Moisture dependent physical-mechanical properties of maize, rice, and soybeans as related to handling and processing

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Abstract: The knowledge about the physical and mechanical properties of cereal grains is crucial for machine design, operational efficiency, and handling. Due to the diversity of types of grains and their differences in internal structure, still there is a lack of knowledge of the influence of moisture content on the physical-mechanical properties and its consequences as related to machine design. The aim of this study was to investigate and describe the changes in the selected physical-mechanical properties of grains (maize, rice, and soybeans) subjected to compression loads in various moisture content (10, 14, 18, 22, 26%) at two loading rates: 1.25 mm/min and 125 mm/min. This research involved the size and shape measurement and determination of breakage force, stress, and energy of 100 randomly selected single kernels at each moisture content level and loading rate. It was found that the increase in moisture content increases kernel size, changes kernel shape, and decreases bulk density. The effects of moisture content and loading rate on breakage force, stress, and energy vary depending on the grain type, its internal structure and mechanical behavior. The increase in moisture content modified the mechanical behavior from brittle to viscoelastic. The results presented here will be useful for designing and improving performance of cereals handling and processing equipment. The indicated values of force and stress can be used in the machines design as the limit values in processing conditions to prevent quality losses from kernel damage.

Keywords: moisture content, strength, compression test, single grain compression, size, shape

Nomenclature

MC	moisture content
IRRI	International Rice Research Institute
Q	the amount of water to be added for rewetting (L)
m	the weight of the grain at the initial moisture content (kg)
MC_1	the initial moisture content of the grain (%)
MC_2	the desired moisture content of the grain (%)
M	the sample mass (g)
V	the container volume (cm^3)
W	width (mm)
L	length (mm)
T	thickness (mm)
F_B	force inducing the rupture (N)
A_p	the area of the compressed sample (mm^2)
f	sphericity index
AR	aspect ratio
FR	flatness ratio
D_e	equivalent diameter (mm)
LSD	least significant difference

1. Introduction

The physical and mechanical properties of grains play an important role in machine design, for processes such as grinding, handling, conveying, extrusion, and compacting equipment (Jan et al., 2019; Mannheim, 2011; Tomporowski, 2012). For designing storage containers, the bulk density and particle mass are the most important grain property (Horabik & Rusinek, 2002). Size and shape affect the design of harvesting and separation equipment (Jan et al., 2019). Size and shape have significant impact on sowing efficiency and uniformity, because it determines the position and filling rate of the seed drill dispensing units (Gierz et al., 2022). With a decrease in size, the cohesive strength of grains increases thus reducing the flowability, which is the one of the parameters determining the optimal angle for hopper and outlet dimensions in storage containers. Moreover the changes in grain size result in variation in wall friction angle and number of contact points, which will affect the design of conveyors, feeders, and other equipment (Schulze, 2008). The shape of grain will affect the moisture diffusivity of water and thus influencing the drying, aeration, and storage of grains (Jan et al., 2019). The physical-mechanical behavior and size and shape characteristics also play a significant role in simulation of bulk grain behavior using discrete element simulation approach (Hlosta et al., 2020). As the prediction accuracy of the computational models depends on the type of grains and contact parameters (Gierz et al., 2022), it is crucial to know variability in properties at different moisture contents.

There are several studies dealing with the changes in physical properties such as size, angle of repose, and static friction with the moisture content for rice (Cao et al., 2004), maize (Babic et al., 2013), and soybeans (Tavakoli, Rajabipour, et al., 2009) but very little attention is paid to mechanical behavior characteristics such us forces, strength, deformations, and especially breakage energy. Breakage is a common phenomenon that occurs during handling and processing, which decreases grain quality. On the other hand, cereals are subjected to some processing operations where breakage is needed, e.g. starch extraction, milling, etc (Babic et al., 2013). Published studies have shown that the moisture content, genotype, and chemical composition of grains impact mechanical behavior and breakage susceptibility (Corrêa et al., 2007; Mabasso et al., 2020; Qiao et al., 2022). For example, maize grains with corneous endosperm are more resistant to high loads and their hardness is higher than maize with soft endospherm (Wang & Wang, 2019). Increase in moisture content results in grain softening and their ductility (Qiao et al., 2022; Tavakoli, Mohtasebi, et al., 2009). Other factors affecting the behavior of kernels subjected to load are the size and shape, loading rate, and grain orientation (Kruszelnicka, 2021; Saiedirad et al., 2008; Zareiforoush et al., 2012). Published evidence suggests that the failure of flat grains need higher forces and energy than the failure of rounded or grains with higher thickness (Dziki & Laskowski, 2003; Kruszelnicka, 2021; Su et al., 2020). The higher loading rate can result in increase or decrease in force, deformation, and breakage energy depending on the grain type and structure (Ardebili et al., 2012; Tavakoli, Mohtasebi, et al., 2009; Zareiforoush et al., 2012). The changes in the mechanical behavior results in variability in grinding, milling, and affects other performance indicators such us energy consumption and efficiency (Probst et al., 2013; Tomporowski, 2012). The knowledge about the changes in physical-mechanical parameters is then essential to properly design the operating machines and improve processing conditions by decreasing the material losses during processing (Mabasso et al., 2020).

The aim of this research was to investigate and describe the changes in important physical-mechanical properties of maize, rice, and soybeans grains subjected to compression loads at different moisture content levels. This study focused on describing the effect of moisture content on the size, shape, and mechanical characteristics such as breakage force, deformation, and stress. To achieve the goals, a sequence of measurements on single grain kernels at five levels of moisture content, 10%, 14%, 18%, 22%, and 26%, were conducted. The measurements included three characteristic dimensions, the weight of kernels, and force-deformation characteristics using single grain kernel compression test.

2. Materials and methods

2.1. Sample preparation

Maize, soybeans, and rice were chosen in the study because they are the most processed grains by the food and feed industry. The main components of these grains are endosperm, germ, and outer layer, each of these with different chemical composition in the three selected grains. Detailed information on the chemical composition and structure could be found in Juliano and Tuaño (2019); Medic et al., (2014) and Singh et al., (2014). The maize and soybeans were acquired from Purdue University research farm in West Lafayette, IN, USA. The rice grains, a medium grain variety white rice (NISHIKI Brand), was purchased from a local store. To obtain the samples with 10%, 14%, 18%, 22%, and 26% moisture content, the rewetting procedure was conducted. Eight kg of samples were rewetted for each grain type. First, the initial moisture content of grains was determined. Then, proper amount of water was added to increase the moisture content of the samples to 28%. The mass of water needed for rewetting was calculated from the equation (Jan et al., 2019):

$$Q = \frac{MC_2 - MC_1}{100 - MC_2} \cdot m \tag{1}$$

where Q is the amount of water (L), m is the weight of the grain at the initial moisture content (kg), MC_2 is the desired moisture content of the grain (%), and MC_1 is the initial moisture content of the grain (%).

In order to uniformly rewet, the grain samples were mixed in a rotating drum for 24 hours. After determining the moisture content of rewetted samples, the grains were then divided into 5 smaller subsamples using the Boerner divider. To obtain the samples at desired moisture content, the subsamples were spread in a tray and dried at room temperature.

2.2. Moisture content measurement

For maize and soybeans, the moisture content was determined following the ASAE S352.2 standard (American Society of Agricultural and Biological Engineers, 2017), which recommends drying the grains at the temperature of 103°C for 72 hours in a hot air convection oven. Rice kernels were dried at a temperature of 130°C for 16 hours in an hot air convection oven as per International Rice Research Institute (IRRI) guidelines (IRRI Rice Knowledge Bank, 2010). The MC measurement was done in 3 replications involving 15 g samples (100 g was used in the case of maize after rewetting as recommended by the ASAE S352.2 standard for grains with MC higher than 25%). The mass of samples before and after drying was recorded with an accuracy of 0.001 using the Mettler Toledo ME203E analytical scale, and the MC was determined from the loss in weight and reported in wet basis.

2.3. Bulk density characterization

The bulk density (ρ_B) was measured with the one-pint test weight apparatus according to the standard test weight procedure (Guo, 2015). Bulk density was determined for grains at the initial MC and after rewetting. For each MC level, three replicates were done. The bulk density was calculated based on equation 2.

$$\rho_B = \frac{M}{V} \tag{2}$$

where: M is the sample mass (g), V is the container volume, which equals to 550.6 cm^3

2.4. Size measurement

The size measurement was done for a representative sample of 100 grains of rice, maize, and soybeans at the defined MC levels. For each grain kernel, the width (W), length (L), and thickness (T) (fig. 1) were measured with a digital caliper.

