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Analysis of the breakage characteristics of rice particle beds under confined compression tests

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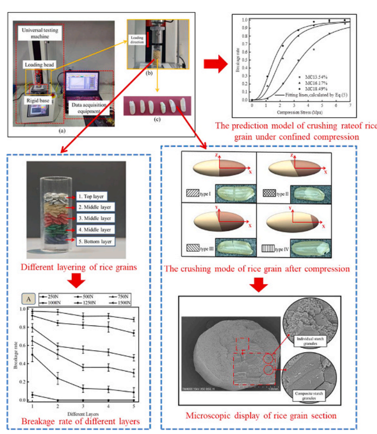
HIGHLIGHTS

- The compression resistance of rice is inversely proportional to moisture content.
- The models of breakage rate of rice bed under different conditions were proposed.
- There are four main modes of rice breakage in the group response.
- Rice grains are broken because of the loss of adhesion between starch grains.

GRAPHICAL ABSTRACT



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ABSTRACT

Agricultural materials breakage is quite common under high stress during harvesting, transportation and processing. The breakage of particles occur in particle beds, and the interaction between particles makes it more difficult to study the breakage characteristics. In this work, the confined compression test method is used to analyze the effect of moisture content and stress on the breakage characteristics of rice grains. The results show that the ability to resist compressive force of rice particle beds was negatively correlated with moisture content, and the breakage rate of rice was positively correlated with stress and moisture content. The breakage rate of rice particle beds decreased gradually from top to bottom. There are four broken rice forms after the confined compression tests. On the microscopic scale, the mechanism of rice breakage is that the cohesive force between starch granules disappears. The results are helpful to understanding the breakage characteristics of rice grains.

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1. Introduction

Agricultural materials exist in the form of granules in nature, such as corn, soybeans and rice [1]. As a consequence of particle-particle or particle-equipment interactions, particularly under high compression loads, the breakage of materials often occurs in the processing, transportation and storage [2], which will causes a waste of resources and economic losses [3]. The crop yields were increased by reducing the breakage rate of grain. Unfortunately, although the mechanical device has been constantly optimized, the material breakage characteristics are not clear, and the material breakage still exists [4]. The studies of particle groups breakage characteristics can be used to deepen the understanding of failure processes and mechanisms. At the same time, it is of great significance to food security and increase cereal production.

Lots of experimental studies into the breakage characteristics of particle materials have been presented in literature, which mainly focus on two aspects: single particle breakage and inter-particle breakage [5]. For the single particle breakage, a variety of breakage characteristics were studied, such as breakage modes, breakage behavior and breakage condition [6–9]. For example, Han et al. [4] analyzed the breakage characteristics of single grain rice in impact and compression tests, including compression failure force, breakage modes, and breakage probability, and provided a basic reference for rice processing. Saiedirad et al. [10] performs quasi-static compression on single seed cumin under different conditions, the relationship between the force and energy required for cumin seed breakage was proved, these findings provided for proper design of harvesting, processing machineries. A single particle compression test can be helpful for determining the single granule properties and the critical breakage condition for breakage [4,11]. But there is considerable discrepancy between breakage characteristics of particle bed breakage and single particle.

On the other hand, more complex breakage characteristics of particle beds can be expected owing to the friction and collision between adjacent particles [12]. Extensive experimental studies have also been conducted on various particle beds by many researchers. For the inter-particle breakage, a variety of breakage characteristics were studied, such as resist compression ability, breakage process and breakage mechanism [13–15]. For example, Yu et al. [16] experimentally investigated the evolution and distribution for particle size of the coal particle with different temperature and stress, results indicated that both temperature and stress have influence on the crushing characteristics of coal particles. Schnoert et al. experimentally revealed that the particle breakage characteristic differ with respect to number and size of the neighbourghed particles and the stressing situation. Meanwhile, the breakage of particle beds was affected by particle size distribution [17,18]. Barrios et al. simulated the particle bed breakage process using a DEM particle replacement model, the modeling method for particle breakage was proposed [19,20]. Most granular materials exist in nature as particle groups, thus, the breakage characteristic for particle groups was closer to the real processing conditions in comparison with the single particle. The fragmentation characteristics was studied of particle groups can be helpful to deepen understanding of the breakage process of particles, and guide mechanical equipment optimization in engineering applications. Furthermore, the inorganic particles were broken manifested mainly as brittle failure, the organic particles were broken manifested mainly as elastoplastic failure, which is due to starch and protein are present in organic particles. The breakage characteristics of particles are affected by the physical properties of particles [9,14,21]. The inorganic mineral particles (such as ores, ceramics, Al_2O_3 and agglomerates) were test in quite lots of studies. As an organic particle, the breakage characteristics of particle groups of agricultural materials have been scarcely reported.

For agricultural materials, the breakage process of grain is significantly affected by physical properties such as variety, composition, and moisture content [10,22,23]. In addition, for different crops, the breakage result is often very different and non-reproducible, this is a unique characteristic for bio-materials [4]. At present, researchers have carried out abundant studies concerning the breakage characteristics of single particles of agricultural materials. For example, Figueroa et al. [24] made uniaxial compression tests on wheat grains, and analyzed the effects of biological structure and water content on the elasticity and strength of wheat grains. Li [25] tested the impact crushing of corn grains, the breakage characteristics such as breakage mode, critical speed and breakage degree are analyzed. In experimental studies on single particle breakage characteristics, only one or two contact points of particles are considered. Unlike single particle, the contact behavior between particles was more complex when particles are broken in particle groups. Hence, the breakage characteristics of agricultural materials still needs to be further clarified during particle groups.

Rice is an important food crop, and in the process of harvesting, milling, warehousing, the grains to grains contact was inevitable, meanwhile, the rice grains will break under high stress. For example, when the brown rice is in the milling stage, the rice grains was breakage by high stress in the rice milling cavity, which is an important way of rice grain loss [3]. Understanding the crushing mechanism of rice grains under high stress, and can provide guidance for the optimization of high pressure zone in rice mill.

The grain deforms and breaks kernels due to high compressive forces is an important way of grain quality loss [3]. The tri-axial compression was usually used to analyze the breakage characteristics of the grain beds under high stress [2,13,16]. Based on this, in this paper, the confined compression test is used to analyze the breakage characteristics of the rice particle beds. Firstly, the rice particle bed was considered as a whole, the ability to resist compressive force, breakage rate and breakage process of the rice particle bed was analyzed. Based on this, the prediction model of breakage rate of rice grain was proposed under different moisture contents and different stress. Then, the broken mode of rice grains was analyzed after different conditions. Finally, the SEM was used to observe the Micro-morphology of fracture surfaces of selected fragments from rice particle beds after the compression test, and the influence of stress and moisture content on the breakage of rice grains was analyzed to explore the underlying mechanism. The findings are useful for providing guidance for the explanation of breakage mechanism and optimizing related agricultural equipment design.

2. Materials and methods

2.1. Experimental materials

The rice variety selected for the experiment was the japonica rice Dongnong 429 with samples being harvested in October 2021, which was provided by the Rice Research Institute, Northeast Agricultural University, China. These rice grains were stored at room temperature. The initial moisture content of the rice grain sample is 13.54%. It is important to note that paddy rice becomes brown rice through the shelling process, which is a mixture of whole rice, husk rice and broken rice, the whole rice was artificially selected. In addition, the part of the rice grains were dyed in different colors by atomized spray paint before the experiment, and rice being dyed does not change the physical properties [26]. The physical properties of rice grains can be affected by changing the moisture content [4]. Therefore, the samples with different moisture content are determined and prepared. The rice grains were placed in a closed environment with constant temperature and humidity, temperature was a constant 23 °C with 60% humidity. The moisture content of rice increases by absorbing moisture from the air, rice is humidified for different times and thus controlled at different moisture contents. In this paper, the rice was humidified for 0 h, 48 h and 96 h, the moisture content of rice grains were measured by oven method [27], and the final moisture content values was 13.54% ± 0.3%, 16.17% ± 0.4% and 18.49% ± 0.3%. The rice grains were sealed and refrigerated after humidification was completed. It should be noted that the contact between rice-rice have no adhesion.

