wheat grains are compressed at the L-axis direction, the main load-carrying parts are germ, peel, and endosperm. The germ is rich with a large amount of oil and protein, of which the structure is relatively loose and the crushing resistance is weak. The germ will be destroyed before the cracking of wheat grains, and the load-carrying parts are peel and endosperm at the later stage, so the failure force is relatively small during compression of wheat grain at the L-axis direction. When wheat grains are compressed at the H-axis direction, the main load-carrying parts are ventral groove and endosperm. And, it is easy to produce stress concentration for there is a certain gap between compression plate and the ventral groove of wheat grain, so the failure force is the smallest when wheat grains are compressed at the H-axis direction. Above all, the crushing resistance of wheat

grains is not only related to moisture content but also compression direction and internal structure of grains.

#### *Relationship between failure energy and moisture content*

Failure energy is the minimum energy consumed by wheat grains during the plate compression process, and it is related to the failure force and deformation of wheat grains during the compression process. The failure energy of wheat grains with moisture content during the compression process is shown in Figure 6. Results show that failure energy of wheat grains decreases with moisture content under different compression orientations. Internal structure of wheat grains with lower moisture content is hard, and the ability to resist compression failure is much stronger, so the failure energy consumed by wheat grains is much greater. By increasing the moisture content of wheat grains, the internal structure of wheat grains becomes much softer, and the ability to resist compression failure becomes much weaker, so the failure energy decreases, which is consistent with the change trend of the failure force with different moisture content. The energy consumed by wheat grains with the same moisture content during the compression process is as follows: failure energy during compression at the L-axis direction (88.436 mJ–58.884 mJ) > failure energy during compression at the B-axis direction (81.089 mJ–58.132 mJ) > failure energy during compression at the H-axis direction (67.108 mJ–43.706 mJ). However, the failure energy of wheat grains with moisture content higher than 14.7% during compression at the B-axis direction gradually approaches to that at the L-axis direction. This is mainly because of the fact that the compression deformation of wheat grains with moisture content higher than 14.7% at the B-axis direction increases greatly, and the compression deformation at the L-axis direction increases greatly when the moisture content of wheat grains is higher than 17.9%. The failure force of wheat grain during compression at the B-axis direction is nearly the same to that at the L-axis direction, so the failure energy of wheat grains with higher moisture content during compression at the B-axis direction approaches to that at the L-axis direction.

#### *Relationship between apparent contact elastic modulus and moisture content*

Apparent contact elastic modulus of wheat grains is the ability to generate elastic deformation of the wheat grain during the compression process, and it depends on geometry dimensional size at different directions, compression deformation and failure force of wheat grains. Apparent contact elastic modulus of wheat grains with different moisture contents is shown in Figure 7. Results show that apparent contact elastic modulus decreases linearly with moisture content at different compression directions, indicating that the elastic deformation of wheat grains increases with moisture content within the