Based on the measurement of the three dimensions, the equivalent diameter D_e of each kernel was calculated based on the equation (Han et al., 2021):

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

Additionally, the weight of each kernel was measured using the Mettler Toledo ME203E analytical scale with an accuracy of 0.001 g.

2.5. Shape characteristics determination

The indices chosen to describe the shape of the kernels include the sphericity index (f), aspect ratio (AR), and flatness ratio (FR) using the formula given below (Han et al., 2021; Kruszelnicka, 2021) :

$$f = \frac{(L \cdot W \cdot T)^{\frac{1}{3}}}{L} \tag{4}$$

$$AR = \frac{W}{L} \tag{5}$$

$$FR = \frac{T}{W} \tag{6}$$

2.6. Compression test

The compression test was performed at two loading rates, 1.25 mm/min and 125 mm/min, for 100 grains to evaluate the breakage force, deformation, and strength at low and high velocities of loading. The compression tests were conducted using the MTS testing machine (MTS Systems Corporation, 14000 Technology Drive, Eden Prairie, MN, USA)) with the compression load cell of 5 kN (force measurement accuracy of ±0.001 N and deformation measurement accuracy of 0.001 mm). Single kernel was placed between the two parallel plates in the horizontal position (fig. 2), which is the natural position that prevents grain movement during loading (Chen et al., 2021). The test was stopped at the first break, and the force and deformation at this point (also called the bioyield point) were recorded. In this study, deformation was defined as the change in the grain dimension, which equals the load head displacement. The load cell and plate deformation during loading were neglected.

The strength of the particles was calculated according to equation (Kruszelnicka et al., 2020):

$$\sigma = \frac{F_B}{A_P} = \frac{F_B}{\frac{\pi L W}{4}} \tag{7}$$

where F_B is the force inducing the rupture (N), and A_p is the area of the compressed sample (mm^2).

The energy needed for the breakage initiation was calculated from the area under the force-displacement curve (Zareiforoush et al., 2012).

2.7. Statistical analysis

After removing up to 20% outliers (data with values more than two standard deviations from the mean), descriptive statistics, Pearson correlation, and regression analysis were conducted to identify the relationships between MC and the physical and mechanical properties at a significance level of 0.05. In the regression analysis, the F-test was performed to choose between linear and polynomial models, which compares the models and determines the best fit model. The null hypothesis in this test was set that model 2 (quadratic) does not fit the data significantly than model 1 (linear). The null hypothesis was rejected when the value of F is greater than the critical value of the F-distribution with a false rejection probability of 0.05. Two-way ANOVA was performed to check if there exist any significant differences in means between breakage forces, stresses, deformations and energy at both loading rates. For pairwise comparisons, the post-hoc Fisher least significant difference (LSD) test was done with a 95% confidence level.

3. Results and discussion

3.1. Effect of moisture content on the grain size

Table 1 presents the values of exact moisture content at five selected levels after drying for rice, maize, and soybeans. For simplicity, throughout the discussion, the moisture content values are rounded off to nearest whole number.

The results showed that the characteristic dimensions, i.e. length, width, thickness, equivalent diameter (fig. 3), as well as the weight (fig. 4) and bulk density (fig. 5) changes with MC. For the three tested grains, an increase in dimensions and weight was observed with increase in MC. This can be confirmed by higher than 0.88 positive Pearson's correlation coefficient values and statistical significance at the level of $p < 0.05$ (Table 2). The increase in dimensions with increasing MC results were due to the specific moisture absorption behavior of grain kernels and their diffusion properties during drying (Gierz et al., 2022; Ituen et al., 1986). Increase in moisture content resulted in a linear increase in grain mass (fig. 4). The weight increased by 24.18%, 19.24%, and 17.90% from the low to high moisture content for maize, soybeans, and rice, respectively. Changes in the water content affecting the size of the grain could be linked to the phenomenon of swelling (during soaking) and shrinkage (during drying). The differences in dimensions with the change in MC between the types of grains can be observed from Figure 3. This is due to the difference in structure and internal composition of rice, maize, and soybeans. The increase in grain size with moisture content was confirmed by the high positive Pearson correlation coefficient values (table 2). This relations can be described by linear or quadratic functions (fig. 3), which is consistent with the previously reported dependencies for maize (Babic et al., 2013), rice (Kibar et al., 2010), and soybeans (Chhabra & Kaur, 2017).

The change in grain size is caused by the absorption of water at the molecular level, which is greater in the case of grains containing starch (Gierz et al., 2022; Ituen et al., 1986; Kibar et al., 2010), but smaller for grains with a vitreous structure (Cao et al., 2004). Glassy materials are characterized by a low coefficient of expansion, diffusivity, and specific volume (Cao et al., 2004). This explains the least susceptibility (among the examined grains) to dimensional changes with MC increase for rice, which is characterized by the vitreous structure. On the other hand, some differences in the rate of changes in dimensions in relation to moisture and weight increase were observed between the grains. This is evidenced by the square functions of moisture content describing the changes of length and equivalent diameter of maize kernels, rice grain thickness, and length of soybeans (fig. 3). In case of rice, it can be seen that the difference in grain size with a moisture content of 22% and 26% is not as high as, for example, between grains with a moisture content of 10% and 14%. From the relationship between weight, dimensions and MC, it can be concluded that in the case of rice grains with a moisture content of 22% and 26%, the change in weight was primarily due to the evaporation of unbound water from the grain surface, which did not cause significant changes in the grain size. A further decrease in MC below 22% resulted in a significant reduction in the dimensions of rice grains that was proportional to the weight loss. In case of maize and soybeans kernels, a faster reduction in dimensions was observed with a decrease in moisture to 18%. Below this MC value, the differences in the dimensions of grains at lower moisture content were much smaller. As a result of rapid changes in moisture content in the seed coat, additional stresses may arise, causing contraction of seed coat (Dobrzański, 1998).

Research has shown that the effect of swelling as a result of water absorption or shrinkage as a result of its evaporation from the grain structure does not homogeneously affect change in size. For soybeans, the length was one of the properties affected the most by the moisture content – a 12.95% increase in length from the lowest average value obtained for 14% MC to the highest for 26% MC. It is worthwhile to note that the thickness of soybeans increased only slightly (about 1.73%) with changes in MC. For rice, the thickness was the dimension influenced the most by the MC, while for maize it was width. Differences in changes in the dimensions of maize, soybeans, and rice grains may result from differences in the content of starch, proteins, and fat (Sfayhi-Terras et al., 2021) and their ability to absorb water as well as their distribution in the internal structure, which may determine the direction of grain enlargement caused by the water absorption. As reported by Dobrzański (1998) for legume seeds, including soybeans, the seed cover may experience shrinkage by up to 26% as a result of drying, and the shrinkage proportions may differ in the transverse and longitudinal directions.

As a result of the changes in weight and grain dimensions, which are related to the grain volume and shape, a strong negative correlation between bulk density and MC was noticed (Table 2). In case of maize and rice, bulk density was the second most property highly influenced by the MC, which decreased about 10.77% for maize and 12.16% for rice when the MC was increased from 10% to 26% MC (fig. 5). For soybeans the bulk density decreased the lowest (of 8.27%) in the three tested grains. The increase in dimension with MC, causes the enlargement of contact diameter between the grains and the creation of larger voids, so the porosity increases (Kocabyik et al., 2004). Differences in the dynamics of changes in bulk density between the tested types of grains are, in turn, the result of differences in the grain original size and shape characteristics, as well as their changes with MC. For soybeans, the change in dimensions with MC was not proportional in the three axes which resulted in decreasing of sphericity. In contrary, the change in dimension in three axes for rice and maize was rather similar, so the sphericity increased slightly with MC. The decrease in sphericity of soybeans with the increase in MC causes a reduction in porosity. However, the soybeans size enlargement along the three axes have higher influence on the porosity than change in sphericity, so the bulk density decrease. This explains the lower decrease in bulk density with the MC for soybeans compared with maize and rice kernels.

