Effects of moisture content, loading rate, and grain orientation on fracture resistance of barley grain

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Abstract: Force and deformation curves of agricultural materials must be provided for the proper design of harvesting and processing machineries. In this research, the fracture resistance of barley grain was measured in terms of the grain rupture force and energy. In this study, 8 treatments were performed as a randomised complete block design with 10 replications. The barley grains were quasi-statically loaded in horizontal and vertical orientations with the moisture content at four levels: 7.34, 12.11, 16.82, and 21.58% dry basis, and loading rates at two levels: 5 and 10 mm/min. Based on the results obtained, the force required for initiating the grain rupture decreased from 161.97 to 93.94 N, and from 75.37 to 50.16 N, and the energy absorbed at the grain rupture increased from 36.42 to 74.70 mJ and from 27.34 to 62.65 mJ, for horizontal and vertical orientations, respectively, with the increase in the moisture content from 7.34 to 21.58% dry basis. This showed that seeds are more flexible in the horizontal orientation.

Keywords: barley grain; mechanical properties; fracture resistance; grain processing

Barley (*Hordeum vulgare* L.) is an ancient and important cereal grain crop. It ranks fifth among all crops in the dry matter production in the world today. In Iran barley is also widely cultivated on approximately 1 817 572 ha with an annual production of 2.9×10^6 t (FAO 2007). It was one of the first agricultural domesticates together with wheat, pea (*Pisum sativum*), lentil (*Lens culinaris*), goats (*Capra aegagrrus hircus*), sheep (*Ovis aries*), and cattle (*Bos taurus*) dating from about 10 000 years ago in the Fertile Crescent of the Middle East (Smith 1998). Historically, barley has been an important food source in many parts of the world, including the Middle East, North Africa, and northern and eastern Europe (Iran, Morocco, Ethiopia, Finland, England, Denmark, Russia and Poland), and in Asia (Japan, India, Tibet, and Korea) (Newman & Newman 2006; Baik & Ullrich 2008). Due in part to the rise in prominence over wheat and rice, barley is mainly used as feed, malting, and brewing grain.

Physical properties of barley grains are essential for the design of the equipment for handling, harvesting, aeration, drying, storing, grinding, and processing. These properties are affected by numerous factors such as the form and moisture content of the grain. Moreover, the knowledge of fracture characteristics of grain is imperative for a rational design of efficient grinding systems, as well as the optimisation of the process and product parameters.

Prasad and Gupta (1973) studied the behaviour of paddy grains under quasi-static compressive loading. It was reported that the maximum compressive strength of paddy grains ranged from 40.6 to 160.7 N in the moisture content range of 12–24% dry basis. The values of maximum compressive strength of paddy grain decreased with increasing moisture content. The modulus of toughness varied from 3.96 to 30.87 mJ and was at maximum between the moisture contents of 14–16% dry basis. The deformation at rupture was maximum at a moisture content of 15% dry basis.