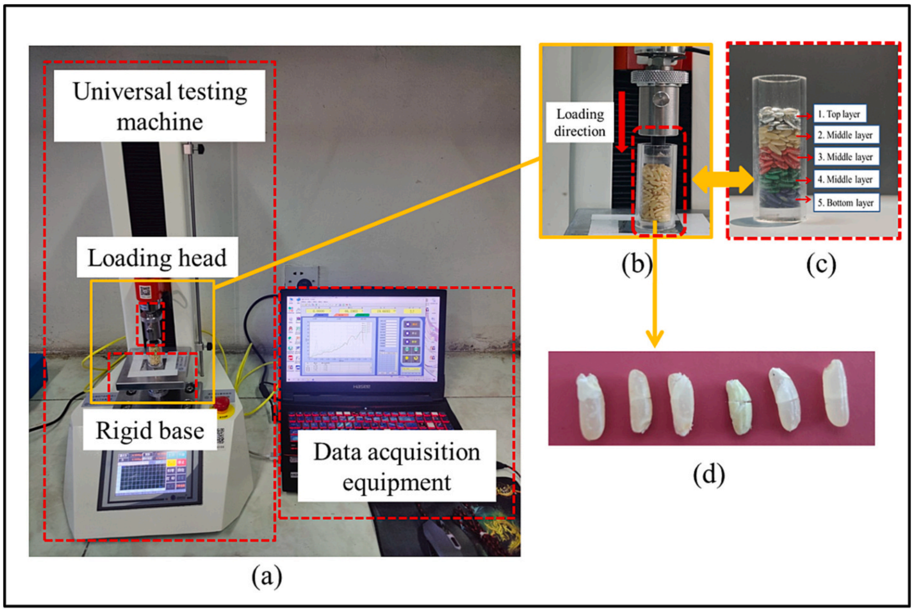


Fig. 1. Schematic of the confined compression tests for the rice particle beds. (a) The equipment of compression test. (b) The compression process of rice beds. (c) Rice grains were dyed for compression testing. (d) The appearance of rice particles after compression test.

Table 1
The triaxial size of rice grains with different moisture content.

Moisture content	Length/mm	Width/mm	Thickness/mm
13.54%	6.63 ± 0.16	2.33 ± 0.08	1.86 ± 0.08
16.17%	6.65 ± 0.15	2.35 ± 0.10	1.86 ± 0.11
18.49%	6.63 ± 0.18	2.34 ± 0.12	1.87 ± 0.10

2.2. Critical equipment

A Universal Testing Machine (ZQ-990A Dongguan Zhiqu Precision instrument Co., Ltd.) was used to determine the breakage characteristics of rice particle beds, which is composed of a rigid base, loading head and date acquisition equipment (Fig. 1 (a)). The rigid base support was immovable, and the loading head was moved by a servo motor, the loading rate range is 0.5–500 mm/min. The development process of reaction force versus compression displacement was recorded using date acquisition equipment, the interval for data collection was 0.001 s. The maximum measuring range for pressure sensor is 2000 N.

The Eosin Y solution (Solarbio, Beijing, China) was used to analyze the location of cortical missing in rice. Standard sieve was used to screen broken rice with different grain sizes, the sieve with pore size of 1 mm, 1.5 mm, 2 mm, 2.5 mm in this work. The Electron Microscope Scanner (15KvTM4000j, Hitachi, Japan) was used to observe micro morphology of broken rice.

2.3. Experimental methods

2.3.1. Confined compression test

The shape of the rice grain was considered to be ellipsoidal, the same batch of rice grains have similar dimensions, meanwhile, the discrepancy in size were ignored as moisture contents effects are negligible [4]. The three principal axes of 100 grain rice particle were measured with a Vernier caliper (accuracy: ± 0.02 mm), and the average values of the measured results are shown in Table 1. The equivalent diameter D was calculated by Eq. 1 [28]:

$$D = \left(\frac{L \times (W+T)^2}{4}\right)^{1/3} \tag{1}$$

where D is the equivalent particle size, mm, L, W and T were the length, width and thickness, mm. The D was calculated as 3.03 mm, on the basis of ratio standard in rock mechanics (1:5 or 1:6) [16], the inner diameter of the container is required to be larger than 15.15 mm. On this basis, the experimental container was selected with 17 mm in inner diameter, 27 mm in outer diameter, and 50 mm in height. It should be noted that to observe the rice grains accumulation and compression directly, a cylindrical container made of transparent high-strength plexiglass were adopted.

The method of the confined compression test is shown in Fig. 1 (b). For each test sample, the rice of 9.5 g (± 0.04 g) was gradually fed into the container, the pressure indenter was controlled at the loading rate of 1 mm/min was applied ensuring a quasi-static loading condition. In addition, in order to observe the process of breaking up the rice particle beds, the stained rice grains are successively placed into containers for compression testing, and the same mass of each color rice (Fig. 1 (c)). As the pressure value reached the target value, then the broken rice particles were taken out for sieving, and the quality of rice particles with various sizes having been sieved were counted. In this experiment, the test stops when the sensor pressure values respectively reach 250 N , 500 N , 750 N , 1000 N , 1250 N , 1500 N. In addition, it needs to be emphasized that each experiment was carried out for thrice.

2.3.2. Handling of broken rice after compression test

The morphology of the initial broken rice was shown in Fig. 1 (d). When rice grains are broken in the confined compression tests, a penetrating crack was found inside the rice. Interestingly, the rice grains are not separated into two separate fragments, and they are connected by a small number of starch granules. In order to ensure the unity of the results in the experiment, the broken rice was artificially separated in the experiment.

In this work, the quality of rice grains was counted before compression test, m_t, g, the whole quality of rice grains was counted after compression test, m_w, g. The breakage rate (P_b, %) of rice grains was calculated by Eq. (2).

$$P_b = \frac{m_t - m_w}{m_t} \times 100\% \tag{2}$$

Broken rice was screened according to Feed crushing particle size determination two layer sieve sieving method (Chinese national

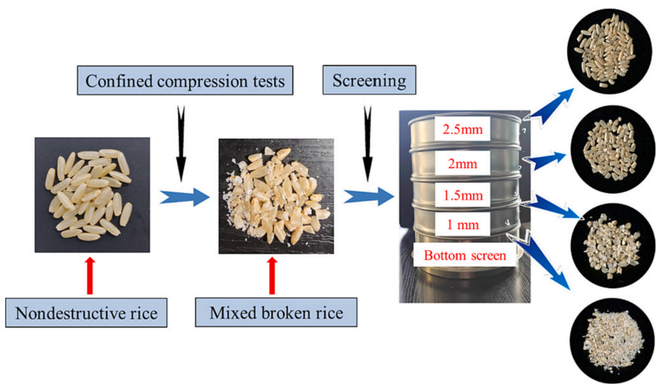


Fig. 2. The screening process of broken rice.

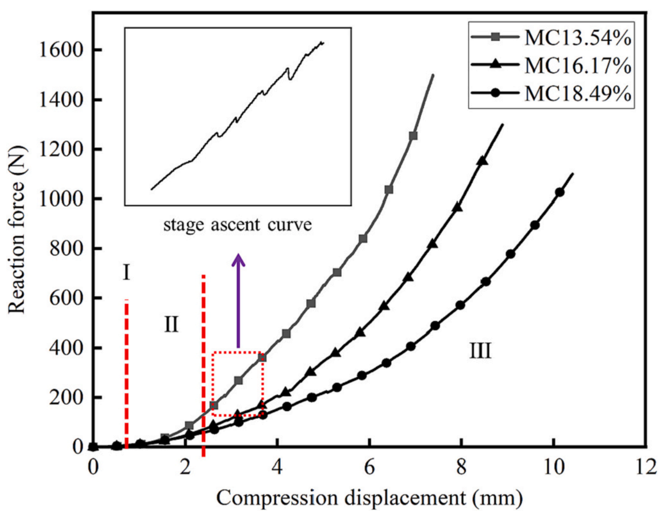


Fig. 3. Load-displacement curves from rice particle beds with different moisture content and the details of wave-like rising curve (inset).

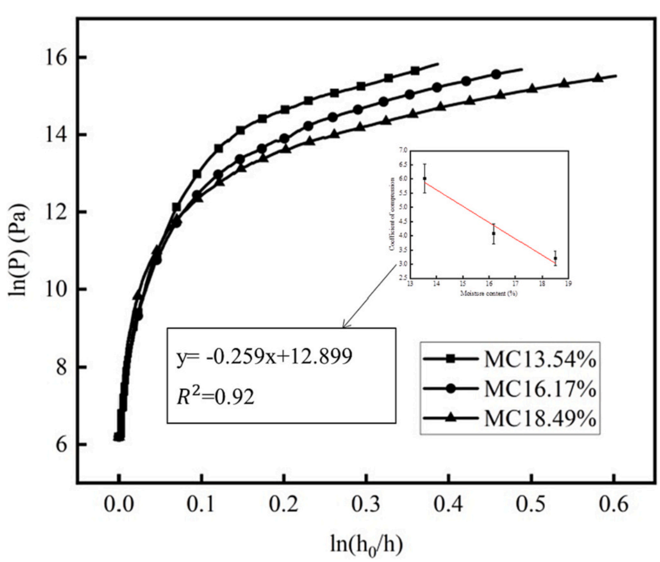


Fig. 4. ln P vs. strain for rice particle beds and the compression coefficient fitting with different moisture content.

standard, GB/T 5917.1–2008). The test sieve and bottom cover was stacked according to the aperture size of the sieve from large to small, the samples of rice grains after compression test were put into the top sieve, the sample sieve was plane rotation 5 min by artificial, the grains of rice on each layer of sieve were collected and weighed after screening (the precision is 0.0001 g). The mass fraction of rice grain on each layer of sieve P_i (%) was calculated by the following formula:

$$P_i = \frac{m_i}{m} \times 100 \tag{3}$$

where m_i is the mass of rice grains corresponding to the i ($i = 1, 2, 3, 4$) layer, g, m is the total mass of test material, g. The screening process is shown in Fig. 2.