3.2. Effect of moisture content on the shape of grain kernels

Due to the changes in the dimensions of the grains with the change in MC, as previously discussed, the changes in grain shape were also noticeable (fig. 6-8). The soybeans kernels have the shape closer to spherical among the studied grains, as evidenced by sphericity index, flatness, and aspect ratio values that are close to 1 (fig. 8). As well known, the rice kernels have the most elongated shape (fig. 7).

The sphericity, aspect ratio, and flatness ratio were negatively correlated with MC for soybeans (table 3) and decreased by about 4.7-5.8% from 10% to 26% MC. As was shown in the previous section, the thickness of soybeans changed only slightly with MC, while the length and width increased significantly, resulting in the shape of soybeans to become more elongated and less spherical. Thus, at higher MC, the rolling ability of soybeans will decrease, and the points of contact will change, and the pattern of filling a given volume. For soybeans kernels, the relationship between MC and flatness ratio can be described with a very good fit (R^2= 0.891) using a linear function (fig. 8c), which results from the linear increase in grain thickness and width with MC. Sphericity and aspect ratio, as the resultant of nonlinear change of length with MC, take the form of a quadratic function (R^2 = 0.998 and R^2 = 0.999 respectively, fig. 8a and 8b).

In contrary to soybeans, the shape of maize and rice grains changed only slightly when the MC increased. A positive correlation was noticed between MC and sphericity of this kernels (table 3), however the increase was only about 1% from the lowest to the highest MC level. As discussed earlier, water absorption caused an almost uniform increase in the dimensions of rice and maize grains along the three axes, hence slight changes in sphericity (fig. 6a, fig. 7a) . As a consequence, for the aspect ratio and flatness ratio of these grains, there were slight changes caused by the change in MC (fig. 6b, fig. 7b). The aspect ratio of rice grains decreased with the MC (negatively correlated, table 3) by about 1.90% for 26% MC compared to the value of this parameter for grains with 10% MC due to their slightly greater expansion in the longitudinal direction than in the transverse direction. The greater increase in grain thickness in relation to its width caused that the flatness ratio increased by about 3.99%. For maize, however, the flatness ratio decreased by about 3.94% for grains with 26% MC compared to grains with 14% MC, and the aspect ratio increased by about 2.42%. The relationships between MC and sphericity, aspect ratio, and flatness ratio for rice and maize grains are linear ($R^2 > 0.781$ for all fitted functions, fig 6 and fig. 7).

The difference in the shape changes with the MC of different types of grains is the result of their internal structure and composition. As observed, the change in the shape of the grain depends on the changes in dimensions due to changes in the water content. Slight changes in sphericity, aspect ratio, and flatness ratio for rice and maize indicate that for these grains the change in dimensions due to water content changes occurred almost proportionally in three axes, with only a slightly larger change in one of the dimensions in relation to the others, hence the observed 2 -3% difference in shape characteristics between wet (26% MC) and dry (10% MC) grains.

Differences in the internal structure of the grains may also be important. Rice and maize consist mainly of starchy endosperm with varying degrees of packing. Maize additionally has an outer layer, which the rice is devoid of. In the case of soybeans, the main components are an embryo, two cotyledons surrounded by a seed coat with hilum that held the seed to the pod. The presence of hilum may be the impediment for the seed coat deformation, forcing the soybeans kernel to expand less along its thickness. The arrangement of the cotyledons and their separation in the plane determined by the length and width of the grain also may have an influence on the non-uniform change in dimensions in three axes, and thus change the shape. In case of maize, the loose structure of the starchy endosperm allows the cells to expand while absorbing water, which may result in changes in starch arrangements (Qiao et al., 2022), thus swelling in all directions. The shape of the soybeans changes the most from the tested grains, which shows that it becomes more flexible with the increase of MC than rice and maize kernels.

3.3. Effect of moisture content and loading rate on the mechanical behavior of grain kernels during compression

Moisture content had the greatest influence on the deformation for the tested grains at both loading speeds (fig. 9-11). Deformation increased approximately 3.2 times, 2.53 times, and 3 times, respectively, for maize, rice, and soybeans with a moisture of 26% from the value recorded for grains with a moisture of 10% when loaded with a speed of 1.25 mm/min. At 125 mm /min, the increase in deformation for grains with 26%

moisture compared to grains with 10% moisture was 2.88 times for maize, 1.5 times for rice, and 2.92 times for soybeans, respectively. The greatest difference in forces and stresses between grains with 10% and 26% moisture content was recorded for rice grains (fig. 10). Forces and stresses decreased by approximately 74% (72% when loaded with a speed of 125 mm/min) and 78% (74% for 125 mm/min loading rate), respectively. The lowest impact of MC on the change in the value of forces and stresses was noted for maize kernels (fig. 9). In this case, the breaking forces for grains with 26% moisture increased by 20.3% (40.3% for 125 mm/min loading rate), and stresses by 11% (28.3% for 125 mm /min loading rate) compared to grains with 10% moisture.

It was observed that for the two loading rates, the changes of forces, displacements, and stresses with the MC follow the same tendency. The breakage forces increased with the increase in MC in the case of maize (positive correlation, r=0.930, table 4), while in the case of rice and soybeans the breakage forces decreases (negative correlation, table 4.). In the case of maize, the stress values increase with increasing MC (positive correlation, table 4), and for rice and soybeans, an inverse relationship was noted - a decrease in stress with an increase in MC (negative correlation, table 4). The deformation of the grains increased with increasing moisture content, which was observed for all three types of grains tested. The relationships between MC and destructive force, deformation, and stresses can be described with a high fit using linear or quadratic functions, as shown in Figure 12.

Based on the presented results, it can be concluded that the nature of the material's response to the set loads changes with increasing MC. Grains with low MC during compression were characterized by lower deformations and their compression behavior was similar to brittle materials, while grains with high MC were softer and showed greater plastic deformation ability. For maize grains, the forces and stresses increased with the MC, while for rice and soybeans it decreases. This could be a result of the different compositions of the grains. All three grains become softer because of water absorption. However, the maize kernels having a fibrous outer layer become more elastic and have higher resistance to damage at high MC. This agrees with the earlier studies reporting the lower breakage rates for maize grains with higher MC in the MC ranges from 8 to 25% (Guo et al., 2022; Shahbazi & Shahbazi, 2018). Zdunek et al. (2008) stated that the high turgor can be responsible for higher resistance of materials to loading, while it may cause high cell wall tension. Although soybeans also have a seed coat, their load susceptibility decreases, as is the case with rice. The soybeans seed coat is mainly composed of protein, and as indicated by Li et al., (2019), soaking can cause the seed coat to become increasingly less packed with larger gaps between cells due to the release of proteins. It was previously reported that the cell packing as well as the occurrence of biochemical reactions can affect the mechanical properties (Obuchowski et al., 2010). Moreover soybeans experience severe deformation at higher moisture content that could be due to the increase in stress on the seed coat, that it can sustain at lower external loads. Probably it is caused by the high soaking ability of soybeans and texture changes during water absorption (Li et al., 2019) and higher protein and fat content (Dobrzański, 1998) than in the case of rice and maize. Dobrzański stated that the fat content changes with the MC and this could be responsible for the high deformability of wet soybeans. Qiao et al., (2022) showed that the protein content is responsible for grain hardness and elastic properties, while the starch for viscosity and during water absorption the pores between starch granules increase so viscosity and deformation is higher, which was observed for rice and maize. Moreover it was found that during soaking some changes in the crude protein, crude ash, and starch content may occur resulting in the structure modification, which may influence the ability to bind water in grains and deform their shape (Sfayhi-Terras et al., 2021).

It was reported that important factors affecting the mechanical behavior are: interaction between carbohydrates and proteins (Qiao et al., 2022), structural composition, density, cell adhesion, and turgor pressure of cells (Zdunek et al., 2008). Other factors include the ratio of horny to floury endospherm in the grain composition (Babic et al., 2013), as well as size, shape, temperature, and strain rate (Obuchowski et al., 2010; Qiao et al., 2022; Su et al., 2020; Zareiforoush et al., 2012). It was also proved that the horny endosperm, germ, and floury endosperm show different mechanical properties – the horny endosperm has lower deformation and can sustain higher forces than the floury endosperm (Wang & Wang, 2019).