Recently, rheological properties of several grains have been reported in the literature. According to Waananen and Okos (1988), the failure stress of corn decreased, whereas the failure strain increased with an increase in the moisture content and temperature. The maximum compressive stress for wheat and canola decreased linearly with an increase in the moisture content (Bargale *et al.* 1995). The stress, strain, modulus of deformability, and energy to the yield point were found to be functions of the loading rate and moisture content for different varieties of wheat kernels (Kang *et al.* 1995). Some engineering properties of locust bean seed were investigated by Ogunjimi *et al.* (2002), who concluded that the seed orientation that gave the least resistance to cracking was along the thickness. The cracking force found in loading along the thickness lay between 154 and 204 N. Loading on the vertical axis gave the highest resistance to cracking. In their study, Işık and Ünal (2007) observed that the shelling resistance of white speckled red kidney bean grain decreased from 98.26 N to 53.67 N as the moisture content increased. Lately, a similar study was done by Altuntaş and Karadag (2006) in that the mechanical properties of sainfoin, grasspea, and bitter vetch seeds were determined in terms of the average rupture force, specific deformation and rupture energy along X-, Y- and Z-axes. The mean values of the rupture force, specific deformation, and rupture energy for sainfoin seed were 7.40, 9.72, and 4.56 N; 8.94%, 1.71%, and 9.97%; and 1.97, 0.46, and 0.71 N mm along X-, Y- and Z-axes, respectively. The mean values of the rupture force, specific deformation, and rupture energy for grasspea seed were 254.40, 42.60, and 100.80 N; 27.53%, 0.29%, and 14.03%; and 187.20, 29.25, and 38.77 N mm along X-, Y- and Z-axes, respectively. The mean values of the rupture force, specific deformation, and rupture energy for bitter vetch seed were 57.60, 45.00, 87.00 N; 7.60%, 1.62%, 1.93%; 10.14, 4.42, 0.86 N mm along X-, Y- and Z-axes, respectively. Saiedirad *et al.* (2008) studied the effects of the moisture content, seed size, loading rate, and seed orientation on the force and energy required for fracturing cumin seed under quasi-static loading. Their results showed that the force required for initiating the seed rupture decreased from 15.7 to 11.96 N and 58.2 to 28.8 N, and the energy absorbed at the seed rupture increased from 1.8 to 8.6 mJ and 7.6 to 14.6 mJ, with an increase in the moisture content from 5.7% to 15% dry basis for vertical and horizontal orientations, respectively. They determined the fracture resistance of cumin seed for the loading rates of 2 and 5 mm/min, and showed that both the rupture force and energy decreased as the loading rate increased.

The review of the literature showed that the effect of the moisture content, loading rate, and grain orientation on the fracture resistance of barley grain has not been determined. Therefore, the objective of this study was to determine the fracture behaviour of barley grain by examining the effects of the moisture content, loading rate and grain orientation on the rupture force and energy of the grain.

Figure 1. Barley grains

MATERIAL AND METHODS

The barley variety, Nosrat (Figure 1), used in this study, is one of the prevalent varieties in Iran, and was obtained from the Seed and Seedling Research Institute, Karaj, Iran. The samples were manually cleaned to remove foreign matter, dust, dirt, and broken and immature grains. The initial moisture content of the samples was determined by oven drying at 103 ± 1°C for 24 h (ASAE 2006). The initial moisture content of the grains was 7.34% dry basis.

The samples of the desired moisture contents were prepared by adding the amount of distilled water, Q, as calculated from the following relationship (Bulent Coşkun *et al.* 2006):

$$Q = \frac{W_i(M_f - M_i)}{100 - M_f} \quad (1)$$

where:

Q – mass of water added (kg)

W_i – initial mass of the sample (kg)

M_i – initial moisture content of the sample (dry basis %)

M_f – final moisture content of the sample (dry basis %)

The samples were then transferred to separate polyethylene bags and the bags were sealed tightly. The samples were kept at 5°C in a refrigerator for a week to enable the moisture to distribute uniformly throughout the sample. Before starting the test, the required quantities of the samples were taken out of the refrigerator and allowed to warm up to the room temperature for about 2 h. All the mechanical prop-