2.3.3. Microscopic observation of rice grains

The 200 broken rice grains were randomly selected at the end of the compression test, and they were photographed one by one with microscope. Then, the 200 rice grains were randomly selected under high stress compression, and the Eosin Y solution was used to dye rice grains according to Chinese national standard [29], and rice grain is photographed one by one with microscope.

After the completion of compression test, four breakage modes were found. Typical fragments showing the four types of breakage modes were chosen and SEM observations were conducted to investigate breakage characteristics from a micro-scale viewpoint. Furthermore, in order to analyze the effects of moisture content on breakage mechanism, the rice grains with moisture content of 13.54% and 18.49% was selected and then SEM.

3. Results and discussions

3.1. Compression resistance of rice particle beds

Fig. 3 summarizes the reaction force versus compression displacement curves from the test results of rice particle beds. It is shown that the reaction force increases as compression displacement increases. In addition, it is found that most of the test curves can be subdivided into three consecutive segments.

In the first segment, the curve shifts horizontally to the right, initiating from the origin point, indicates the compression displacement mainly from rice particle beds compaction, no deformation of rice grains due to pressure in this segment. The second segment is characterised by a concave rising curve pattern, during which rice particle beds are being compressed to a denser state, meanwhile the increase of compression displacement more difficult due to the rice particles are deformed. The final segment is characterised by a stage ascent curve pattern, Fig. 3 inset showing the details of stage ascent curve, this can be interpreted as the evolution of force chain caused by rice breakage. Random force chains are formed within a bed of rice grains in compression test, the pressure on the rice particle beds is transmitted by force chains, the force chain disappear when the rice grains breakage, and the pressure of the rice bed drops. At the same time, a new force chain is formed inside the rice particle beds and pressure transfer. This result was similar to the result simulation by Kang et al. They show that the pressure at the top of the particle bed is transmitted through the force chain within the particle bed, and particle breakage can also reduce the strength of the force chain [30].

Moreover, Fig. 3 clearly shown that the reaction forces by the same compression displacement from rice particle beds of larger moisture content are smaller than those with smaller moisture content. This means that the initial moisture content of rice can greatly influence the breakage behavior and overall mechanical response of the rice particle beds, which can be explained by the higher strain energy and harder properties of rice with low moisture content. By assuming the bed of granules under confined compression as a series of parallel load-bearing columns, Adams et al. [31] proposed a pressure-volume equation as

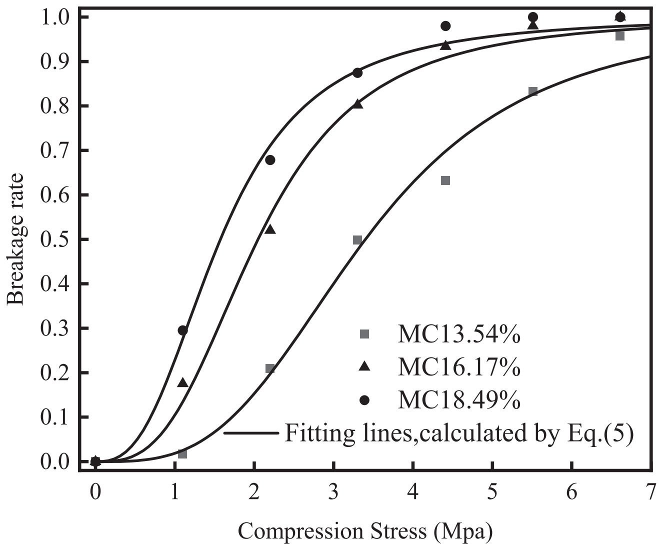


Fig. 5. The breakage rate of rice particle beds under different compression stress.

Table 2
The fitting parameters of the model for the different moisture content values in Eq. 6.

Moisture content	S_N	α	R^2
13.54%	3.399	3.224	0.99
16.17%	2.047	2.992	0.9949
18.49%	1.573	2.681	0.9957

follows:

$$ln(P) = ln\left(\frac{\tau_0}{\alpha}\right) + \alpha\varepsilon + ln\left(1 - e^{-\alpha\varepsilon}\right) \tag{4}$$

where P is the compressive stress of the rice particle beds, Pa, τ_0 is the fracture strength of a single rice, α is a constant of friction coefficient, ε is the natural strain calculated by Eq. 5.

$$\varepsilon = ln\left(\frac{h_0}{h}\right) \tag{5}$$

where h_0 and h are the bed height at applied pressures zero (h_0) and P (h), mm. It needs to be emphasized that at sufficiently large compression displacement, the last term of the Eq. 4 is negligible and can be omitted.

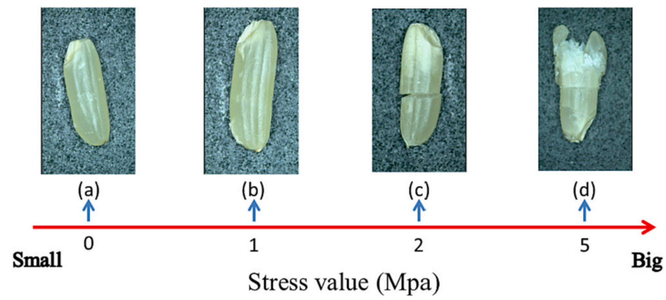


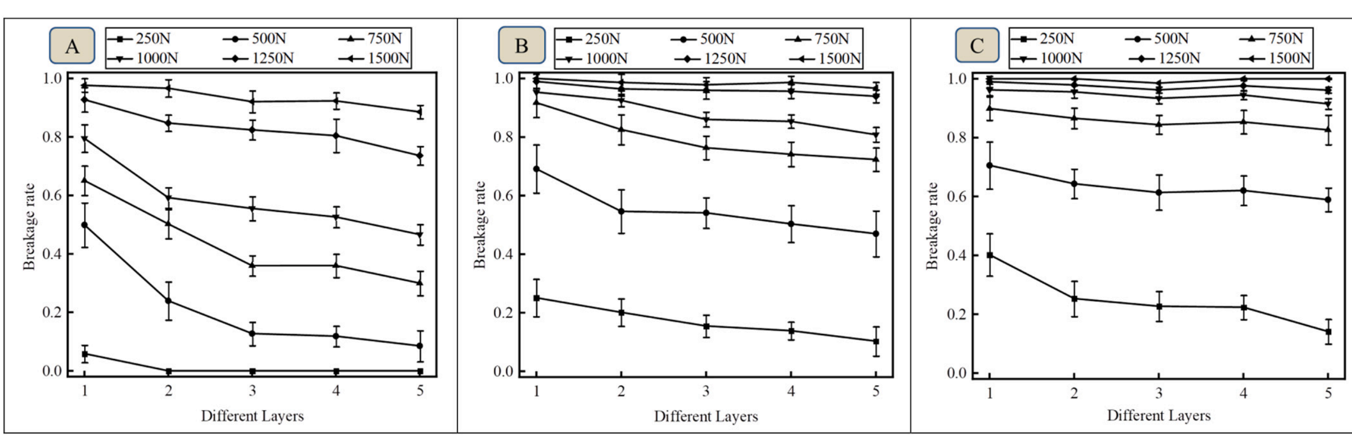
Fig. 7. The breakage process of single rice grain in particle beds.

Therefore, the Admas equation is considered as a straight line when the compression displacement is large, and a linear in ln*(P)* - ε relationship can be used to estimate the coefficient of compression of rice particle beds. The present test data are convert into the relationship between ln P and ε as given in Fig. 4. It is shown that an excellent linear relation exists for each set of test data at sufficient large compression strain as predicted by the Adams equation. The slops of the final linear approximations are 6.02, 4.07 and 3.20 respectively for the moisture content of the rice particle beds grew from small to large, which indicates a larger resistance to compression for a rice particle beds with low moisture content. Fig. 4 inset showing the coefficient of compression relationship with moisture content, and it can be seen within the scope of this study, the coefficient of compression decline linearly with the increase of moisture content.

3.2. Breakage rate of rice grains

Breakage rate is considered to be an indicator that not can be ignored, the breakage rate of rice is calculated to help the equipment parameters to be modified. It is commonly adopted that breakage rate is influenced by intrinsic and extrinsic factors, such as the particle size distribution, stress magnitude, stress path, loading time, particle properties [32]. In this test, the physical properties of the rice were considered and the breakage rate was analyzed at different stress values and moisture contents.