For rice kernels, a significant difference based on the result of the two-way ANOVA test and the Fisher LSD test (different letters below box chart on figure 10) between forces causing the breakage, stress, and deformations at two loading rates were observed. For this grain, the forces, stresses, and deformations were higher at a loading rate of 125 mm/min than at the low loading rate of 1.25 mm/min. The increase in stresses in rice subjected to loading at a higher rate could be due to fast crack propagation, so that it is not possible to differentiate the force causing breakage initiation with the force leading to grain rupture.

In the case of maize and soybeans, the influence of the loading rate on the breakage behavior is not obvious. For maize, slightly higher fracture forces were recorded during the compression test at a speed of 125 mm/min. However, statistically significant differences between the mean values for the two compression speeds were obtained only for grains with a moisture content of 22% and 26% (fig. 9). There were no statistically significant differences between the mean stresses for the two different loading speeds. The deformations obtained during compression at a speed of 125 mm/min turned out to be slightly lower than during compression at a speed of 1.25 mm/min, however, statistically significant differences occurred between the average deformations for grains with two moisture levels of 14% and 26%.

Statistically significant differences between the average breaking forces and stresses (higher at the speed of 125 mm/min) for the two loading speeds in the case of soybeans occurred only for grains with 10% and 22% moisture content (fig. 11), however, the influence of the loading speed on the change of forces and stresses is not clear. The mean deformations of soybeans obtained in the compression test at a speed of 125 mm/min were lower than those at low loading rate. In this case, statistically significant differences between the averages for two different loading speeds did not occur only for grains with a moisture content of 26%.

For soybeans and maize, similarly to rice, the increase in force and stress during loading at a higher rate is a result of higher internal friction between cells inside the grain. This could be also the reason of observed lower deformation for higher loading rate, as the internal pressure increasing due to the fast increase in cells packing, so the failure starts earlier. Moreover, in contrast to the rice grains, soybeans, and maize grains had a seed coat, which may affect the course of deformation during compression at different speeds. The presence of seed coat may provide an additional internal pressure and stress during compression. When kernels experience transverse deformation, particles and grain-building cells moves perpendicular to the direction of loading and between the cells and the seed coat additional pressure can appear (Dobrzański, 1998). In the case of rice grains without seed coat, it was primarily the endosperm that was compressed. The lack of a seed coat, i.e. the outer layer of the grain containing, among others, cellulose and fibers, may cause that during compression, particles and grain-building cells may move perpendicular to the direction of loading without being limited by the deformation ability of seed coat. Hebda and Frączek (2005) found that the seed outer layer being more flexible, transfers the loads during compression and is responsible for maintaining (bonding) the internal structure, as well can change its shape relatively easily. Their study gave them the basis for the claim that the grains can be treated as thin-walled vessels filled with a material of a certain viscosity. So, due to the increased water content the internal pressure in grains with seed coat will raise, causing additional stress. This could explain that in case of maize and soybeans the higher stresses and forces and lower deformation was observed for compression at high loading rate. Moreover Hebda and Frączek stated that the thickness of seed coat affects the elasticity of the grains and the ability to deform, especially for wet grains, the seed coat will be responsible for deformation. Wet maize can sustain higher forces, stress, and deformation as they have fibrous outer layer with elastic behavior when wet and is more resistant to cell movement and internal pressure in the softer endosperm. Rice do not have a seed coat, so, at high moisture condition they have higher deformation due to softening caused by the water absorption but can sustain the lower forces and stress than in dry conditions. In case of soybeans, with increasing moisture content very high deformations are observed, because of the softening of internal structure and high elasticity of seed coat.

A literature review shows different observations for changes in forces, stresses, and deformations for the point of breakage initiation with the loading rate. Tavakoli et al. (2009) found that the lower rupture forces occurred during barley compression with 10 mm/min than with a 5 mm/min loading rate. Similar results were reported during wheat (Gorji et al., 2010) and rice (Zareiforoush et al., 2012) compression. The forces were lower for the compression of cumin seed with a loading rate of 5 mm/min than with a loading rate of 2 mm/min (Saiedirad et al., 2008). Su et al. (2020) reported a decrease in forces with loading rate for pyramidal and rectangularly cut maize grains for compression along the X, Y, and Z axes and an increase in force with loading rate for round kernels along the Z axis. Similar to the results presented in this study for rice, Zhao et al. (2018) showed that the deformation during compression of oat kernels had an increasing trend with the increase in loading rate in the range of 0.02-0.10 mm/s, and forces and stresses firstly increased and then decreased with increase with loading rate. On the contrary, Uguru et. Al. (2021) reported that the deformation during compression of groundnut decreased with the increase in loading rate (tested rates 15, 20, and 25 mm/min), which was also observed in our study for maize and soybeans. The negative correlation between forces and loading rate was presented in the study of JinCheng et al. (2021) for lotus seeds. The increase in forces at bioyield point with the increase in loading rate was observed for castor seeds (Ardebili et al., 2012).

The different observations of changes in the forces, stresses, and deformations at bioyield or rupture point with the changes in loading rate indicate that further research is needed, especially in the wider range of loading rates, while most of the studies report the results for narrow ranges of loading rate variability, to establish reliable dependencies.

3.4. Consequences of variable grain moisture content on the grain processing and machine design

Variability of physical properties such as grain size, shape, weight, and bulk density is of great importance in the design of machines and processing processes. The significant differences in weight, shape, and dimensions at low and high MC indicate that it may be necessary to use different sets of sieves or establish other technological parameters for the classification and separation processes for grains at different MC. Changes in the rolling ability of materials and changes in contact points with the surface that characterizes grain flowability and behavior during handling processes should also be taken into account. The changes in the particle sizes and shapes are responsible for changes in bulk density, which will cause changes in the pressure on the storage equipment walls and transmission of loads (Horabik & Rusinek, 2002). As indicated by Horabik and Rusinek (2002), the pressure ratio, bulk density, and friction coefficient are the most important parameters that should be taken into account when determining loads for containers, silos, and other storage structures. Bulk density decrease with the increase of MC, as shown in this study and other studies (Jan et al., 2019). Dale and Robinson (1954) showed that an increase of MC by 4% w.b., the lateral and vertical loads increased by 6 and 4 times, respectively. The results from this research show that in storage equipment design the variability of bulk density in MC range from 10% to 26% of about 10.8%, 8.3%, and 12.2% for maize, rice, and soybeans kernels, respectively, should be considered. The observed changes in grains mechanical properties induced by the change in MC are very important in the processing. As a consequence of changes in mechanical properties with moisture, the energy needed to break the grain also changes, which is of great importance in industrial processes, especially in the context of energy consumption during processing operations such as grinding, component extraction and flour preparation (Qiao et al., 2022; Tavakoli, Mohtasebi, et al., 2009; Tomporowski, 2012). In this study, the energy for grain breakage was calculated as the area under the force-deformation curve, so the values of breakage forces and deformations to damage, as well as the slope of the force-deformation curve will affect the energy values. Thus the trends in energy changes with MC will be similar as in the case of changes in forces and deformations. Figure 13 shows the energy range required to initiate cracking in maize, rice, and soybeans kernels at different moisture and loading rates. The results of ANOVA show that the moisture content has a significant influence on the energy needed for breakage initiation in maize, rice, and soybeans. Significant differences (based on the Fisher LSD post-hoc test) between the means of grains with different moisture content were observed (table 5).