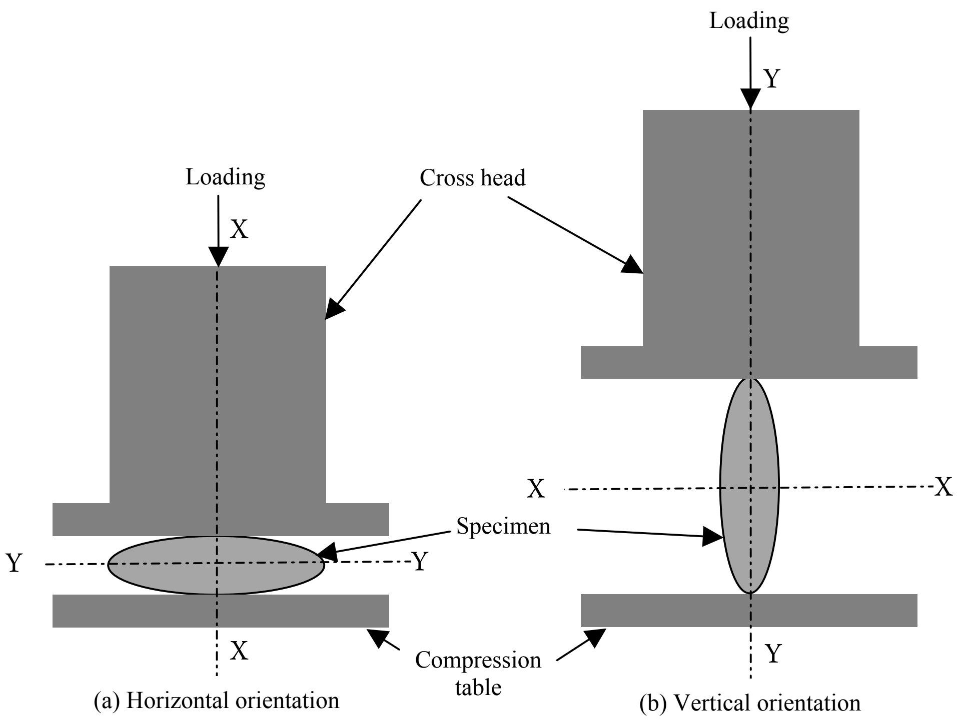

Figure 2. Orientations of barley grain under compressive loading

erties of the grains were assessed at the moisture levels of 7.34, 12.11, 16.82, and 21.58% dry basis.

The mechanical properties of barley grain were determined in terms of the average rupture force and energy at horizontal and vertical orientations (Figure 2) with the moisture contents of 7.34, 12.11, 16.82, and 21.58% dry basis. The experiments were also conducted at two loading rates of 5 and 10 mm per min. Quasi-static compression tests were performed using a proprietary tension/compression testing machine (Instron Universal Testing Machine/SMT-5, SANTAM Company, Tehran, Iran). For each treatment, ten grains were randomly selected and the average values of all the 10 tests were reported. The individual grains were loaded between two parallel plates of the machine and compressed under the preset conditions until rupture occurred as denoted by a bio-yield point in the force-deformation curve. The bio-yield point was detected by a break in the force-deformation curve. Once the bio-yield point was detected, the loading was stopped. To determine the effect of the loading orientation, the grains were loaded in two orientations, horizontal and vertical (Figure 2). For the horizontal loading (Figure 2a), the major axis and the crease of the grain were normal to the direction of loading, while for vertical loading (Figure 2b), the major axis of the grain was parallel to the direction of loading. The deformation (strain) was taken as the change in the original dimension of the grain. Note that the load cell deflection under load was found to be negligible for the loads used in this study. The energy required for causing rupture (failure) in the grain was determined by calculating the area under the force-deformation curve up to the grain rupture. The latter procedure was done by the utilisation of the computing software installed on the apparatus used. An example of the force versus deformation curves is shown in Figure 3.

This study was planned as a completely randomised block design. Experimental data were analysed using analysis of variance (ANOVA) and the means were separated at the 5% probability level applying Duncan's multiple range tests in SPSS 15 software.

RESULTS AND DISCUSSION

The variance analysis of the data indicated that the moisture content, loading rate, and grain orientation exerted a significant effect on the rupture energy and force ($P < 0.01$). The average force to rupture the grain was obtained as 97.62 N varying from 47.21 to 172.39 N, while the average rupture energy of the grain was calculated as 50.73 mJ ranging from 25.58 to 78.24 mJ. Based on the statistical analyses, the interaction effect of the moisture content × grain orientation on the rupture force was significant at 1% level, while the effect on the rupture energy was not significant ($P > 0.05$). The interaction effect of the moisture content × loading rate on the rupture force was significant at 5% level, while the effect on the rupture energy was not significant ($P > 0.05$). The interaction effects of the grain orientation ×