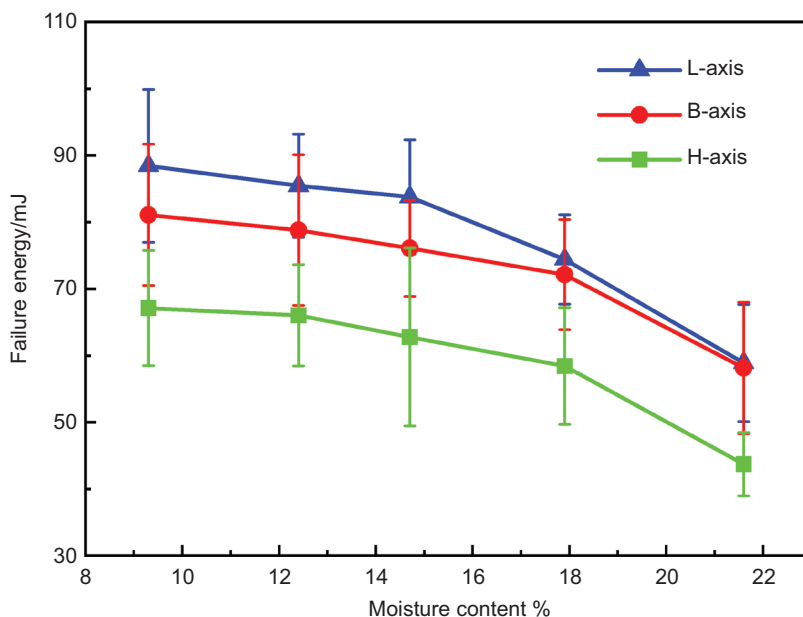


Figure 6. Changes in the failure energy of wheat grain in compression fracture for different moisture contents (9.3% ± 0.14%, 12.4% ± 0.05%, 14.7% ± 0.10%, 17.9% ± 0.17%, 21.6% ± 0.31%). L-axis, B-axis, and H-axis are the compression of length, width, and height orientation, respectively. Results are expressed as mean ± standard deviation (n = 20).

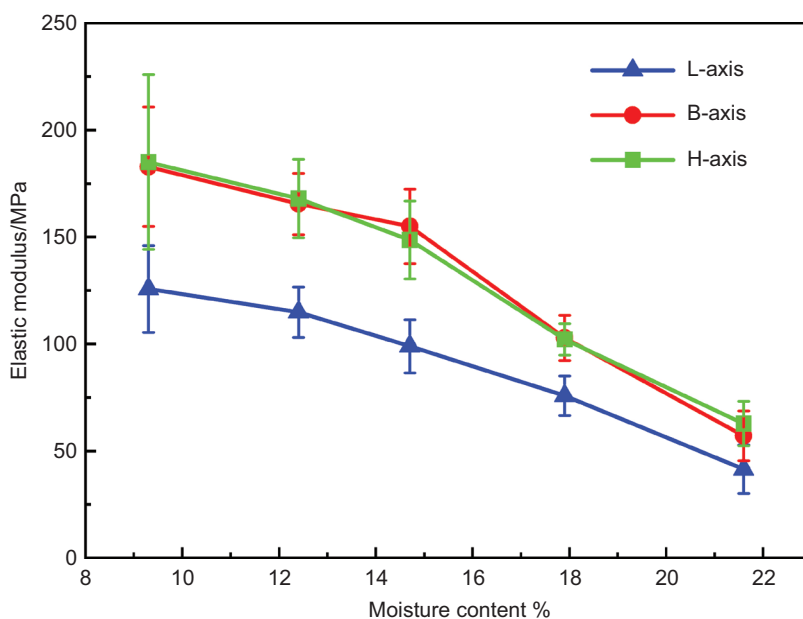


Figure 7. Changes in the elastic modulus of wheat grain in compression fracture for different moisture content (9.3% ± 0.14%, 12.4% ± 0.05%, 14.7% ± 0.10%, 17.9% ± 0.17%, 21.6% ± 0.31%). L-axis, B-axis, and H-axis are the compression of length, width, and height orientation, respectively. Results are expressed as mean ± standard deviation (n = 20).

elastic range of wheat grains themselves under the same failure force, which is similar to that for failure force of wheat grains with different moisture contents, indicating that failure force plays the major role during the compression process. The apparent contact elastic modulus of wheat grains (182.865 MPa–57.057 MPa) during

compression at the B-axis direction is close to the apparent contact elastic modulus (185.039 MPa–62.790 MPa) of wheat grains with the same moisture content during compression at the H-axis direction, which is much larger than the apparent contact elastic modulus (125.703 MPa–41.502 MPa) of wheat grains during compression

at the L-axis direction. The above phenomenon is mainly because the deformation and geometry dimensional size of wheat grains are relatively large during compression at the L-axis direction, and the apparent contact elastic modulus decreases with geometry dimensional size at a different direction and the compression deformation of wheat grains. Therefore, the apparent contact elastic modulus of wheat grains during compression at the L-axis direction is the smallest.