The breakage energy of maize kernels increased with increase in MC (Fig. 13a). The increase in MC resulted in grains becoming more deformable and could withstand greater loads than dry grains (fig. 9a). This in turn resulted in the observed increase in energy with MC increase. Maize grains at higher MC will therefore be more resistant to damage caused by external loads. However, the load-bearing capacity of maize will depend heavily on its variety and the content of horny and floury endosperm, which is unique to each grain variety (Babic et al., 2013). Wang and Wang (2019) indicated that the soft, floury endosperm is characterized by lower resistance to loads and greater deformation than the horny endosperm. Thus, the predominance of one type of endosperm over the other will determine the mechanical properties such as force, deformation, and energy to failure. The increase in MC decreased the energy to yield point for rice kernels (fig. 13b). The absorption of water into the grain resulted in a significant reduction of forces and strength (fig. 10a,b), which resulted in the reduction of energy along with MC, despite the observed increase in deformation. The energy and mechanical properties are closely related to the glassy structure of the rice in which the starch cells are tightly packed. Under the influence of water absorption, the intercellular distance changes (the grain volume increases), causing the mobility of starch chains, thus increasing the plasticity of the grain and lowering its hardness (Cao et al., 2004; Qiao et al., 2022). Rice grains with low moisture are characterized by high hardness, which decreases with increasing MC. On the other hand, the reduction of hardness contributes to the reduction of breakage forces and energy during compression (Dziki et al., 2014). The obtained results indicate that rice grains will be most susceptible to damage at high MC values and even small loads of a few kilograms during processing operations will damage them. For soybeans, it was observed that with the increase in MC the energy first increased and then decreased (fig. 13c). The highest energy values were observed for soybeans with MC of 14% and a loading rate of 1.25 mm/min (73.26 mJ) and at 125 mm/min loading rate for soybeans with MC 18% MC (66.16 mJ). The observed decrease in energy for soybeans grains with high MC (from about 14-18% MC and higher) is a result of a slight increase in the deformation with the MC and higher differences in forces. For 10% MC, the soybeans kernels were characterized by higher hardness than the wet grains, as evidenced by higher force values and smaller displacements for grains with lower MC. The highest energy values for 14-18% MC may prove that in this MC range the soybeans grains are characterized by visco-elastic properties, and above 18% MC, plastic properties are dominant. During the increase in MC in the range of 22-26%, no increase in forces and deformations for soybeans was observed, which may be related to the seed coat reaching the tensile strength values. This results in no further deformation to breakage of soybeans grains with increasing MC, as well only slight changes in breakage forces, as the less strong seed coat will crack first, although the cotyledons will be able to deform plastically further. The relation between soybeans breakage energy and MC strongly depended on changes in mechanical properties (quadratic relationship for both loading rates, fig. 12) with changes in water content. As indicated by Dobrzański (1998), with the change in moisture content in soybeans kernels, the share of fat in the total weight of the grain changes and it shows plastic properties with high water content. This suggests that soybeans will be damaged more likely at low MC values, while in the high MC (above 18%) the damage will appear on the seed coat but not necessarily in the cotyledons.

It was also found that the influence of loading rate was significant only for rice and soybeans (table 5). A detailed comparison between means considering the interaction effect of MC and loading rate is presented in table 6. The lack of statistically significant differences in the breakage energy for maize compressed at two loading rates results from the fact that both the forces and deformations for the two loading rates were at a similar level in the tested MC ranges. The increase in loading rate caused the increase in energy to yield point during rice compression. The observed increase of forces and deformations because of loading with higher velocity contributes to obtaining higher values of the breakage energy of rice grains. For soybeans, statistically significant differences in energy between the two loading rates were noted for beans with 10%, 14% and 22% MC. The increase in energy in the MC range of 10%, 14% with decreasing load rate results from greater deformations obtained at lower deformation rate. The occurrence of a crack at lower deformations for a loading rate of 125 mm/min may be due to cell accumulation as a result of an increase in the deformation speed. For 18% and 22% MC at the speed of 125 mm/min, higher values of destructive energy were obtained than at the speed of 1.25 mm/min (for 18% the difference was statistically insignificant), which may result from the plasticization of soybeans at higher MC and then increased resistance of moist grains during rapid deformation. For 26% MC, the breakage energy values of soybeans kernels at both speeds were comparable (fig. 13), as were the values of forces and deformations (fig. 12).

The presented results suggest that the value of the breakage energy will depend on the properties of the materials and their behavior under loads, and more precisely on the elastic and plastic deformations during loading. Moisture content changes the proportion of share of elastic and plastic deformations in the total grain deformation, which seems to have an impact on changes in energy values during loading at different speeds, which may be indicated by the obtained energy values for the tested ranges MC and load rate levels.

The strong influence of moisture content on breakage characteristics, described in this study on the example of single grain compression, was also evidenced in the research on the comminution equipment reported by other researchers. During hammermilling of maize, the increase in specific comminution energy, while decrease in throughput and breakage rate was observed with an increase in MC (Probst et al., 2013). For rice grinding on a five-disc mill, an increase in specific energy and size reduction rate was observed with an increase in MC, while the throughput decreased with an increase in MC (Tomporowski, 2010). Although during single rice grain compression, a decrease in the energy required for grinding was observed, but, in the case of grinding in a mill, an increase in energy was observed with an increase in MC. This may be caused by a greater increase in energy due to the friction of rice grains between each other and between the grinding elements compared to the increase in energy on the effect of changes in MC.

4. Conclusions

This paper presents an analysis on the influence of moisture content on changes in selected size and shape characteristics as well as the mechanical properties of maize, rice, and soybeans kernels. It was found that an increase in moisture content causes an increase in grain size and a change in their shape. For rice and maize, the sphericity of grains increased with the increase in moisture, the opposite relationship was observed for soybeans. The increase in grain moisture content also caused changes in the values of forces, stresses, and strains causing grain cracking. A significant increase in strains was observed with increasing moisture content for the three tested grains. In the case of maize, there was also an increase in forces and stresses causing fracture with increasing moisture content, while for rice and soybeans grains the opposite relationship was observed. The results indicate a strong relationship between the moisture content of the grains and their mechanical properties. It should also be noted that the increase in the moisture content of the grains contributes to the change in the nature of the crack propagation, from more brittle at low moisture to a more plastic behavior at high moisture content. In the case of rice, it was found that increasing the load speed causes an increase in forces, stresses, and strains during compression. For maize and rice, these relationships were not so obvious, although a slight increase in forces and stresses as well as a reduction in strains was observed. It was indicated that the relationship between moisture content and selected physical and mechanical properties can be described with a good fit by means of linear or quadratic functions. The presented considerations show that changes in dimensions, shape and mechanical properties caused by changes in MC depend on the internal structure of the grain, the content of starch, protein, and fat. In addition, the presence of cereal grains seed coat will have an influence on the properties

The obtained results indicate that changes in physical and mechanical properties should be taken into account in the process of designing machines, devices, and processes of granular materials, especially taking into account significant changes in bulk density (approximately 20% from the lowest to the highest moisture content) and forces causing fracture (approximately 75% decrease in forces for high moisture kernels for rice grains, about 43% decrease for soybeans and about 20% increase for maize kernels). The significant influence of moisture content on the energy inducing the breakage was observed for all three tested grains. In the case of rice energy decreases, in the case of maize energy increases, and for soybeans firstly increases and then decreases with MC increase. The increase in the loading rate causes an increase in energy in the case of rice and a decrease in the case of soybeans. The presented energy values and the relationships describing its relationship with MC constitute an important indicator of the grains mechanical resistance to loads during technological operations and taking into account the design process, can help to reduce material losses due to mechanical damage.

The obtained results constitute an important database for modeling and designing machines for processing cereal grains. In addition, the properties will be valuable for conducting simulations using discrete element method.

Conflict of Interests

The author declares no conflict of interest.

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Tables

Table 1. Grain moisture content values after conditioning to selected levels

	Moisture content, %		
	Maize	Rice	Soybeans
Level 1: 10%	10.02	9.98	9.76
Level 2: 14%	13.95	13.96	14.10
Level 3: 18%	18.02	17.91	17.92
Level 4: 22%	22.09	21.80	21.94
Level 5: 26%	26.40	25.71	26.19

Table 2. Results of correlation analysis between moisture content and physical properties of grain kernels

		Thickness	Length	Width	Equivalent diameter	Weight	Bulk density
Maize	Pearson Corr.	0.961*	0.968*	0.946*	0.939*	0.956*	-0.972*
	p-value	0.009	0.007	0.015	0.018	0.011	0.005
Rice	Pearson Corr.	0.956*	0.963*	0.892*	0.937*	0.976*	-0.975*
	p-value	0.011	0.008	0.042	0.019	0.004	0.005
Soybeans	Pearson Corr.	0.889*	0.958*	0.935*	0.899*	0.969*	-0.996*
	p-value	0.045	0.010	0.020	0.038	0.007	0.000

A 2-tailed test of significance is used, *: Correlation is significant at the 0.05 level

Table 3. Results of correlation analysis between moisture content and selected shape characteristics (based on average values)

		Sphericity	Aspect ratio	Flatness ratio
Maize	Pearson Corr.	0.960*	0.884*	-0.934*
	p-value	0.009	0.047	0.020
Rice	Pearson Corr.	0.953*	-0.942*	0.972*
	p-value	0.012	0.017	0.006
Soybeans	Pearson Corr.	-0.973*	-0.965*	-0.944*
	p-value	0.005	0.008	0.016