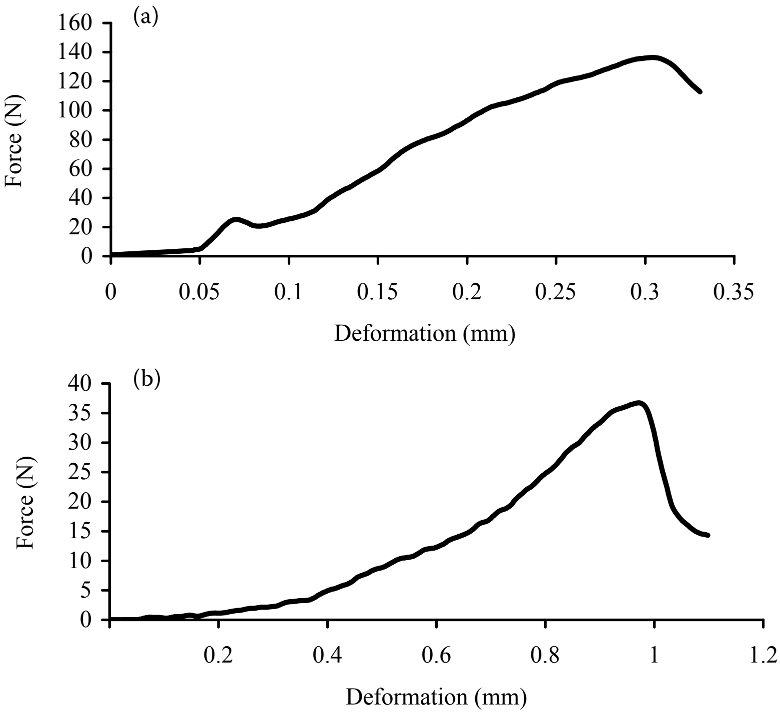

Figure 3. The force versus displacement curve for barley grain in (a) horizontal and (b) vertical orientations

loading rate and moisture content × loading rate × grain orientation on the rupture force and energy were not significant ($P > 0.05$).

In the following paragraphs, the effects of each factor on the rupture energy and force are comprehensively discussed.

Moisture content

The force required for initiating the grain rupture at different moisture contents and grain orientations is shown in Figure 4a. The rupture force decreased with an increase in the grain moisture content. As given in Table 1, the rupture force decreased from 118.67 to 72.05 N as the moisture content increased ($P < 0.01$). This may be due to the fact that at a higher moisture content the grain became softer and required less force. This conclusion is consistent with the findings of Konak *et al.* (2002), who reported that the highest rupture force of chick pea seeds was obtained as 210 N with a moisture content of 5.2% dry basis. It was also stated that the seeds be-

Table 1. Mean comparison of rupture force and energy of barley grains at different moisture contents, loading rates and grain orientations

	Rupture force (N)	Rupture energy (mJ)
Moisture content (% dry basis)		
7.34	118.673[a]*	31.882[a]
12.11	107.419[b]	42.323[b]
16.82	92.356[c]	60.037[c]
21.58	72.051[d]	68.675[d]
Loading rate (mm/min)		
5	104.289[a]	54.387[a]
10	90.961[b]	47.071[b]
Grain orientation		
Horizontal	132.840[a]	56.509[a]
Vertical	62.410[b]	44.950[b]

*the means with minimum common letter are not significantly different ($P > 0.05$) according to Duncan's multiple ranges test