The breakage rate of rice under confined compression tests is shown in Fig. 5. It is shown that the breakage rate is positively correlated with pressure and moisture content, which is consistent with the results of the breakage study of single grain rice. On the one hand, rice grains are deformed due to pressure, and rice grains are broken when the deformation volume reaches the critical condition. On the other hand, some studies indicate the variability of grain strength properties mainly



(b)

Fig. 6. The breakage rate of rice particle beds under different conditions after confined compression tests. (A: moisture content is 13.54% B: moisture content is 16.17% C: moisture content is 18.49%).

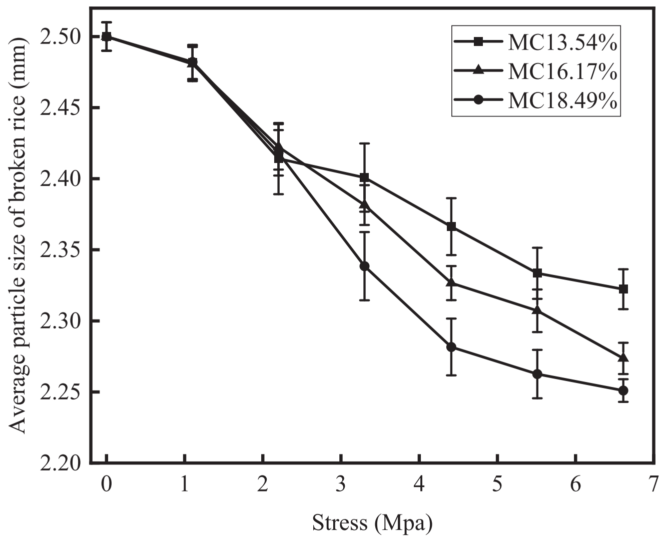


Fig. 8. Average particle size (Ds) distribution of broken rice under different stresses.

depend on the species, internal structure, moisture content, and Han et al. [4] passed the compression test of single-grain rice, found the compression crushing force decreased from 78.77 N to 32.89 N when the moisture content of rice grain increased from 12.5% to 18.5%, this result indicates that the rice strength decreases with increasing moisture content.

In addition, it is worthy to note that the breakage rate of the rice particle beds increases at different rates with pressure at the same moisture content, the breakage rate trend of rice particle beds increases faster in the early stage and slower in the later stage. A similar phenomenon was found in the study of homogeneous sand by DE BEER et al. [33], in which the increase of breakage probability is obvious when the pressure reaches 15 Mpa, and the increase of breakage probability is slowly when the pressure reaches 34 Mpa. This result can be interpreted as during which particle fragmentation were ongoing, but the compression induced rearrangement of fragmented and non-fragmented particles led to a more tightly compacted and solid skeleton [2].

Additionally, the breakage rate of rice grains conforms to the logistic function [34] with the increase of pressure. Thus, Eq. (6) was proposed to describe the rice fragmentation rate distribution in Fig. 5.

$$P_r = 1 - \frac{1}{1 + \left(\frac{S}{S_N}\right)^{\alpha}} \times 100\% \tag{6}$$

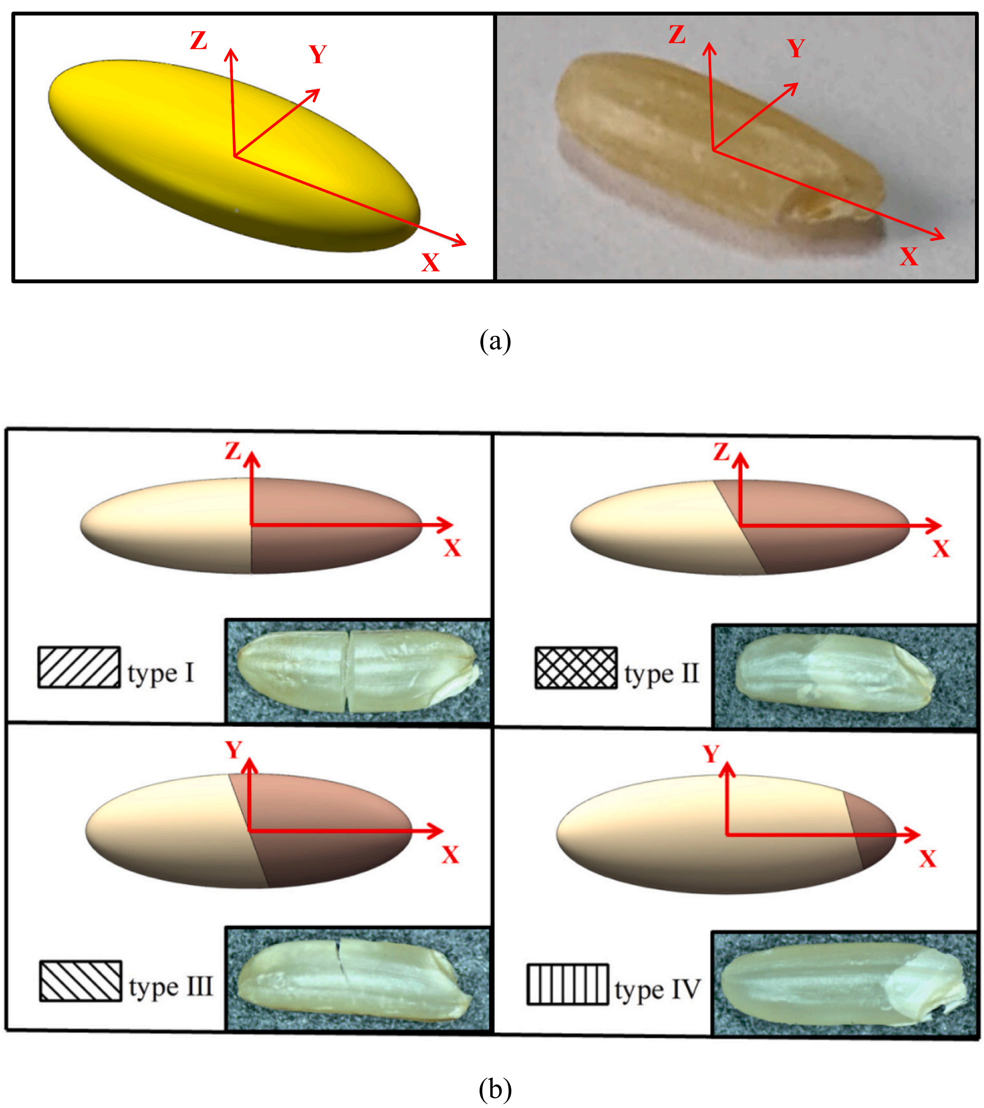
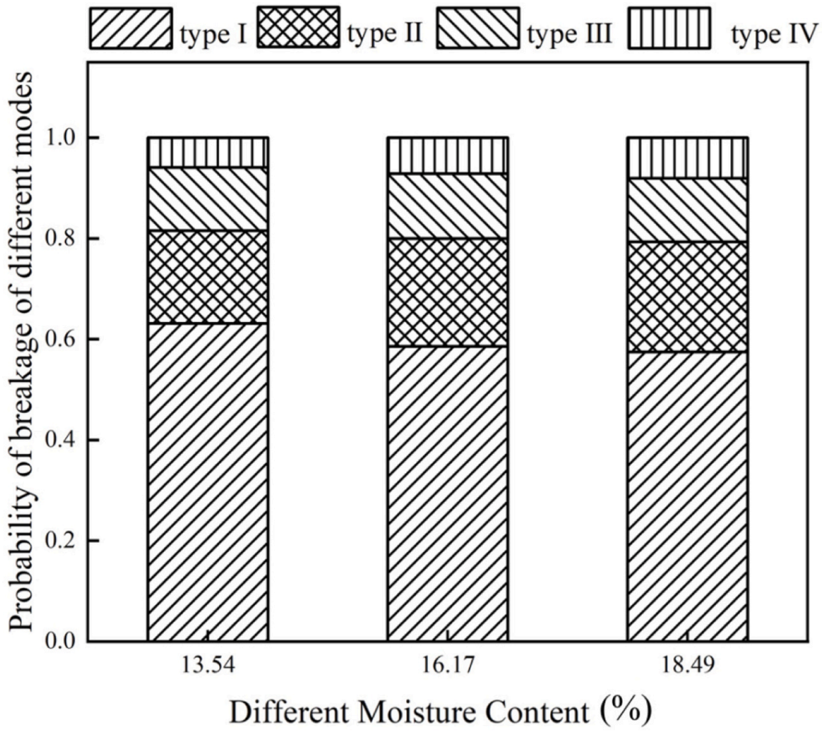
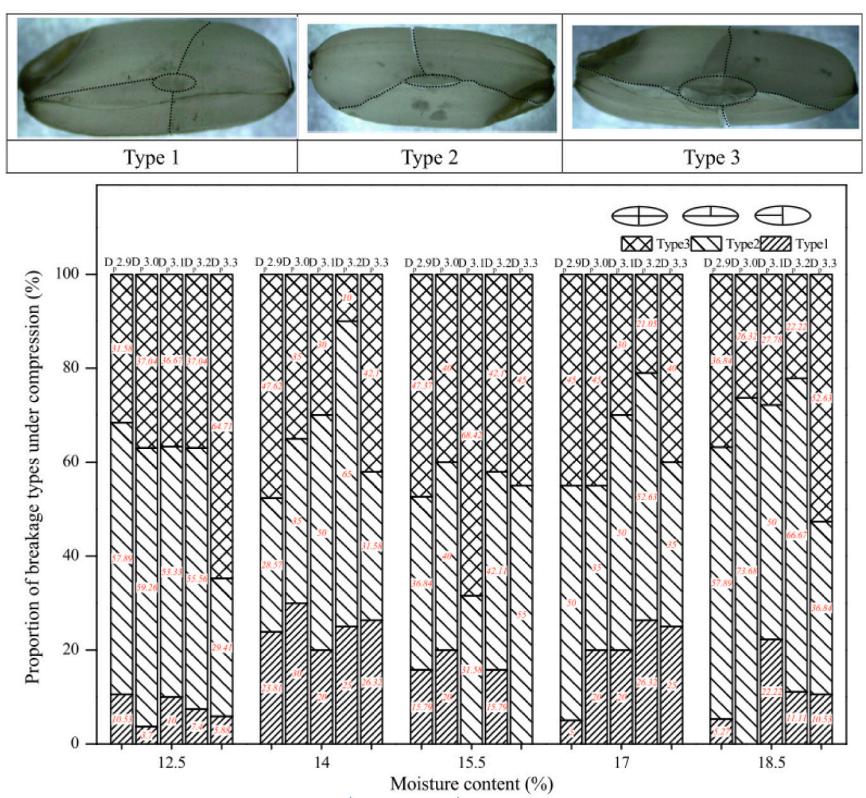