A 2-tailed test of significance is used, *: Correlation is significant at the 0.05 level

Table 4. Results of correlation analysis between moisture content and mechanical characteristics (based on average values)

		Loading rate 1.25 mm/min			Loading rate 125 mm/min		
		Breakage force	Breakage stress	Deformation	Breakage force	Breakage stress	Deformation
Maize	Pearson Corr.	0.930*	0.940*	0.974*	0.959*	0.907*	0.968*
	p-value	0.022	0.017	0.005	0.010	0.033	0.006
Rice	Pearson Corr.	-0.980*	-0.965*	0.777	-0.997*	-0.995*	0.949*
	p-value	0.003	0.008	0.122	1.81x10^{-4}	4.19x10^{-4}	0.014
Soybeans	Pearson Corr.	-0.825$^{\#}$	-0.908*	0.847$^{\#}$	-0.759	-0.797	0.957*
	p-value	0.086	0.033	0.070	0.137	0.106	0.011

2-tailed test of significance is used, *: Correlation is significant at the 0.05 level, $^{\#}$: Correlation is significant at the 0.1 level,

Table 5. The means comparison of energy needed to induce breakage at different MC and loading rates

	Energy (mJ)		
	Maize	Rice	Soybeans
Loading rate			
1.25	61.14(a)	1.01(b)	58.02(a)
125	62.36(a)	3.02(a)	53.88(b)
MC			
10%	29.53(e)	2.69(a)	43.80(e)
14%	46.25(d)	2.21(b)	61.86(b)
18%	56.39(c)	1.87(c)	65.17(a)
22%	80.62(b)	1.61(d)	57.36(c)
26%	99.76(a)	1.53(d)	51.40(d)

()grouping letters of post-hoc Fisher LSD means comparison test; means that do not share a letter are significantly different

Table 6. The means comparison of energy needed to induce the breakage for interactions effect of MC and loading rates

	Energy (mJ)					
	Maize		Rice		Soybeans	
Loading rate	1.25 mm/min	125 mm/min	1.25 mm/min	125 mm/min	1.25 mm/min	125 mm/min
MC						
10%	31.57(e)	27.29(e)	1.58(f)	3.90(a)	53.01(c)	34.79(e)
14%	46.96(d)	45.54(d)	0.98(g)	3.48(b)	73.26(a)	50.58(c,d)
18%	53.68(c,d)	59.10(c)	0.72(g)	3.00(c)	64.07(b)	66.16(b)
22%	77.74(b)	83.82(b)	0.84(g)	2.58(d)	48.19(d)	65.87(b)
26%	98.62(a)	100.98(a)	0.93(g)	2.14(e)	51.57(c,d)	51.22(c,d)

() interactions grouping letters of post-hoc Fisher LSD means comparison test; means that do not share a letter are significantly different

Figure captions

Fig. 1. The representation of three dimensions measured for each grain: width (W), length (L), and thickness (T)

Fig. 2. Grain position between parallel plates

Fig. 3. The dependencies between moisture content and thickness: a) maize, $T = 0.0205MC + 4.438$, $R^2 = 0.923$, b) rice, $T = -5.95 \cdot 10^{-4}\,MC^2 + 0.0306\,MC + 1.522$, $R^2 = 0.999$, c) soybeans, $T = 0.00602\,MC + 5.887$, $R^2 = 0.786$; length: d) maize, $L = 0.00272\,MC^2 - 0.0463\,MC + 13.253$, $R^2 = 0.996$, e) rice, $L = 0.0209\,MC + 5.605$, $R^2 = 0.928$, f) soybeans, $L = 0.00374\,MC^2 - 0.0736\,MC + 7.747$, $R^2 = 0.994$; width: g) maize, $W = 0.0448\,MC + 7.700$, $R^2 = 0.895$, h) rice, $W = 0.0925\,MC + 2.663$, $R^2 = 0.796$, i) soybean, $W = 0.0273\,MC + 6.382$, $R^2 = 0.874$; equivalent diameter: j) maize, $D_e = 0.00233\,MC^2 - 0.0534\,MC + 8.536$, $R^2 = 0.997$, k) rice, $D_e = 0.0120\,MC + 2.988$, $R^2 = 0.877$, l) soybeans, $D_e = 0.00283\,MC + 6.314$, $R^2 = 0.808$; ○ – data, ▲- mean, — – fitted curve, ---- – 95% confidence band

Fig. 4. The dependencies between moisture content and weight: a) maize, $m = 0.00578MC + 0.305$, $R^2 = 0.914$, b) rice, $m = 0.000233\,MC + 0.0180$, $R^2 = 0.953$, c) soybeans, $m = 0.00243\,MC + 0.164$, $R^2 = 0.939$; ○ – data, ▲- mean, — – fitted curve, ---- – 95% confidence band

Fig. 5. The dependencies between moisture content and bulk density: a) maize, $\rho_B = -0.00555\,MC + 0.833$, $R^2 = 0.946$, b) rice, $\rho_B = -0.00664\,MC + 0.905$, $R^2 = 0.950$, c) soybeans, $\rho_B = -0.00379\,MC + 0.795$, $R^2 = 0.991$; ○ – data, ▲- mean, — – fitted curve, ---- – 95% confidence band

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Fig. 6. The relationship between moisture content and selected shape characteristics for maize: a) sphericity, $f = 0.000353\,MC + 0.602$, $R^2 = 0.922$, b) aspect ratio, $AR = 0.00105\,MC + 0.617$, $R^2 = 0.781$, c) flatness ratio, $FR = -0.00132\,MC + 0.577$, $R^2 = 0.873$; ○ – data, ▲- mean, — – fitted curve, ---- – 95% confidence band

Fig. 7. The relationship between moisture content and selected shape characteristics for rice: a) sphericity, $f = -0.000021\,MC + 0.515$, $R^2 = 0.999$, b) aspect ratio, $AR = -0.00058\,MC + 0.483$, $R^2 = 0.887$, c) flatness ratio, $FR = 0.00147\,MC + 0.632$, $R^2 = 0.945$; ○ – data, ▲- mean, — – fitted curve, ---- – 95% confidence band

Fig. 8. The relationship between moisture content and selected shape characteristics for soybeans: a) sphericity, $f = -0.000158\,MC^2 + 0.00249\,MC + 0.900$, $R^2 = 0.998$, b) aspect ratio, $AR = -0.000193\,MC^2 + 0.00357\,MC + 0.904$, $R^2 = 0.999$, c) flatness ratio, $FR = -0.00254\,MC + 0.918$, $R^2 = 0.891$; ○ – data, ▲- mean, — – fitted curve, ---- – 95% confidence band

Fig. 9. The breakage force a), stress b), and deformation c) during maize grains compression for five levels of MC and two loading rates. Letters below the box charts are the interactions grouping letters of the post-hoc Fisher LSD means comparison test. Means that do not share a letter are significantly different. □ – mean, —— – median, ♦ – outliers

Fig. 10. The breakage force a), stress b), and deformation c) during rice grains compression for five levels of MC and two loading rates. Letters below the box charts are the interactions grouping letters of the post-hoc Fisher LSD means comparison test. Means that do not share a letter are significantly different. □ – mean, ── – median, ♦ – outliers

Fig. 11. The breakage force a), stress b), and deformation c) during soybeans grains compression for five levels of MC and two loading rates. Letters below the box charts are the interactions grouping letters of the post-hoc Fisher LSD means comparison test. Means that do not share a letter are significantly different. □ – mean, ── – median, ♦ – outliers

Fig. 12. The dependencies between moisture content and selected mechanical properties for maize (circle), rice (triangle), and soybeans (square) grains and two loading rates: 1.25 mm/min (black) and 125 mm/min (white)

Fig. 13. The dependence between moisture content and energy needed for single grain compression; a) maize, b) rice, c) soybeans

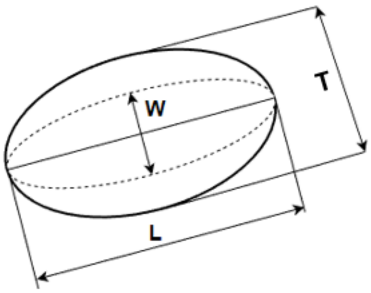
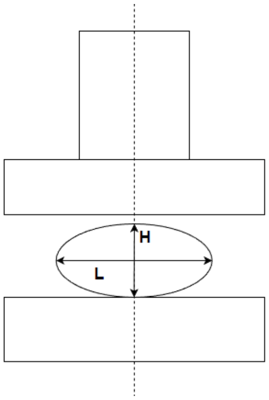


Fig. 1.