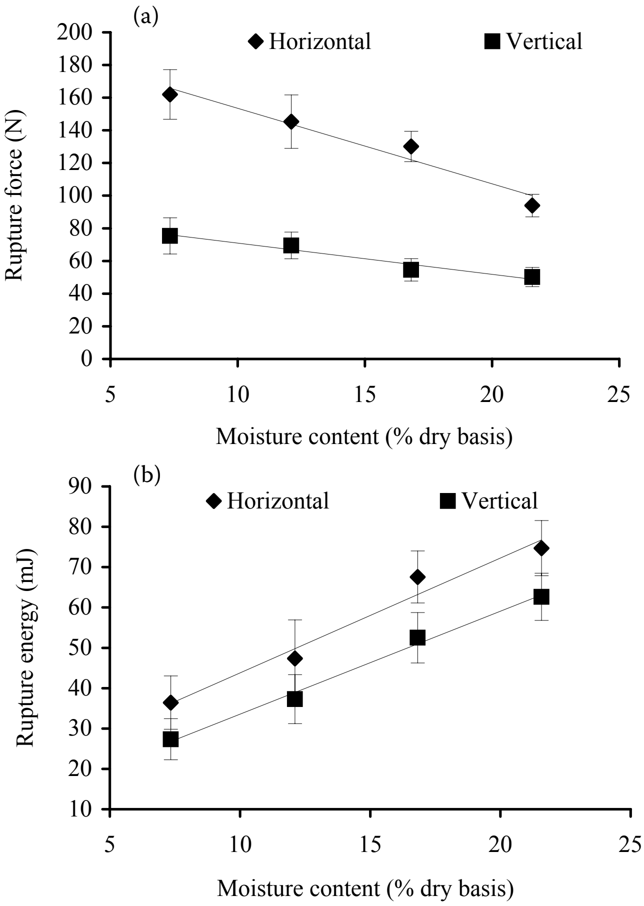

Figure 4. Interaction effect of moisture content and grain orientation on (a) force and (b) energy required to initiate grain rupture

came more sensitive to cracking at a higher moisture content; hence, they required less force to rupture. Altuntaş and Yildiz (2007) conducted a study on the effects of the moisture content on some physical and mechanical properties of faba bean (*Vicia faba* L.) grains and reported that, as the moisture content increased from 9.89% to 25.08%, the rupture force values ranged from 314.17 to 185.10 N; from 242.2 to 205.56 N; and from 551.43 to 548.75 N for X-, Y-, and Z-axes, respectively. There are conflicting reports on the effect of the moisture content on the rupture force. Paulsen (1978), Hoki and Tomita (1976) and Liu *et al.* (1990) reported a decrease in the rupture force values for soybean with an elevation in the moisture content, which is true for the present work, too. Similar decreasing trend was reported by Saiedirad *et al.* (2008) for cumin seed. On the other hand, the compressive strength for snap bean (*Phaseohs vulguris* L.) was reported to increase with the elevation in the moisture content (Bay *et al.* 1996).

The energy absorbed for initiating the grain rupture at different moisture contents and grain orientations

Table 2. Mean comparison of rupture force and energy of barley grains considering interaction effect of moisture content and grain orientation

Moisture content (% dry basis)	Grain orientation			
	rupture force (N)		rupture energy (mJ)	
	horizontal	vertical	horizontal	vertical
7.34	161.973[a]*	75.373[e]	36.422[e]	27.342[f]
12.11	145.315[b]	69.523[e]	47.349[d]	37.297[e]
16.82	130.130[c]	54.581[f]	67.565[b]	52.509[c]
21.58	93.941[d]	50.161[f]	74.698[a]	62.651[b]

*the means with minimum common letter are not significantly different ($P > 0.05$) according to Duncan's multiple ranges test

Table 3. Mean comparison of rupture force and energy of barley grains considering interaction effect of moisture content and loading rate

Moisture content (% dry basis)	Loading rate			
	rupture force (N)		rupture energy (mJ)	
	5 mm/min	10 mm/min	5 mm/min	10 mm/min
7.34	128.040[a]*	109.306[c]	34.372[ef]	29.392[f]
12.11	116.495[b]	98.343[d]	47.425[d]	37.221[e]
16.82	96.957[d]	87.754[e]	63.546[b]	56.528[c]
21.58	75.663[f]	68.439[g]	72.206[a]	65.143[b]

*the means with minimum common letter are not significantly different ($P > 0.05$) according to Duncan's multiple ranges test

is shown in Figure 4b. The energy absorbed at the grain rupture increased from 31.88 to 68.67 mJ with the increasing moisture content from 7.34 to 21.58% dray basis (Table 1). The energy absorbed at the grain rupture was a function of both force and deformation up to the rupture point. At a low moisture content, the grain required high force to be ruptured and its deformation was low, but at a high moisture content the rupture force was low and the deformation was high. This fact showed that the energy absorbed at the grain rupture increases as the moisture content of the grain increases indicating a high resistance to the grain rupture during compressive loading. The latter result has been documented by Khazaei (2002), who investigated the energy absorbed in the pea rupture under quasi-statistically loading and reported that, with an increase in the seed moisture content, the energy absorbed increases significantly. A similar result was reported by Saiedirad *et al.* (2008) for cumin seed. This attribute caused the broken grain percentage to be reduced during dynamic loading (Kirk & McLeod 1967).

