Breakage Behavior of a Layer of Corn Kernels under Uniaxial Compression

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Abstract. Corn breakage is principal phenomenon in corn industrial processing. In the roller mills, or flakers material is loaded continuously controlled by the working gap. While several studies showed the different aspects of single kernel compression of corn kernels, a little is known about the differences in breakage between a single particle and a layer of corn kernels breakage as influenced by size and moisture content. The aim of the study was to assess the effect of moisture content and kernel thickness on breakage probability in cereal grain layer under monotonic compression, and to interpret the observed variability using energy-based modelling. The results showed that mechanical response of the layer is dependent on the moisture content and the thickness of kernels compressed. At lower moisture content, kernels tend to be more brittle and characterized by the higher breakage rates at lower energy levels. At higher moisture content, kernels have higher ability to dissipate energy through deformation, which cause the lower breakage rates at similar energy levels. These findings may support future analysis of grain processing operations where local variability of kernel affects the energy requirements.

1. Introduction

Mechanical damage, fracture and breakage occur frequently during handling and processing affecting cereal grains quality and market grade, processing efficiency including energy efficiency [1]. The importance of studying the breakage phenomenon for cereals can be considered twofold. The adequate and reliable model of particle breakage based on the stochastic distribution of primary fracture characteristic (force, deformation, strength, energy) will improve fracture predictions and decrease in mechanical damage and kernels losses as the operating conditions and mechanical design of machines can be optimized through usage of those models. In other hand, energy-based probabilistic models are highly relevant for size reduction operations to maximize their efficiency and lowering the energy demand, so operating in the minimum energy mode. Literature evidence shows that particle breakage is still far from the minimum-energy mode, as only less than 10% of the input energy is effectively utilised for particle disintegration [2,3]. This shows that breakage modelling remains highly relevant in food and particulate process engineering.

Till date research on cereals fracture has been focused on characterization of single kernel behavior during compression and impact demonstrating that material resistance to load and fracture mode depend on the grain type, internal structure, moisture content and loading direction [1]. The existing empirical and energy-based probabilistic models relied on single particle fracture gives good consistency with experimental results, but require time consuming single-particle fracture characterization for high number of particles [4]. On the other hand, the complex particle behaviour in industrial applications, where groups of particles formed in dens streams, beds or monolayer, is not captured in the single particle compression.

In corn processing, roller mills, crushers, flakers, and other devices that utilize a working gap between compressing elements are frequently used [5]. In this type of equipment material is loaded as a layer of known thickness controlled by the working gap, not a single grain. This is a specific case of loading differing between single particle and particle beds. As shown in the study of Campos et al [6], the particle breakage mode differs between the single-particle and particle bed composed of different number of layers due to different stress end energy distribution within particles. While several studies showed the different aspects of particle beds behaviour for corn kernels [7–9] and other particulates [6,10,11], a little is known about the differences between single particle and monolayer breakage and interpretation of breakage probabilities obtained through these two approaches for corn kernels. Moreover, for cereals the influence of

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particle size and moisture content in the transition from single particle breakage to monolayer remains unexplored.

In this study the above gaps are addressed by exploring the breakage probability of single-particle and monolayer of 40 non-contacting corn kernels of different size ranges and moisture content subjected to monotonic compression. This creates a physically meaningful intermediate configuration, in which global loading can be related to partial fracture of a grain population rather than to failure of one isolated kernel or to collective breakage in a confined bed. This in turn could lay the foundation to go from time consuming single particle-characterization of breakage probability to monolayer tests.

The aim of the study was to assess the effect of moisture content and layer thickness on breakage probability in cereal grain layers under monotonic compression, and to interpret the observed variability using energy-based modelling.

2. Materials and methods

2.1. Materials

The study was conducted on the example of yellow dent corn with properties presented in Table 1 and four moisture content (MC) levels: 8.20%, 11.95%, 16.00%, 20.02%, as described elsewhere [12].

Table 1. Properties of corn kernels used in the study [12]

Property	value
Starch content	61.33% ± 0.76%
Protein content	6.63% ± 0.40%
Oil content	3.33% ± 0.15%
True density	1.220 ± 0.002 g/cm^3

2.2. Single particle static compression

To initially evaluate the mechanical properties of kernels, such as engineering failure stress, failure force, failure deformation, failure energy, monotonic compression test on single particle was conducted on universal testing machine (MTS systems) with 1 kN load cell. Kernels were placed in the natural rest position – germ down – and compressed one by one [13]. Loading of kernel was stopped when the primary fracture occurred visible as a sharp drop in force on the force-deformation profile.

2.3. Monolayer compression

This experiment was inspired by earlier work of Schönert [11] and Campos et al. [6] and involved the compression of grains in a monolayer, as previously described in [14]. Grains from samples with given moisture contents were divided into 4 narrow size fractions: 3.95-4.05 mm, 4.50-4.60 mm, 5.05-5.15 mm and 5.60-5.70 mm. Monolayers were created from 40 grains from each size range and moisture content level. The number of kernels in the layer resulted from the size of the compression piston and the arrangement of grains so that they did not overlap and formed a single layer (Figure 1).

The response of grains in the layer was analysed for defined load values from the range of 4500 N to 9000N. Loads were applied until the target load was reached, and then the samples were unloaded. Force and displacement were recorded during the tests. The response to compressive loads of the particle layer was analysed using an energy-based approach involving strain energy analysis. The maximum energy during loading was calculated according to [12,15,16], assuming it is equal to the area under the force-deformation curve:

$$E = \int_0^{u_{max}} F(u)\, du \tag{1}$$

Figure 1. The arrangement of kernels in the particle layer

According to [11], the energy absorbed by the layer was defined as the portion of energy indicated by hysteresis loop, i.e., the portion of the surface area contained between the loading and unloading curves. This energy, related to the mass of the grains, was treated as the specific energy absorbed in the layer.