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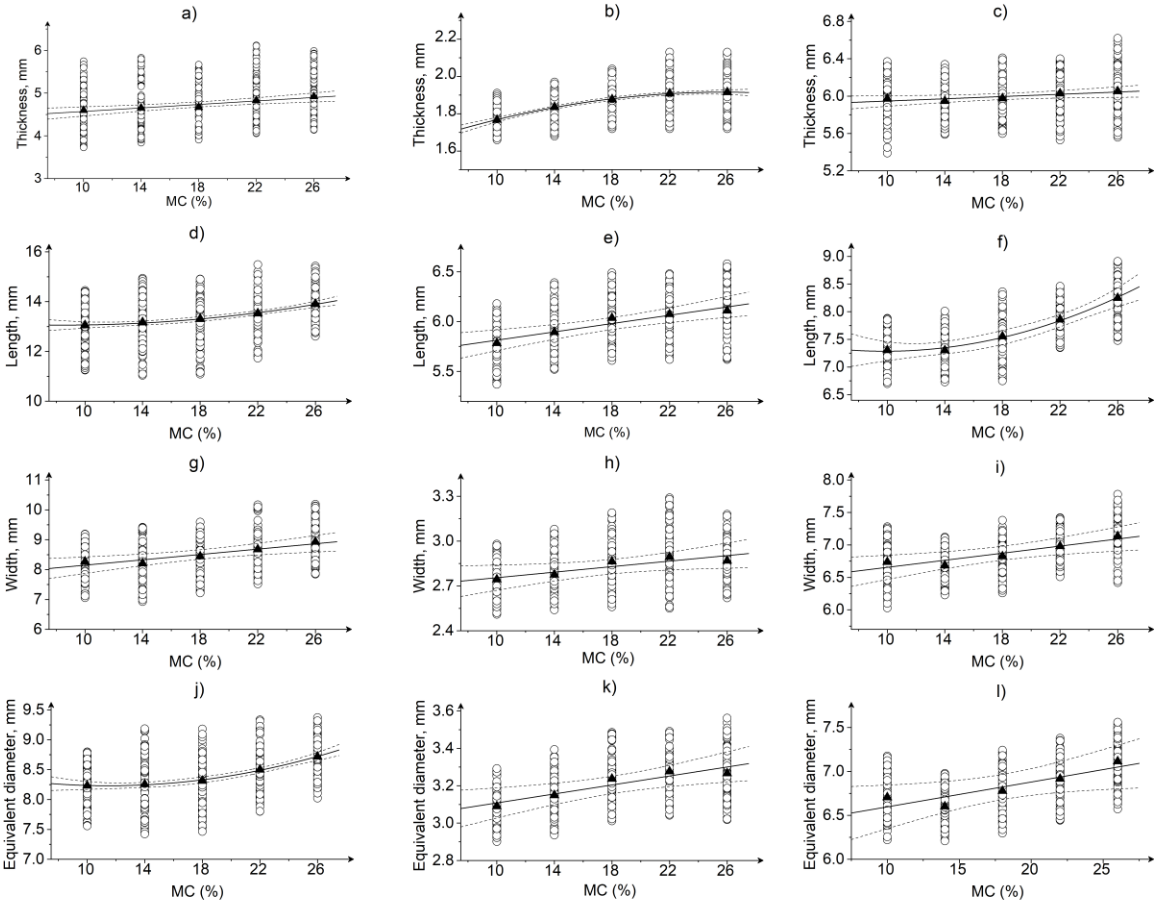

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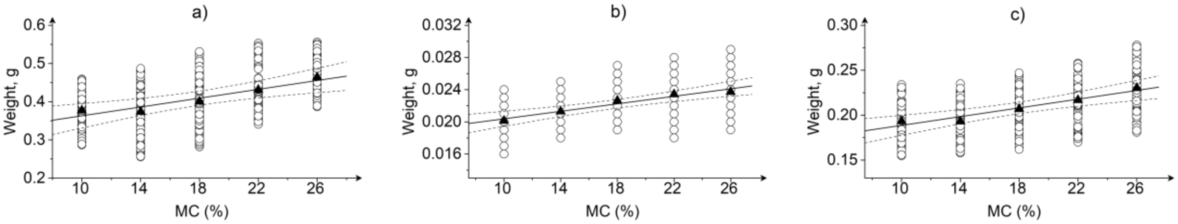

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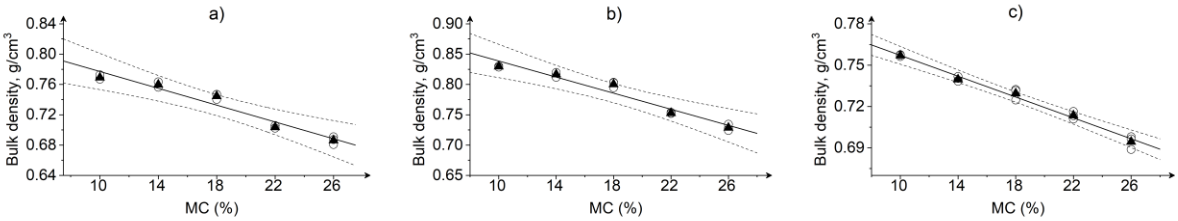
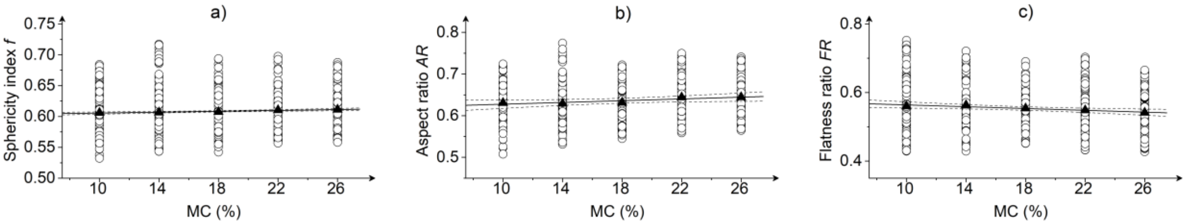


Fig. 5



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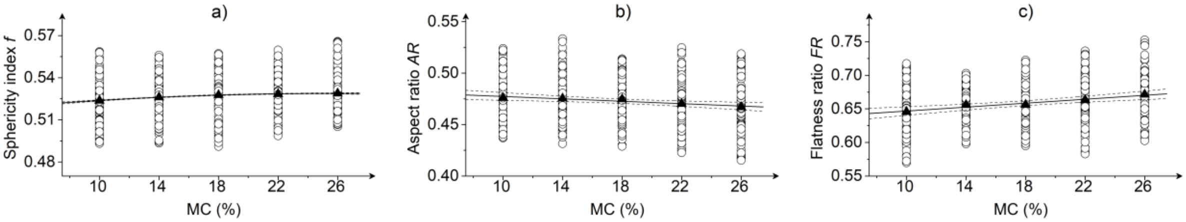

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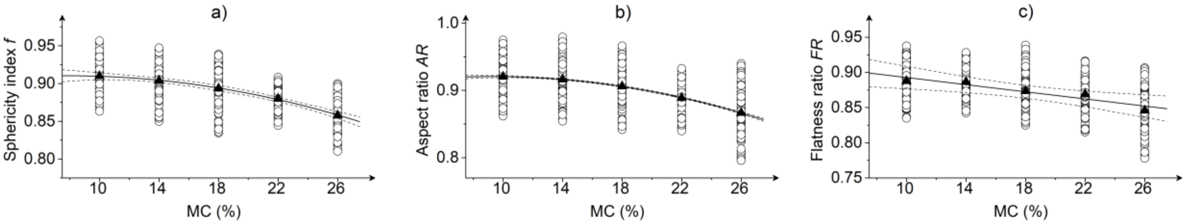

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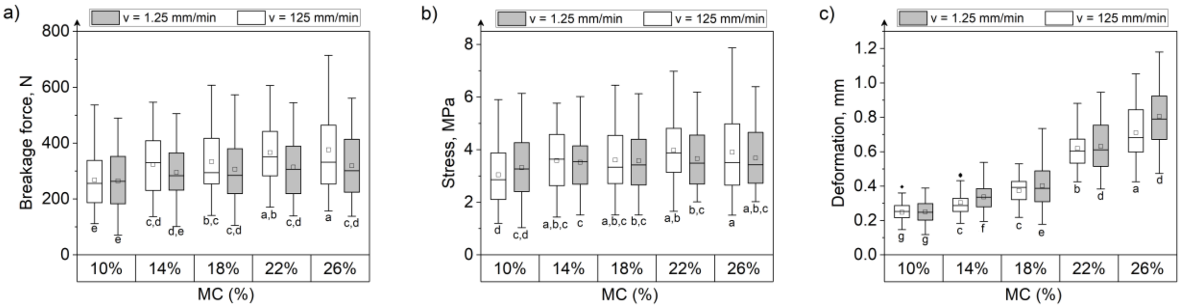


Fig. 9.