#### *Relationship between maximum contact stress and moisture content*

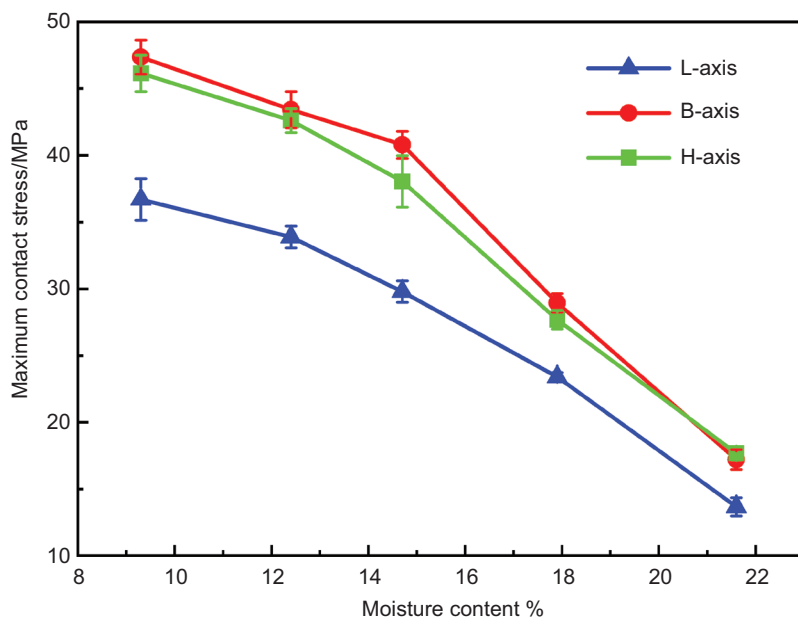
Maximum contact stress of wheat grains refers to the maximum stress generated at the center of the contact area between wheat grain and the top plate and bottom plate under compression failure force during compression of wheat grains. The maximum contact stress of wheat grains with different moisture contents during compression is shown in Figure 8. Results show that the maximum contact stress of wheat grains decreases linearly with moisture content during compression at different directions, which is similar to the change rule for compression failure force of wheat grains with different moisture contents. Maximum contact stress of wheat grains compressed at the B-axis direction (47.357 MPa–17.196 MPa) is slightly larger than that of wheat grains with the same moisture content compressed at the H-axis direction (46.144 MPa–17.671 MPa), and the maximum contact stress of wheat grains compressed at the L-axis direction (36.700 MPa–13.654 MPa) is the

smallest. This is mainly because of the fact that the maximum contact stress of wheat grains decreases with the contact area between wheat grain and the top plate and bottom plate during compression of wheat grains (i.e., the geometry dimensional size at the L-axis direction, at the B-axis direction, and at the B-axis direction), and it increases with the compressive failure force. The geometry dimensional size of wheat grains during compression at the L-axis direction is much larger than that of wheat grains during compression at the B-axis direction and the H-axis direction; therefore, the maximum contact stress of wheat grains during compression at the L-axis direction is the smallest.

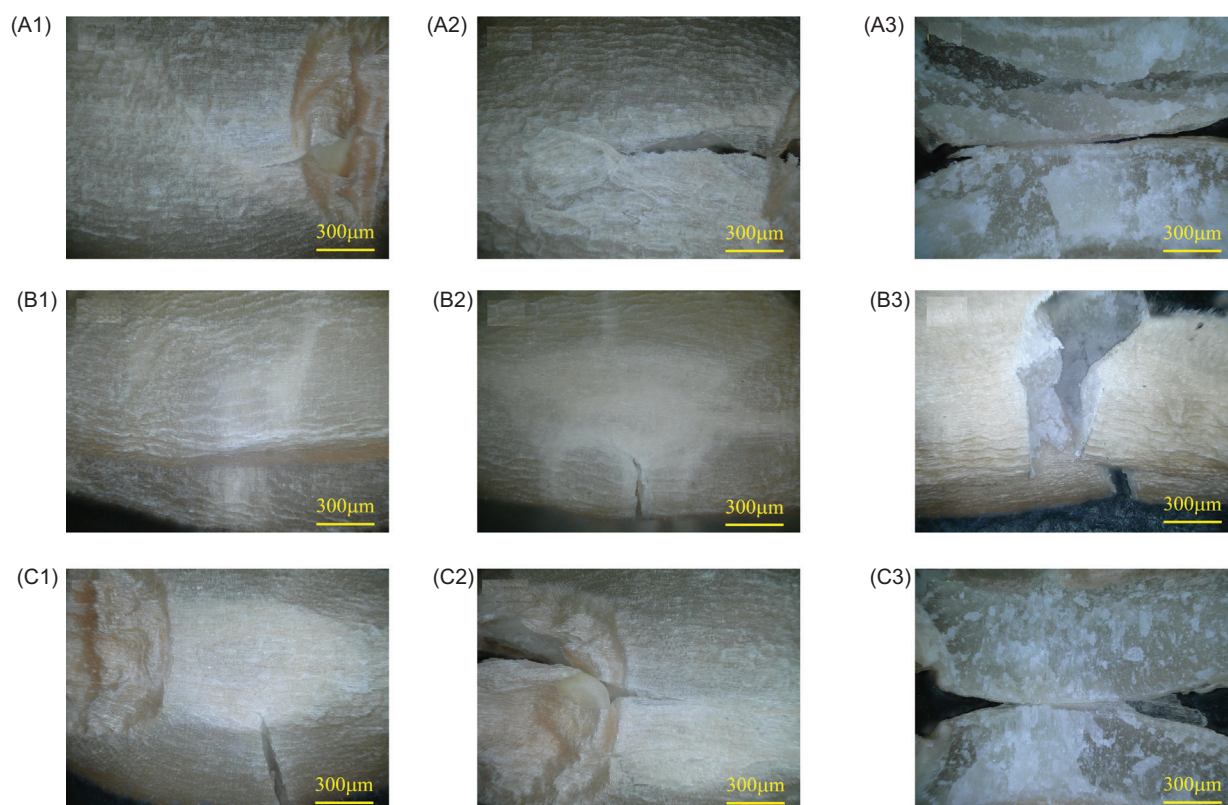
#### **Crack propagation of wheat grains during the compression process**