Fig. 9. Schematic diagram of crack path of broken rice. (a) The triaxial coordinates of rice grain. (b) The four modes of crack paths.



(a)



(b)

Fig. 10. The distribution of broken patterns of rice grains. (a) After confined compression of rice particle beds (b) After compression of single rice [4].

where P_r denotes the breakage rate of rice particle beds, %, S is the stress on the rice bed, Mpa, S_N and α are the parameter of fitting, their values are related to the strength of rice grains. The fitting parameters of the model for the different moisture content values are listed in Table 2. All R^2 are above 0.99, which indicates that Eq. (6) provided a close fit to the experimental data in Fig. 5.

3.3. The breakage process of rice

The breakage rate of rice under different stress was used to indicate the broken process of the rice particle beds. Rice grains of different colors are layered into containers (Fig. 1 (c)), the pressure transfer mechanism in the rice particle beds is analyzed by measuring the breakage rate of different colored rice layers. The breakage rate of each layer of rice under different pressure is shown in Fig. 6. As can be seen, for all cases, breakage rate is greatest on the top layer and decreases with depth into the rice particle beds. A reasonable explanation is that when the rice particle beds was confined compression tests, the porosity of the rice grain layer increases gradually from top to bottom in the stress, and the deformation of rice grains decreases from top to bottom, the rice grains are broken when the deformation reaches a critical condition. From this result, it is inferred that the transfer law of stress within the rice grain group, the stress gradually decreases from the top to the bottom in the rice particle beds. This is in agreement with simulation results from Djordjevic et al. [35], they thought that failure within the particle bed will progress from the crushing surface towards the depth of the bed.

The typical broken morphology of particle is usually used to indicate the broken process of particles [25]. Therefore, the typical broken morphology of rice grains in particle beds was analyzed, and the results are shown in Fig. 7. The results show that the breakage of rice grains is divided into three typical stages. The first stage is the rice grain is deformed and there is no obvious crack in the interior at low stress (Fig. 7 b), the second stage is a penetrating crack appears in the interior of rice with the increase of stress, and the rice was divided into two broken grains (Fig. 7 c), The third stage is the broken rice is divided into more fragments and smaller particle size under higher stress (Fig. 7 d).

Because of the more tiny fragments are present in the broken rice (Fig. 7 d), the particle size distribution of rice after breakage was used to characterize the degree of breakage of the rice particle beds in confined compression test [36]. The particle size distribution of broken rice is quantified by the average particle size (D_s) of broken grains [37], the smaller the value, the greater the degree of breakage.

$$D_S = \frac{\sum (P_s d_s)}{\sum P_s} \tag{7}$$

where D_s is the average particle size of broken rice, mm, d_s is the size of mesh screen with different aperture, mm, P_s is the percentage content of broken rice corresponding to d_s, %. The average particle size of broken rice under different conditions is shown in Fig. 8. It is shown that the breakage degree of rice increases with the increase of stress value and moisture content. Therefore, in some special cases, such as the rice was crushing by rollers, the crushing efficiency is improved by increase the moisture content of rice grains appropriately and apply higher pressure to the grains of rice.

3.4. Breakage mode of rice in the confined compression test

In order to observe the breakage model of rice grains , the crack path of the broken rice is recorded and the different breakage model are

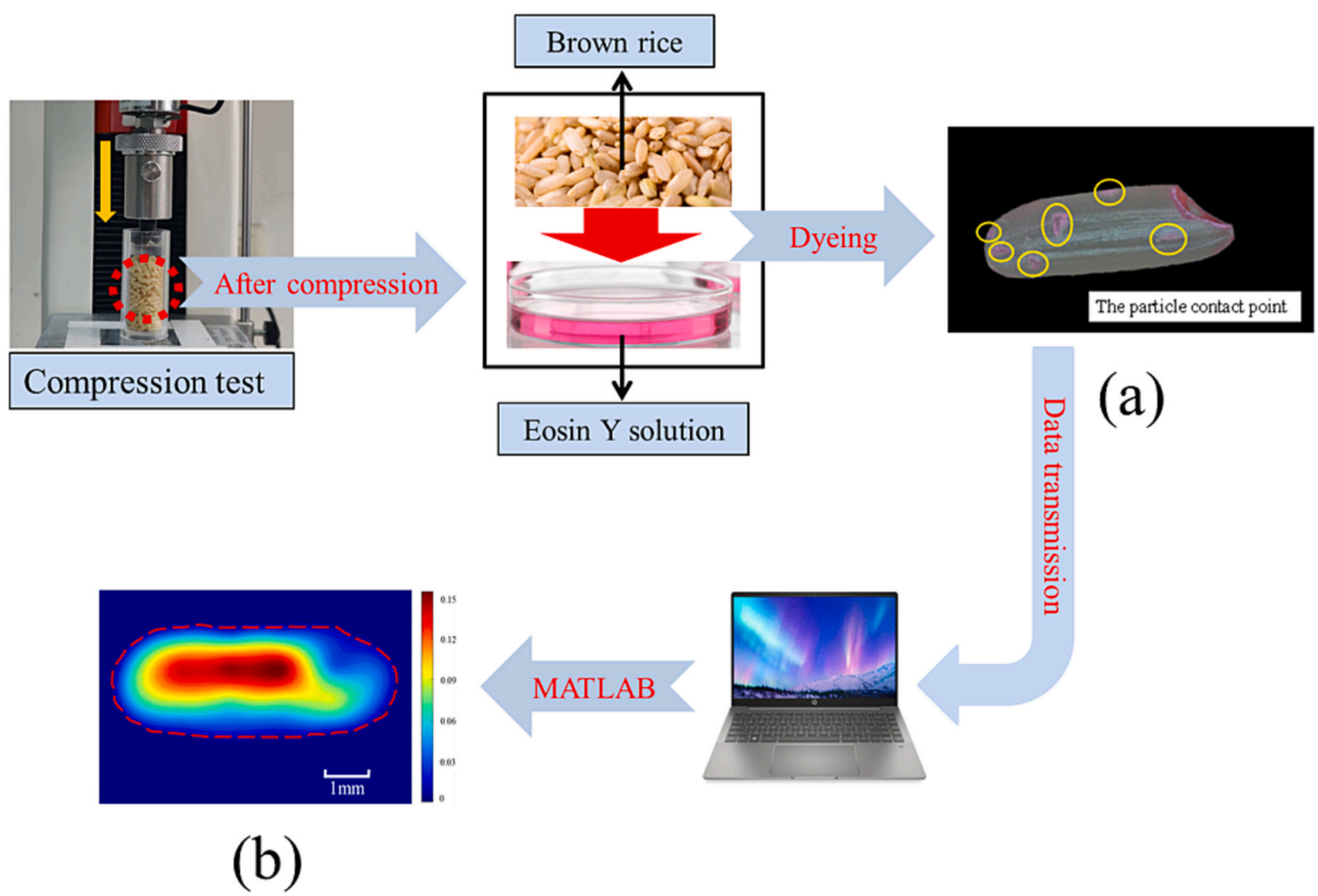


Fig. 11. The contact point distribution of rice grains under confined compression test. (a) The rice grains are stained by eosin Y solution (b) Contact point position statistics of rice grains.