The interaction effects of the moisture content × grain orientation and moisture content × loading rate on the rupture force and energy are presented in Tables 2 and 3, respectively.

Grain orientation

Considering the values presented in Tables 1 and 2 and Figure 4, the grains were more flexible in the horizontal loading direction, thus the rupture under vertical loading direction requires less energy than that under horizontal loading. This is possibly due to the fact that under vertical loading the smaller contact area of the grain with the compressing plates results in the expansion of high stress in the barley grain. The values obtained of the rupture force and energy in the horizontal orientation were statistically more significant ($P < 0.01$) than those of the vertical orientation as shown in Figure 4. In a study conducted by Singh and Goswami (1998), maximum energy absorbed by cumin grain was found to be 14.8 and 20.4 mJ at the moisture content of 7% dry basis, in the horizontal and vertical orientations, respectively. Considering the interaction effect of the moisture content and grain orientation, the highest difference in the grain rupture force under two various loading directions was attributable to 7.34% moisture (Figure 4a). The effect of the moisture content and loading orientation on the rupture force and rupture deformation of safflower hull was studied by Baumler *et al.* (2006), who reported that no important difference in the rupture force between both seed orientations was measured. They suggested that the force required for the hull rupture decreased as the moisture content increased, attaining a minimum value of around 11% (dry basis), followed by an increasing trend with a further increase in the moisture content. Paulsen (1978) for soybeans seed coat and Gupta and Das (2000) for sunflower hull reported a decrease in the rupture force as the moisture content increased. Teotia *et al.* (1989) studied the force required to cause deformation and subsequent rupture in pumpkin seed. It was reported that the hull breaking load varied from 30 to 50 N for dry seeds and from 14 to 36 N for wet seeds, following quasi-static compression with horizontal and vertical orientations of the seed.

Loading rate

The effect of the loading rate on the rupture force and energy was determined for the loading rate of 5 and 10 mm/min. Both the rupture force and energy decreased as the loading rate increased (Table 1). The investigation of the interaction effect of the moisture content and loading rate showed that the values of the rupture force varied from 75.66 to 128.04 N and

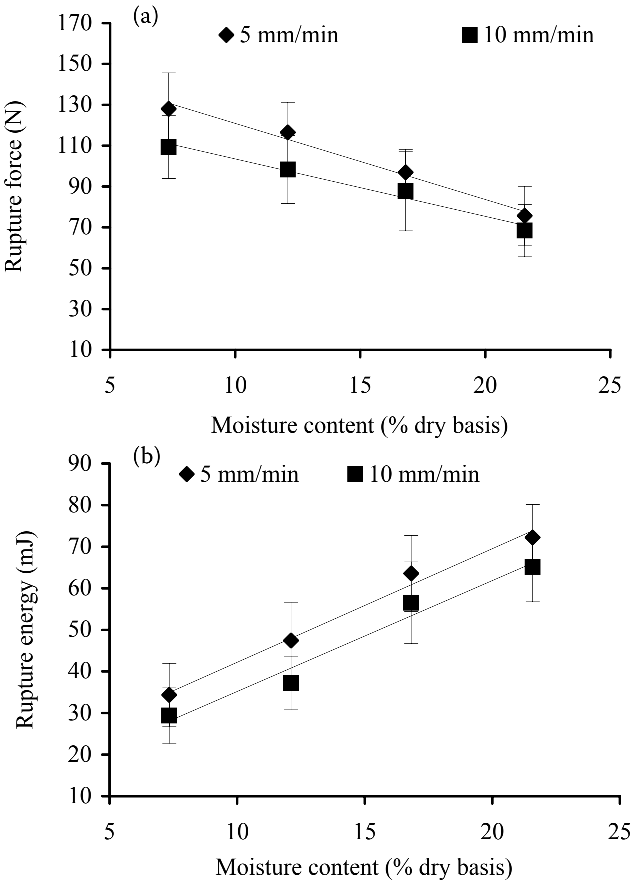

Figure 5. Effects of moisture content and loading rate on (a) rupture force and (b) energy