##### *External crack of wheat grains*

External crack propagation of wheat grains with different moisture contents is the same as each other, so wheat grains with a moisture content of 9.3% are selected as example to study external crack propagation; external crack propagation of grains during compression at different directions are shown in Figure 9. Results show that the formation and fracture positions of external cracks are different when wheat grains are compressed at different directions. When wheat grains are compressed at the L-axis direction, the contact area between wheat grains and the top and bottom compression plates is



**Figure 8.** Changes in the maximum contact stress of wheat grain in compression fracture for different moisture contents ( $9.3\% \pm 0.14\%$ ,  $12.4\% \pm 0.05\%$ ,  $14.7\% \pm 0.10\%$ ,  $17.9\% \pm 0.17\%$ ,  $21.6\% \pm 0.31\%$ ). L-axis, B-axis, and H-axis is the compression of length, width, and height orientation, respectively. Results are expressed as mean  $\pm$  standard deviation ( $n = 20$ ).



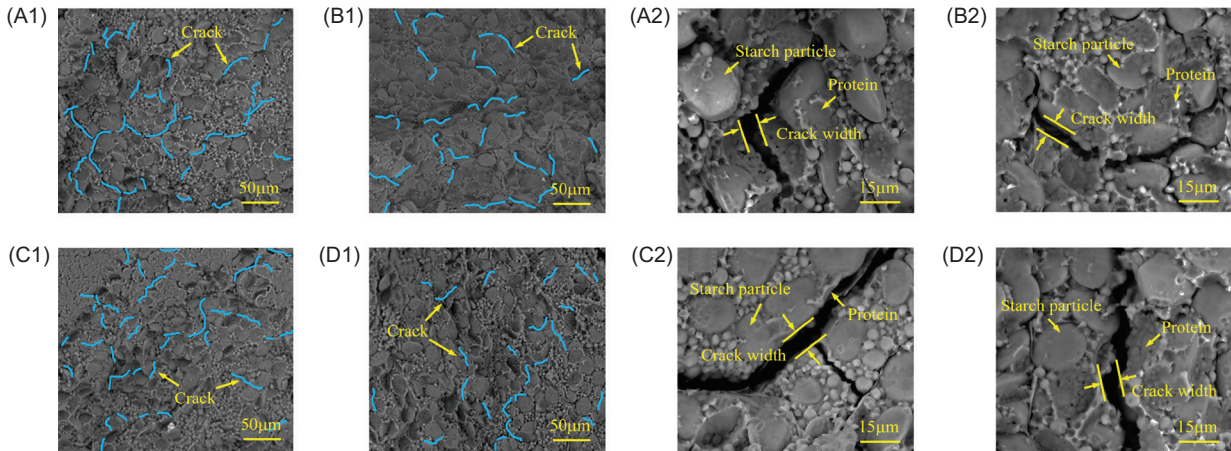
**Figure 9.** Changes in the external crack propagation of the wheat grain in compression fracture for different directions. (A1)–(A3) at the L-axis direction; (B1)–(B3) at the B-axis direction; (C1)–(C3) at the H-axis direction.