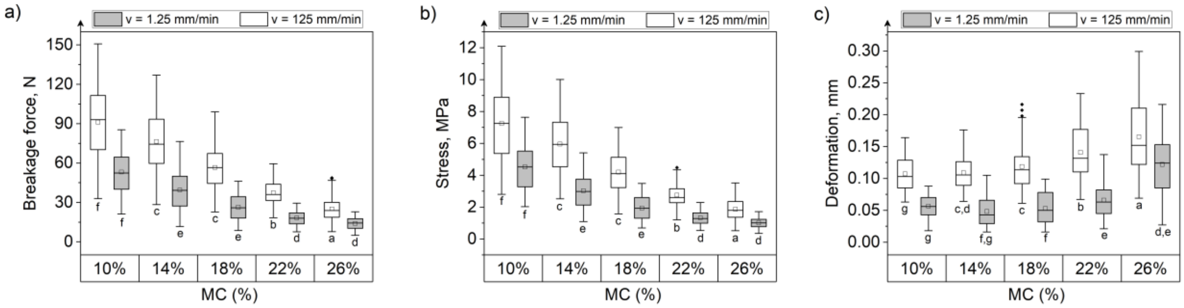


Fig. 10

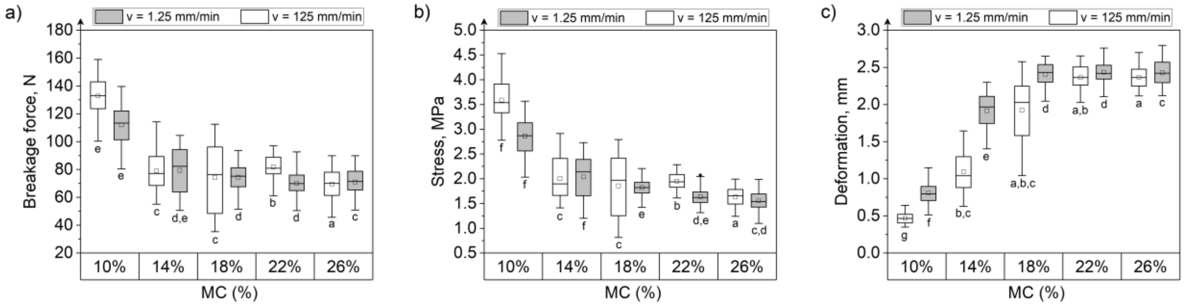
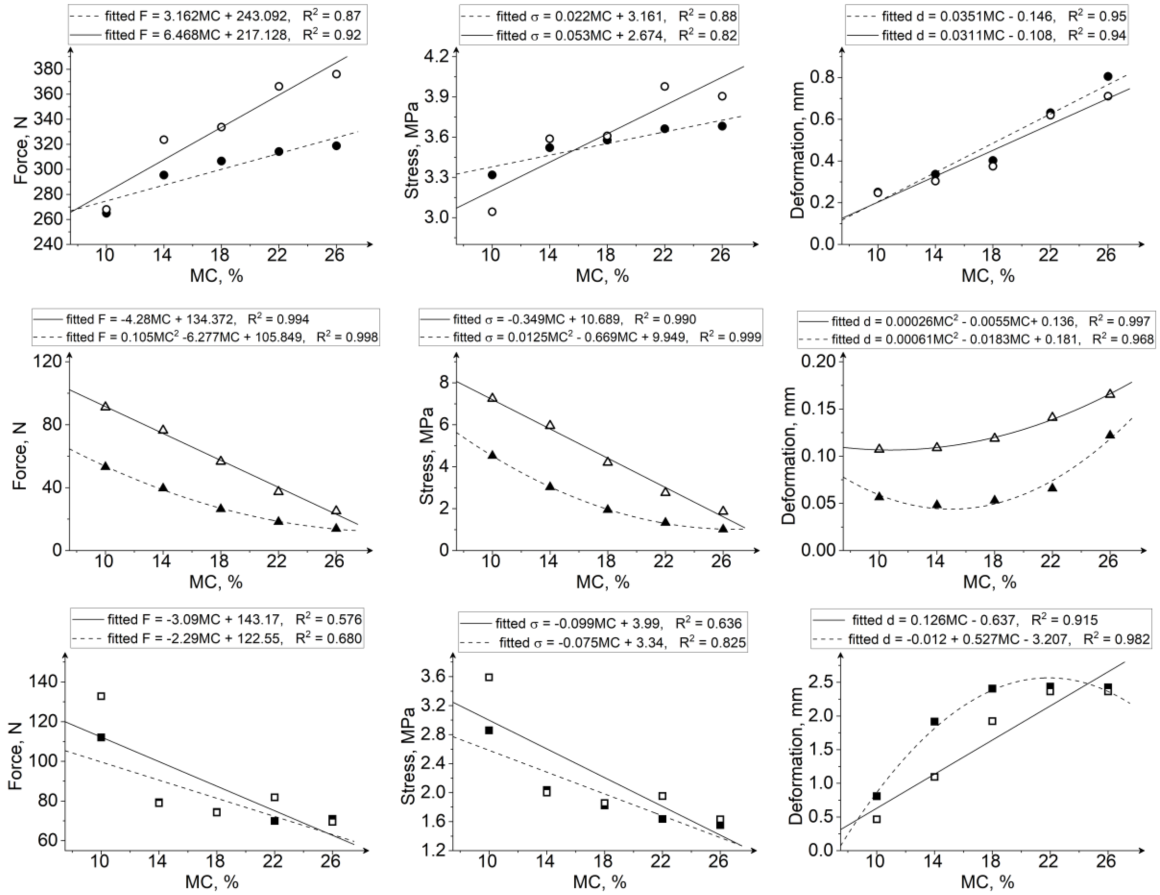


Fig. 11



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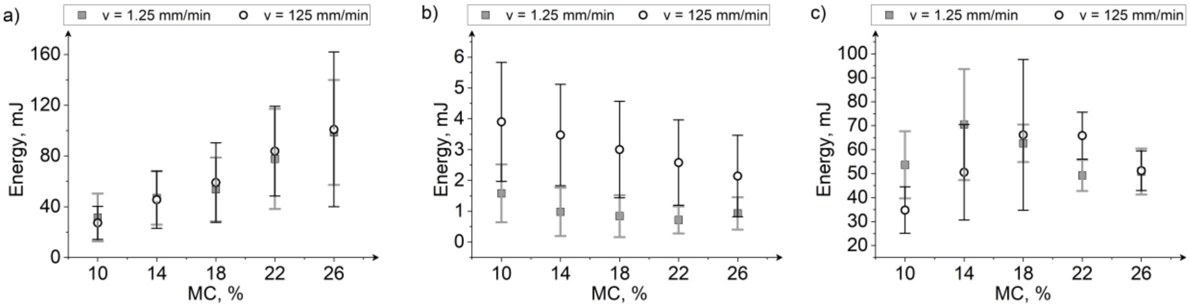
a)
v = 1.25 mm/min
v = 125 mm/min
Energy, mJ
0
40
80
120
160
10
14
18
22
26
MC, %
b)
v = 1.25 mm/min
v = 125 mm/min
Energy, mJ
0
1
2
3
4
5
6
10
14
18
22
26
MC, %
c)
v = 1.25 mm/min
v = 125 mm/min
Energy, mJ
20
30
40
50
60
70
80
90
100
10
14
18
22
26
MC, %

Fig. 13