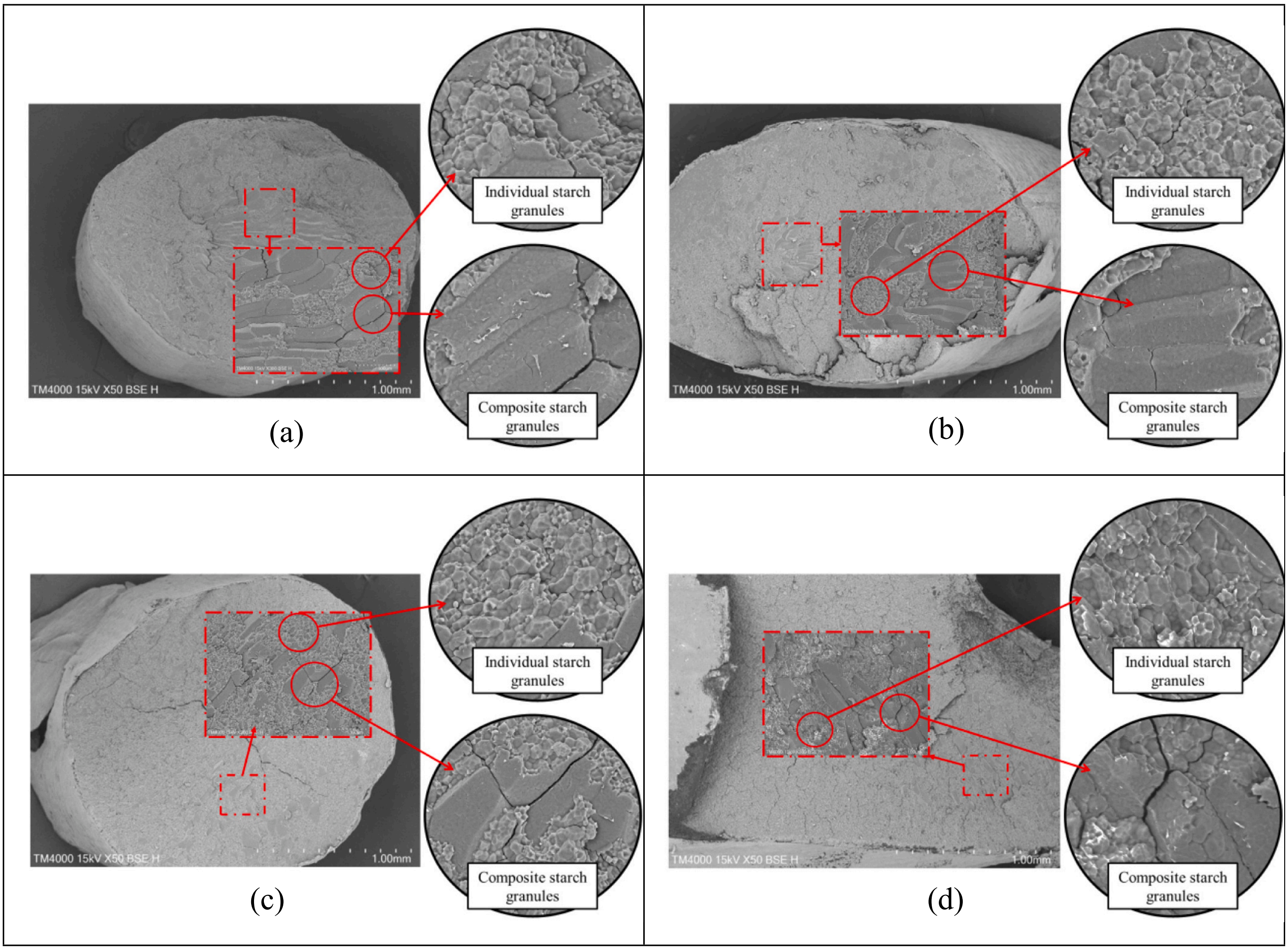


Fig. 12. SEM micrographs of typical surfaces of rice fragments after compression tests. (a) Microscopic display of type I. (b) Microscopic display of type II. (c) Microscopic display of type III. (d) Microscopic display of type IV.

classified accordingly. Rice is considered a triaxial ellipsoid with its X-axis, Y-axis and *Z*-axis is shown in Fig. 9 (a), and the broken rice was divided into 4 breakage modes by breakage path in Fig. 9 (b). It should be noted that the breakage mode of rice is considered only when there is a penetrating crack inside the rice grain, which is because the fragments of rice grains become powdery at higher stresses.

Fig. 10 (a) shows the proportion of breakage mode of rice particles under different moisture content in the confined compression tests, it can be seen the breakage model distribution of rice grain with different moisture content was basically the same. Among all types, type I accounted for 60%, type II accounted for 20%, type III accounted for 13%, and type IV accounted for 7%. The results show that the breakage mode of rice grains has nothing to do with moisture content. The reason for this result is that the triaxial size and critical deformation condition of rice grains are not changed by moisture content [4], and the contact between rice grains of different moisture content is consistent in the container.

In addition, Fig. 10 (b) shows the breakage model of single grain rice in our previous research [4]. It can be seen that rice particles often break into three or four pieces in compression tests. Compared with Fig. 10 (a) and Fig. 10 (b), the result shows that the breakage mode of rice under confined compression is quite different from that of single grain rice. Based on the fact that rice grains are compressed under different test (uniaxial compression and confined compression), we guess that the number and location of contact points of rice grains may result in different breakage models.

Some studies indicate that the crack path always extend along the stress point when the particles are broken [38].Therefore, the contact point between rice grains can be used to explain different breakage mode to a certain extent. In the confined compression test of the rice particle beds, the bran layer at the contact point between rice grains is removed under stress, as well as the starch particle was exposed, and the starch is changed to red in eosin Y solution [29]. The staining method is used to observe the contact point of rice grains.

Fig. 11 shows the process of rice grains being stained to observe contact points. Fig. 11 (a) shows the morphology of rice grains stained with eosin Y solution, and the position of the contact point is counted by MATLAB, the result is show in Fig. 11 (b). It is found that for the confined compression test cases, the contact points between rice grains are more concentrated in the middle of the side, and it decreases from the middle to the periphery. The result is that the breakage path of the grain is more likely to occur in the middle of the grain. The difference is that the single grain rice is broken under compression test, the contact points of rice grains is only in the middle of the side, and the result is that the rice grain breaks in three or four pieces due to tensile stress [4]. This is consistent with the phenomenon in Fig. 10.

It should be emphasized that the contact point is not the only basis for the breakage mode, and there are many reasons for different breakage modes of particles, such as the stress strength of the contact point and the compressive strength of different positions of rice grains. Because these factors are not easy to obtain through experiments, thus it needs to be further explore in the subsequent studies.

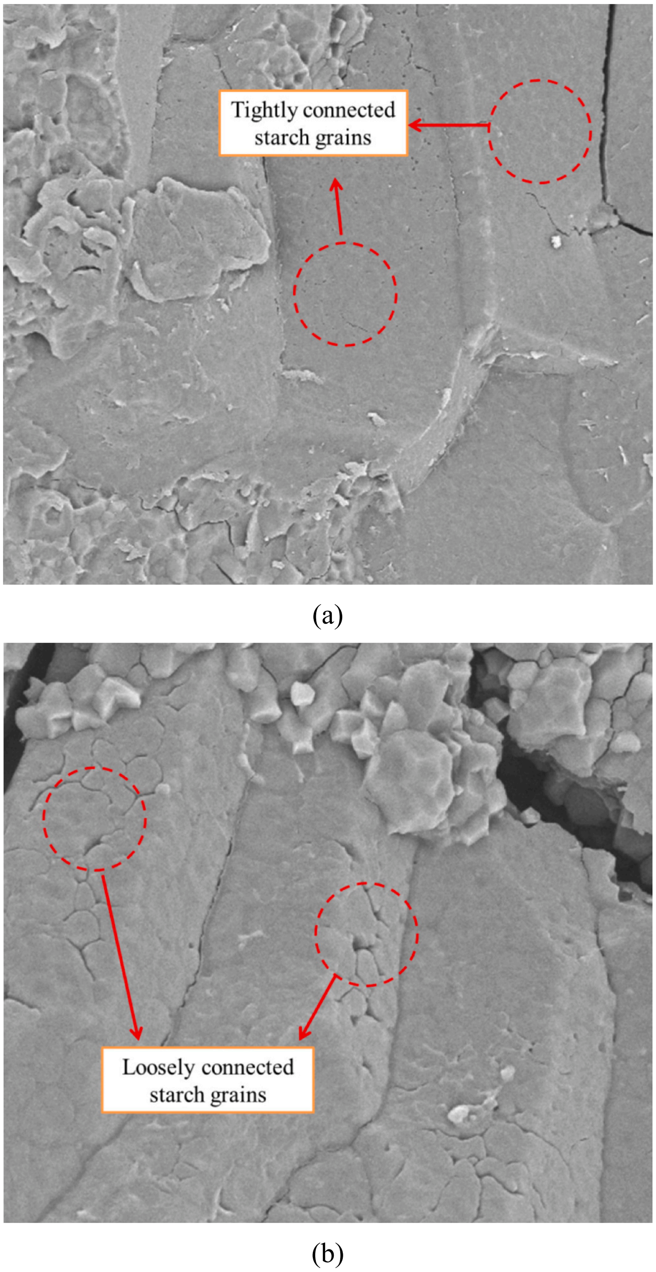


Fig. 13. Microscopic display of rice fragments with different moisture content. (a) Moisture content is 13.54%. (b) Moisture content is 18.49%.