from 68.44 to 109.31 N, and the energy absorbed at the grain rupture increased from 34.37 to 72.21 mJ and 29.39 to 65.14 mJ, for the loading rates of 5 and 10 mm/min, respectively, as the moisture content increased (Figure 5). Mohsenin *et al.* (1963) found that the rate of deformation affected the maximum force that could be exerted by a steel plunger on apples. As the rate of deformation increased, the maximum force of rupture increased. Zoerb (1967) reported that most agricultural materials are elastic during the first part of the load-deformation curve, but acquire viscoelastic properties with increased loading. Thus, once the elastic region is extended, the properties are time-dependent and the effect of the loading rate becomes more noticeable. Based on the reports of Singh and Goswami (1998) for the case of cumin seed, the force required to initiate the seed rupture decreased from 50 to 40 N and 31 to 20.3 N with an increase in the moisture content from 7% to 13% dry basis, for the horizontal and vertical orientations, respectively.

CONCLUSIONS

Grains at 7.34% moisture under horizontal loading at the rate of 5 mm/min were able to withstand a higher value of force amounting to 172.39 N while grains at 21.58% moisture under vertical loading at the rate of 10 mm/min were found to be able to withstand a lower value of force, i.e. 47.21 N.

The highest energy absorbed at the grain rupture was calculated as 78.24 mJ at 21.58% moisture content and under horizontal loading at the rate of 5 mm/min, and the lowest one, namely 25.58 mJ, was found at 7.34% moisture content under vertical grain orientations at the loading rate of 10 mm per min.

The mechanical strength and deformation capability of the barley grain decreased and increased, respectively, as the moisture content increased according to the hypothesis that the energy absorption capability of wet grains compared to dry ones is higher, leading to higher mechanical strength to rupture during compressive loading.

The barley grains are more flexible in the horizontal loading direction, thus the rupture under vertical loading demands less energy than under horizontal loading. This is due to the decreasing contact area of grain with the loading plate and probably the occurrence of the buckling phenomenon.

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Received for publication March 8, 2009
Accepted after corrections May 13, 2009

Abstrakt

H. Tavakoli, S.S. Mohtasebi, A. Rajabipour, M. Tavakoli (2009): **Vliv obsahu vlhkosti, zátěžové rychlosti a orientace zrna na odolnost zrna proti zlomu**. Res. Agr. Eng., **55**: 85–93.

Vhodná konstrukce sklizňových a zpracovatelských strojních zařízení vyžaduje znalost silových a deformačních křivek zemědělských materiálů. Ve studii byla sledována odolnost ječného zrna z hlediska síly a energie při zlomu. Bylo provedeno 8 sledování v randomizovaném kompletním bloku s deseti opakováními. Ječná zrna orientovaná horizontálně nebo vertikálně byla zatěžována quasi-staticky při čtyřech hladinách vlhkosti: 7,34, 12,11, 16,82 a 21,58 % a při dvou zátěžových rychlostech: 5 a 10 mm/min. Bylo zjištěno, že při zvýšení obsahu vlhkosti ze 7,34 % na 21,58 % se síla nutná k vyvolání zlomu snížila ze 161,97 N na 93,94 N při horizontální orientaci a ze 75,37 N na 50,16 N při vertikální orientaci, zatímco energie absorbovaná při zlomu se zvýšila ze 36,42 mJ na 74,70 mJ při horizontální orientaci a ze 27,34 mJ na 62,65 mJ při vertikální orientaci. To prokazuje větší ohebnost zrn při horizontální orientaci.

Klíčová slova: ječné zrno; mechanické vlastnosti; odolnost proti zlomu; zpracování zrna

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