small, and it is easier to generate the stress concentration. Therefore, external crack of wheat grains first forms in the germ of the grains (Figure 9(A1)), and then the crack extends to the connection area between the germ and endosperm (Figure 9(A2)). As the compression process continues, a crack running through the endosperm part of grains is formed on the back of grains, finally a long crack throughout the L-axis direction (ventral groove) of the grain forms and the wheat grains will fracture (Figure 9(A3)). When wheat grains are compressed at the B-axis direction, cracks first form near the contact area between the wheat grain and the compressed plate (on both sides of the ventral groove) (Figure 9(B1)), and then the cracks extend along the plane formed by the B-axis and the H-axis of wheat grains (Figure 9(B2)), and finally wheat grains break (Figure 9(B3)). When wheat grains are compressed at the H-axis direction, the endosperm on the back of wheat grains will be first contacted by the compression plates, and cracks are formed on the side of the grains (Figure 9(C1)). When the wheat grains are compressed to the connection area of the embryo and the endosperm, the compression resistance of the connection area is relatively weak (Figure 9(C2)). At the same time, stress concentration is formed in the ventral groove of the grains, and the ventral groove is sunken

to the center of wheat grains, so the back area of wheat grains is relatively weak. Finally, a crack similar to that when compressed at the L-axis direction is formed on the back of wheat grains, resulting in fracture of wheat grains (Figure 9(C3)).

#### *Internal crack of wheat grains*

Wheat grains with moisture content of 12.4% and 17.9% are selected to study the propagation of internal cracks of wheat grains; internal crack of wheat grains with different moisture contents is shown in Figure 10. Results show that there are about 40 cracks on the observed area of slice I when the moisture content of wheat grains is 12.4%. The total length of cracks observed on slice I is 1240.2  $\mu\text{m}$ , the longest crack is 87.7  $\mu\text{m}$  (Figure 10(A1)), and the widest crack is 4.4  $\mu\text{m}$  (Figure 10(A2)). There are about 32 cracks on slice I when the moisture content is 17.9%, the total length of cracks is 1055.6  $\mu\text{m}$ , the longest crack is 63.3  $\mu\text{m}$  (Figure 10(B1)), and the widest crack is 2.9  $\mu\text{m}$  (Figure 10(B2)). Thirty-seven and 24 cracks can be observed on slice II when the moisture content of wheat grains is 12.4% and 17.9%, and the total length of cracks are 1105.3  $\mu\text{m}$  and 731.3  $\mu\text{m}$ , respectively. The longest crack is 73.1  $\mu\text{m}$  and 54.2  $\mu\text{m}$  (Figure 10(C1), (D1)), and the widest crack is 4.6  $\mu\text{m}$  and 3.8  $\mu\text{m}$  (Figure 10(C2),



**Figure 10.** Changes in the internal crack of wheat grain behind compression fracture for different slice directions (slice I, slice II), different moisture contents (12.4%, 17.9%). (A1), (A2) Internal cracks on slice I of wheat grains with a moisture content of 12.4%; (B1), (B2) Internal cracks on slice I of wheat grains with a moisture content of 17.9%; (C1), (C2) Internal cracks on slice II of wheat grains with a moisture content of 12.4%; (D1), (D2) Internal cracks on slice II of wheat grains with a moisture content of 17.9%

(D2)). Above all, more internal cracks can be observed on the observed area of wheat grains with lower moisture content, and the total length of cracks and length of the longest crack increase with moisture content, and the width of the widest crack is smaller when the moisture content is higher. This shows that wheat grains with low moisture content are prone to produce more cross-cracks during the compression crushing process, which makes the wheat grains more broken and the number of broken grains increases.