3.5. SEM test of rice grains

Brown rice consists of endosperm and embryo. The embryo is roughly 1–3% by weight of the total grain [39] and is located at the basal end on the ventral (abaxial) side of the grain, embryo was considered that it does not affect the breakage characteristics of rice grains. The aleurone layer is the outermost layer of the endosperm, which only a few cells are thick in rice grains [39].The starchy endosperm constitutes the largest portion of the rice grain, mature tissue consists of thin-walled parenchyma cells, usually radially elongated, filled with compound starch granules and protein bodies [39,40]. As mentioned earlier, the decisive factor of the crushing characteristics of rice grains is the starchy endosperm.

Fig. 12 presents typical SEM photos of fracture surfaces of selected fragments from rice particle beds after the compression tests. The results show that two kinds of appearances are on the fracture surfaces of fragments in each type, one is complete composite starch granules, and the other is individual starch granules. Among them, the smaller individual starch granules are not crushed, this means that the particle breakage in the compression test was mainly caused by bond is broken between starch granules.

Fig. 13 shows that SEM photos of fracture surfaces of rice grains with different moisture content. It is found that the starch granules are closely arranged at low water content, and there is no obvious gap in the starch endosperm. However, the gap between starch granules can be clearly observed in the rice grains with high moisture content. This means that higher energy input is needed to destroy the bonding force between starch granules in rice grains with low moisture content, such an observation bears great similarity with the SEM test by Utsunomiya et al. [41], after the rice grains absorb water, in which the spaces between individual starch granules within a compound granule are due to swelling and subsequent shrinkage.

The aforementioned studies presented that the deformation of rice grains occurs under the force, the bonding force between starch granules are destroyed in endosperm, and the tiny cracks occur inside the rice grains. The rice grains are broken when the deformation reaches a critical condition, and the through cracks appeared inside rice grains. The moisture content of rice grains was increased, causing bonding force between starch granules to decrease, thus the strength of rice grains was reduced.

3.6. Discussions

In this paper, the rice particle beds was subjected to a confined compression test, the breakage characteristics of rice grains in the particle beds was analysis, the breakage mechanism of rice grains was elucidated, and this work provides theoretical guidance for optimize agricultural equipment. For example, we can explain the causes of broken rice in rice processing according to the compression breakage mechanism of rice grains proposed in this paper. Based on the breakage rate prediction model of stress and moisture content, the processing quality can be judged in advance according to the physical parameters of rice grains and equipment operating parameters. This is conducive to appropriately adjusting the operating parameters (such as feed flow rate and opening of pressure valve) of the processing machinery in advance. Nevertheless, it is difficult to understand the particle deformation and breakage process of rice grain at micro scale through physical experiments. Jiang et al. analyzed the ceramic materials by three-dimensional refined finite element simulations, the particle breaking behavior was explained from the perspective of micromechanics [42]. Kempton et al. used the sub–particle DEM model to simulate the deformation of a bed filled with wax particles under load [13]. In order to further understanding the rice grains breakage mechanism, the micromechanical properties of rice grain in the compression process need to be studied by numerical simulation method in the subsequent work.

4. Conclusion

In this study, confined compression experiments with rice particle beds of different moisture content were conducted. The resist compression capacity, breakage rate and breakage process of rice grain beds were mainly analyzed. In addition, the breakage mode of rice grain under confined compression was discussed, and the causes of the breakage model were summarized. Furthermore, the rice grains breakage mechanism in different moisture content and stress was revealed by observing the microstructure of the broken surface of rice grains. The main findings can be summarized as follows:

- The mechanical properties of rice particle beds are related to moisture content. The resist compression capacity decreases of rice particle beds with the moisture content increases. The stress gradually decreases from the top to the bottom along the compression direction in the rice particle beds. Meanwhile, the prediction model of rice breakage rate under different conditions was established, which provided a method for judge rice loss in advance.

- There are four main breakage modes of rice grains under the confined compression test, and the formation of breakage mode is independent of moisture content. Meanwhile, the crack path of rice grains is affected by the contact points between rice grains.
- In a confined compression experiment of rice particle beds, the breakage of rice grain was happened because bonding force between starch granules in the endosperm was destroyed. The bonding force between starch granules decreases with the moisture content of rice grains increases. The stress increases lead to deformation of rice grains, the bonding force between starch granules is destroyed due to the tensile stress, and penetrating crack appears inside the rice grain.

CRediT authorship contribution statement

Shaohang Shen: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Yanlong Han:** Conceptualization, Supervision, Resources, Writing – review & editing. **Xianzhi Hao:** Data curation, Formal analysis, Methodology, Investigation. **Peiyu Chen:** Formal analysis, Conceptualization, Investigation. **Anqi Li:** Formal analysis, Conceptualization. **Yinglong Wang:** Data curation, Supervision. **Jincheng Zhang:** Data curation, Formal analysis. **Wenyu Feng:** Investigation, Formal analysis. **Jiaming Fei:** Investigation, Formal analysis. **Fuguo Jia:** Project administration, Resources, Conceptualization.

Declaration of Competing Interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled “Analysis of the breakage characteristics of rice particle beds under confined compression tests”.