Additionally, grain damage in the layer was analyzed using a probabilistic approach. The fraction of damaged grains – the one for which primary fracture occurred - relative to the total number of grains in the layer was used as the determinant [17]:

$$P_b = \frac{n_b}{40} \tag{2}$$

This value was then related to the loading conditions, moisture content, grain layer thickness as well as the specific absorbed energy.

3. Results and discussion

The results of mechanical characterization of kernels during compression showed that the moisture content modify the mechanical response of material. In the Figure 2 the dependence between the specific fracture energy and deformation of individual corn kernels at different moisture content under monotonic compression was presented. It is apparent that the fracture energy increases nonlinearly, or rather, in a power-law manner. According to the Hertzian contact model [18], the force in the elastic region of contact increases approximately as $F \propto \delta^{(3/2)}$, which, when integrated with respect to displacement, leads to a proportionality of the strain energy to the displacement as $E \propto \delta^{(5/2)}$. The power-law exponents deviates from the ideal value of 5/2 due to complex contact topology for non-spherical particles, presence of friction, irreversible phenomena such as: microcrack initiation, plastic deformation, and crack propagation leading to energy dissipation. Noticeably, with increasing moisture content, grain deformability increases at comparable energy levels, and generally, moist grains required more energy to initiate a crack, which is consistent with studies of other researchers [16,19,20].

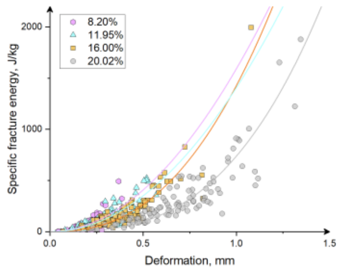
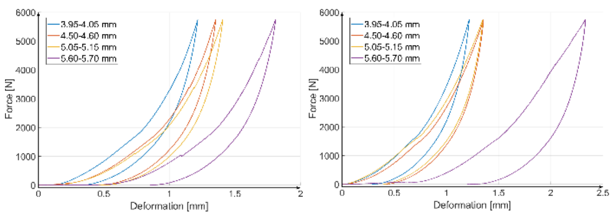


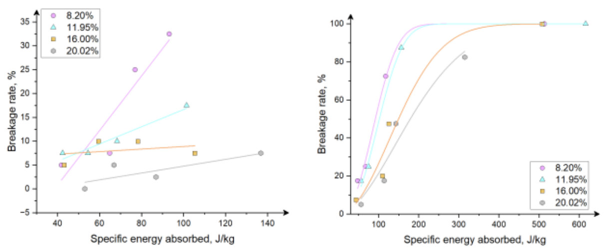
Figure 2. Specific fracture energy at single particle compression plotted against deformation. Solid lines represent fitted power curves

The results presented in Figures 3 and 4 confirm the effect of moisture content on grain breakage in the monolayer. The force-deformation curves (Figure 3) clearly indicate that at first phase of compression individual grains initially contact the compression piston, then deformation of particles in layer occurs with a rapid increase in force. The local changes in slope and irregularities are associated with load redistribution within the layer, while drops in force indicates sequential fracture of individual grains. It is noticeable that with increasing moisture content, the grain layer's deformability increases. Absorbed energy also increases, as indicated by larger hysteresis loops for grains with higher moisture content (20.02%). Increasing moisture content reduces the proportion of broken grains at a given energy level (Figure 4), which is consistent with the relationships observed for individual grains [12].



a) b)

Figure 3. Force-deformation profiles of compression of monolayer of corn kernels with a) 8.20% MC, b) 20.02% MC



a) b)

Figure 4. The dependence of breakage rate on specific energy absorbed in monolayer of corn kernels of different moisture content from narrow size range a) 3.95-4.05 mm b) 5.60-5.70 mm

Analysis of the curves in Figure 3 indicates that as the thickness of the grains forming the layer increased, the energy absorbed in the system (the hysteresis loop increased) increased when the same compressive force was applied. This is also confirmed by the results presented in Figure 4, where the increase in absorbed energy was accompanied by an increase in breakage rate. It can therefore be seen that a monolayer composed of thicker grains has poorer load-bearing capacity. This can be explained by the lower strength exhibited by larger grains [21,22] due to their tendency to have a higher likelihood of structural flaws (voids, cracks, or non-uniformities) compared to smaller ones [4]. When compressed, these act as areas where stress concentrates, leading to greater plastic deformation and a higher probability of breakage. Analysis of the change in breakage rate (Figure 4) also indicates that grains in the layer do not break simultaneously, but gradually, as individual energy thresholds are exceeded for each grain. This phenomenon results from the distribution of individual grain strengths and the uneven distribution of stresses in the monolayer [6,11].

4. Conclusions

In this study the effect of moisture content and particle thickness on breakage of corn kernels forming the monolayer was investigated.

The results showed that mechanical response of the layer is dependent on the moisture content and the thickness of kernels compressed. At lower moisture content kernels tend to be more brittle and characterized by the higher breakage rates at lower energy levels. At higher moisture content, kernels have higher ability to dissipate energy through deformation, which cause the lower breakage rates at similar energy levels.

These findings may support future analysis of grain damage in processing and handling operations where local variability of kernel properties and loading condition is important.

Acknowledgement

The research was funded by the Polish National Agency for Academic Exchange under The Bekker NAWA Programme [grant number: BPN/BEK/2021/1/00201].

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