The gap size between starch particles of wheat grains with different moisture contents is also studied by comparing Figure 10(A2), Figure 10(B2) on slice I and Figure 10(C2), Figure 10(D2) on slice II. Results show that the gap between starch particles of wheat grains with lower moisture content is much larger, and protein attached to the surface of starch particles is much looser, indicating that the viscosity between starch particles is lower when moisture content of wheat grains is lower, and a very small deformation can lead to fracture of wheat grains during the compression test. While the gap between starch particles of wheat grains with higher moisture becomes smaller, wheat grains with high moisture content will absorb more moisture and swell, and protein attached to the surface of starch particles become much tighter, indicating that the viscosity between starch particles is higher when moisture content of wheat grains is higher and the ability to generate elastic deformation is much bigger; therefore, wheat grains with higher moisture content is hard to fracture during the compression process, which is consistent with the above experimental results in 'Relationship between deformation and moisture content' section.

Cracks will develop inside wheat grains under the effect of external force, and they will expand with increasing of the force, finally leading to the fracture of the grains as they cannot bear the load. Cracks are the main internal damage type of wheat grains during harvesting, transportation, processing, and other stages. Changes of moisture content, temperature, and other internal factors may lead to internal force of wheat grains, and they may generate cracks during harvesting, transportation, processing, and other stages because of the combined effect of internal and external forces. Cracks are needed during the processing of wheat grains, and the grinding machines should provide a force higher than the minimum destructive force of grains under corresponding moisture content during the processing stage. However, cracks can reduce the quality of grains during harvest and transportation; therefore, the harvest and transportation equipment should provide a force lower than the minimum destructive force of grains to avoid generation of more cracks inside the grains during harvesting and transportation. In addition, cracks of wheat grains will benefit the growth of microbes, which can lead to a decrease in integrity and activity of wheat grains, and therefore increase the storage difficulty of wheat grains (Huang *et al.*, 2024; Wang *et al.*, 2024).

## Conclusions

- (1) Geometry dimensional size of wheat grains at different directions increases with moisture content, which has a significant effect on the length, width, height, and sphericity of wheat grains ( $P < 0.01$ ), and it shows a very significant effect on arithmetic

average diameter and geometric average diameter ( $P < 0.001$ ). Sphericity of wheat grains with different moisture contents is more than 66%. The ellipsoid model with transverse grooves can be selected as the model of wheat grains when analyzing wheat grains by numerical simulation methods.

- (2) Mechanical properties of wheat grains are greatly influenced by the moisture content of wheat grains. Compressive deformation increases with moisture content. Compressive failure force, failure energy, apparent contact elastic modulus, and maximum contact stress are decreased with moisture content. Failure force of wheat grains compressed at the B-axis direction is the largest, followed by the L-axis direction, and failure force at the H-axis direction is the smallest, which is related to the internal structure of wheat grains.
- (3) A crack through the endosperm of grains is formed on the back of grains, and finally throughout the whole ventral groove of grains when wheat grains are compressed at the L-axis direction and the H-axis direction. And, cracks form on the contact area between grains and compression plates when wheat grains are compressed at the B-axis direction. Number of cracks, total length of cracks, length and width of single cracks in wheat grains decrease with moisture content.
- (4) Cracks are needed during the processing of wheat grains, and grinding machines should provide a force higher than the minimum destructive force under corresponding moisture content during the processing stage. The harvest and transportation equipment should provide a force lower than the minimum destructive force to avoid more cracks inside the grains during the harvesting and transportation stage. In addition, cracks of wheat grains will increase the difficulty of their storage.

## Data Availability Statement

The data used to support the findings of this study are available from the corresponding author upon request.

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## Author Contributions

Conceptualization was done by Chi Zhang; methodology was formulated by Yulei Qi; formal analysis was performed by Haihong Zhang; investigation was the responsibility of Xing Wang; resources were organized by Xing Wang; data curation and original draft preparation were taken care of by Lei Chen; writing—review and editing and funding acquisition were done by Qin Xu; visualization was performed by Haihong Zhang; supervision was done by Mengmeng Li; project administration was the responsibility of Mengmeng Li. All authors have read and agreed to the published version of the manuscript.

## Conflicts of Interest

The authors declare no conflict of interest.

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