Data availability

I have shared the link to my data/code at the Attach File step

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References

[1] J. Su, C.J. Zhou, X.H. Jiang, Z.Z. Qiao, Orderly arrangement of agricultural biomass particles in designed gas–solid fluidized beds using CFD-DEM and image experiment, Comput. Electron. Agric. 204 (2023), 107510, https://doi.org/10.1016/j.compag.2022.107510.
[2] H. Jiang, Y.D. Zhou, C.J. Chi, C.H. Zhang, Transparent confined compression tests on particle beds: observations and implications, Powder Technol. 336 (2018) 339–349, https://doi.org/10.1016/j.powtec.2018.05.050.
[3] Z. Chen, C. Wassgren, R.P. Kingsly Ambrose, A review of grain kernel damage: mechanisms modeling, and testing process, Trans. ASABE 63 (2) (2020) 455–475, https://doi.org/10.13031/trans.13643.
[4] Y.L. Han, D. Zhao, Y.H. Chu, J.X. Zhen, G.R. Li, H.W. Zhao, F.G. Jia, Breakage behaviour of single rice particles under compression and impact, Adv. Powder Technol. 32 (12) (2021) 4635–4650, https://doi.org/10.1016/j.apt.2021.10.017.
[5] C.M. Evertsson, R.A. Bearman, Investigation of interparticle breakage as applied to cone crushing, Miner. Eng. 10 (2) (1997) 199–214, https://doi.org/10.1016/S0892-6875(96)00146-X.
[6] L. Sikong, H. Hashimoto, S. Yashima, Breakage behavior of fine particles of brittle minerals and coals, Powder Technol. 61 (1) (1990) 51–57, https://doi.org/10.1016/0032-5910(90)80065-7.
[7] S. Antonyuk, S. Palis, S. Heinrich, Breakage behaviour of agglomerates and crystals by static loading and impact, Powder Technol. 206 (1–2) (2011) 88–89, https://doi.org/10.1016/j.powtec.2010.02.025.
[8] P. Müller, M. Seeger, J. Tomas, Compression and breakage behavior of γ-Al2O3 granules, Powder Technol. 237 (2013) 125–133, https://doi.org/10.1016/j.powtec.2013.01.023.
[9] S. Antonyuk, J. Tomas, S. Heinrich, L. Mörl, Breakage behaviour of spherical granulates by compression, Chem. Eng. Sci. 60 (14) (2005) 4031–4044, https://doi.org/10.1016/j.ces.2005.02.038.
[10] M.H. Saiedirad, A. Tabatabaeefar, A. Borghei, M. Mirsalehi, F. Badii, M. Ghasemi Varnamkhasti, Effects of moisture content, seed size, loading rate and seed orientation on force and energy required for fracturing cumin seed (Cuminum cyminum Linn.) under quasi-static loading, J. Food Eng. 86 (4) (2008) 565–572, https://doi.org/10.1016/j.jfoodeng.2007.11.021.
[11] J.C. Jaeger, Failure of rocks under tensile conditions, Int. J. Rock Mech. Min. Sci. Geomech. Abstr. 4 (2) (1967) 219–227, https://doi.org/10.1016/0148-9062(67)90046-0.
[12] A. Blaszczuk, A. Zylka, J. Leszczynski, Simulation of mass balance behavior in a largescale circulating fluidized bed reactor, Particuology 25 (2016) 51–58, https://doi.org/10.1016/j.partic.2015.04.003.
[13] L. Kempton, D. Pinson, S. Chew, P. Zulli, A.B. Yu, Simulation of particle deformation within a compressed packed bed, Powder Technol. 320 (2017) 586–593, https://doi.org/10.1016/j.powtec.2017.07.082.
[14] S.S. Lin, Y.C. Chung, C.K. Lin, Y.C. Chen, DEM simulation and experimental validation for mechanical response of ellipsoidal particles under confined compression, Adv. Powder Technol. 29 (5) (2018) 1292–1305, https://doi.org/10.1016/j.apt.2018.02.023.
[15] H. Kalman, Phenomenological study of particulate materials compression – from individual through bed compression to tableting, Powder Technol. 372 (2020) 161–177, https://doi.org/10.1016/j.powtec.2020.05.115.
[16] M.G. Yu, M.Q. Wu, X.L. Yang, R.Y. Lou, F.C. Wang, H.T. Li, L. Wang, Effect of temperature on the evolution and distribution for particle size of loose broken coal during the uniaxial confined compression process, Fuel 318 (2022), 123592, https://doi.org/10.1016/j.fuel.2022.123592.
[17] K. Schönert, The influence of particle bed configurations and confinements on particle breakage, Int. J. Miner. Process. 44-45 (1996) 1–16, https://doi.org/10.1016/0301-7516(95)00017-8.
[18] J. Liu, K. Schönert, Modelling of interparticle breakage, Int. J. Miner. Process. 44-45 (1996) 101–115, https://doi.org/10.1016/0301-7516(95)00022-4.
[19] G.K.P. Barrios, N.J. Herrera, L.M. Tavares, Simulation of particle bed breakage by slow compression and impact using a DEM particle replacement model, Adv. Powder Technol. 31 (7) (2020) 2749–2758, https://doi.org/10.1016/j.apt.2020.05.011.
[20] Narcés Jiménez-Herrera, Gabriel K.P. Barrios, Luís Marcelo Tavares, Comparison of breakage models in DEM in simulating impact on particle beds, Adv. Powder Technol. 29 (3) (2018) 692–706, https://doi.org/10.1016/j.apt.2017.12.006.
[21] Luca Orefice, Johannes G. Khinast, Deformable and breakable DEM particle clusters for modelling compression of plastic and brittle porous materials — model and structure properties, Powder Technol. 368 (2020) 90–104, https://doi.org/10.1016/j.powtec.2020.04.035.
[22] G.F. Kamst, C. Bonazzi, J. Vasseur, J.J. Bimbenet, Effect of deformation rate andmoisture content on the mechanical properties of rice grains, T. ASAE 45 (2002) 145–151, https://doi.org/10.13031/2013.7857.
[23] B. Mehmet, K. Fatih, K. Mazhar, E. Mustafa, Correlation between the protein content and mechanical properties of wheat, Turk. J. Agric. For. 36 (2012) 601–607, https://doi.org/10.3906/tar-1112-51.
[24] J.D.C. Figueroa, Z.J.E. Hernández, M.J.J. Véles, P. Rayas-Duarte, H. E. MartínezFlores, N. Ponce-García, Evaluation of degree of elasticity and other mechanical properties of wheat kernels, Cereal Chem. 88 (1) (2011) 12–18, https://doi.org/10.1094/CCHEM-04-10-0065.
[25] H.C. Li, R. Zeng, T.Y. Yang, Z.Y. Niu, Experimental study on impact crushing characteristics of corn grains, Trans. Chinese Soc. Agricult. Eng. 38 (07) (2022) 29–37. https://kns.cnki.net/kcms/detail/detail.aspx?FileName=NYGU202207004&DbName=CJFQ2022.
[26] P.Y. Chen, F.G. Jia, Y.L. Han, X.Y. Meng, A.Q. Li, Y.H. Chu, H.W. Zhao, Study on the segregation of brown rice and rice husks mixture in inclined chute flow, Powder Technol. 404 (2022), 117393, https://doi.org/10.1016/j.powtec.2022.117393.
[27] V.K. Jindal, T.J. Siebenmorgen, Effects of oven drying temperature and drying time on rough rice moisture content determination, T. ASAE 30 (1987) 1185–1192, https://doi.org/10.13031/2013.30542.
[28] D. Mohapatra, S. Bal, Physical properties of Indica rice in relation to some novel mechanical properties indicating grain characteristics, Food Bioprocess Technol. 5 (6) (2012) 2111–2119, https://doi.org/10.1007/s11947-011-0539-1.
[29] H.B. Ren, S.M. Qi, L.H. Zhang, L. Wang, J. Huang, H.Q. Yang, C.G. Ren, W.C. Zhou, Variations in the appearance quality of brown rice during the four stages of milling, J. Cereal Sci. 102 (2021), 103344, https://doi.org/10.1016/j.jcs.2021.103344.
[30] G. Kang, Y.J. Ning, R. Liu, P.W. Chen, S.P. Pang, Simulation of force chains and particle breakage of granular material by numerical manifold method, Powder Technol. 390 (2021) 464–472, https://doi.org/10.1016/j.powtec.2021.05.088.
[31] M.J. Adams, M.A. Mullier, J.P.K. Seville, Agglomerate strength measurement using a uniaxial confined compression test, Powder Technol. 78 (1) (1994) 5–13, https://doi.org/10.1016/0032-5910(93)02777-8.
[32] H.L. Liu, Y.F. Sun, G. Yang, Y.M. Chen, A review of research on particle breakage characteristics of coarse grained materials, J. Hohai Univ. (Natural Science

Edition) 40 (04) (2012) 361–369. https://kns.cnki.net/kcms/detail/detail.aspx?FileName=HHDX201204002&DbName=CJFQ2012.
[33] E.E. De Beer, The scale effect in the transposition of the results of deep-sounding tests on the ultimate bearing capacity of piles and caisson foundations, Géotechnique 13 (1) (1963) 39–75, https://doi.org/10.1680/geot.1963.13.1.39.
[34] Y. Rozenblat, D. Portnikov, A. Levy, H. Kalman, S. Aman, J. Tomas, Strength distribution of particles under compression, Powder Technol. 208 (2011) 215–224, https://doi.org/10.1016/j.powtec.2010.12.023.
[35] N. Djordjevic, R. Morrison, Exploratory modelling of grinding pressure within a compressed particle bed, Miner. Eng. 19 (10) (2006) 995–1004, https://doi.org/10.1016/j.mineng.2006.05.008.
[36] A. Samimi, M. Ghadiri, R. Boerefijn, A. Groot, R. Kohlus, Effect of structural characteristics on impact breakage of agglomerates, Powder Technol. 130 (1–3) (2003) 428–435, https://doi.org/10.1016/S0032-5910(02)00246-2.
[37] L. Hong, Study on size effects of rock strength and crushing energy consumption characteristics under impact load, (Changsha, China): doctoral dissertation, School of Resource and Safety Engineering Zhongnan University of Technology. https://kns.cnki.net/kcms/detail/detail.aspx?FileName=2009208392.nh&DbName=CDFD2010.
[38] T. Zhang, Triaxial compression and shear deformation characteristics and Micro-mechanical behaviors of crushable sand under high stress, (Jiangsu, China): doctoral dissertation, state key laboratory of deep rock and soil mechanics and underground engineering, China Univ. Min. Technol. https://kns.cnki.net/kcms/detail/detail.aspx?FileName=1021773644.nh&DbName=CDFD2022.
[39] B.O. Juliano, D.B. Bechtel, The Rice Grain and its Gross Composition, 2nd ed., Chemistry and Technology, Philippines, 1985.
[40] R.R. Little, E.H. Dawson, Histology and histochemistry of raw and cooked rice kernels 25, 1960, pp. 611–622, https://doi.org/10.1111/j.1365-2621.1960.tb00005.x.
[41] H. Utsunomiya, M. Yamagata, Scanning electron microscopy of the endosperm of cereal crops, 4: starch cell layer of imperfect grain of rice (non-glutinous) and glutinous rice, Bull. Faculty Agricult. Yamaguchi University (Japan) 26 (1976) 19–44. https://agris.fao.org/agris-search/search.do?recordID=JP7601920.
[42] H. Jiang, Y.D. Zhou, J.T. Wang, C.H. Zhang, Micromechanical investigation of particle breakage behavior in confined compression tests, Comput. Geotech. 133 (2021), 104075, https://doi.org/10.1016/j.compgeo.2021.104075.