

Fracture resistance of wheat grain as a function of moisture content, loading rate and grain orientation

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Abstract

In this research, fracture resistance of wheat grain was measured in terms of grain rupture force and energy. The wheat grains were quasi-statically loaded in horizontal and vertical orientations with moisture content in three levels: 7.8%, 15%, and 20%; and loading rate in two levels: 5 and 10 mm min⁻¹. Based on the results obtained, the force required for initiating grain rupture decreased from 77.68 to 35.7 N and 152.11 to 63.99 N, and the energy absorbed at grain rupture increased from 17.8 to 24.34 mJ and 19.32 to 28.35 mJ, with increase in moisture content from 7.8 to 20% d.b., for vertical and horizontal orientations, respectively. This showed that grains are more flexible in horizontal orientation. Rupture force requires less energy under vertical loading than horizontal loading. Maximum energy absorbed was found to be 32.40 mJ for grain with 20% moisture content under horizontal loading and 5 (mm min⁻¹) loading rate. The highest mechanical strength (162.61 N) is related to grain with a moisture content of 7.8% under horizontal loading and 5 (mm min⁻¹) loading rate. Energy absorbed by the seeds decreased as increased loading rate.

Keywords: Wheat grain; Fracture resistance; Grain processing; Loading rate

Abbreviation: M_{i-} initial moisture content of the sample (d.b.%); M_{f-} final moisture content of the sample (d.b.%); Q_{-} mass of water added (Kg); W_{i-} initial mass of the sample (kg).

Introduction

Based on FAO information, wheat is the second most produced food among the cereal crops in the world. In Iran, wheat is widely cultivated on approximately 6.9 million hectares with an annual production of 14×10^6 ton (FAO, 2007). Physical properties of wheat grains are essential for design of equipment for handling, harvesting, aeration, drying, storing, grinding and processing (Tabatabaefar, 2003). These properties are affected by numerous factors such as size, form, and moisture content of the grain. Moreover, the knowledge of fracture characteristics of the grain is imperative for a rational design of efficient grinding systems, as well as the optimization of the process and product parameters. Recently, mechanical properties of several grains have been reported. 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 obtained in loading along the thickness lay between 154 and 204 N. Loading on the vertical axis gave the highest resistance to cracking. Altuntaş and Karadag (2006) determined the mechanical properties of sainfoin, grasspea, and bitter vetch seeds in terms of average rupture force, specific deformation and rupture energy along X-, Y- and Z-axes. The mean values of 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 for along X-, Y- and Z-axes, respectively. The mean values of 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 for along X-, Y- and Z-axes, respectively. The mean values of

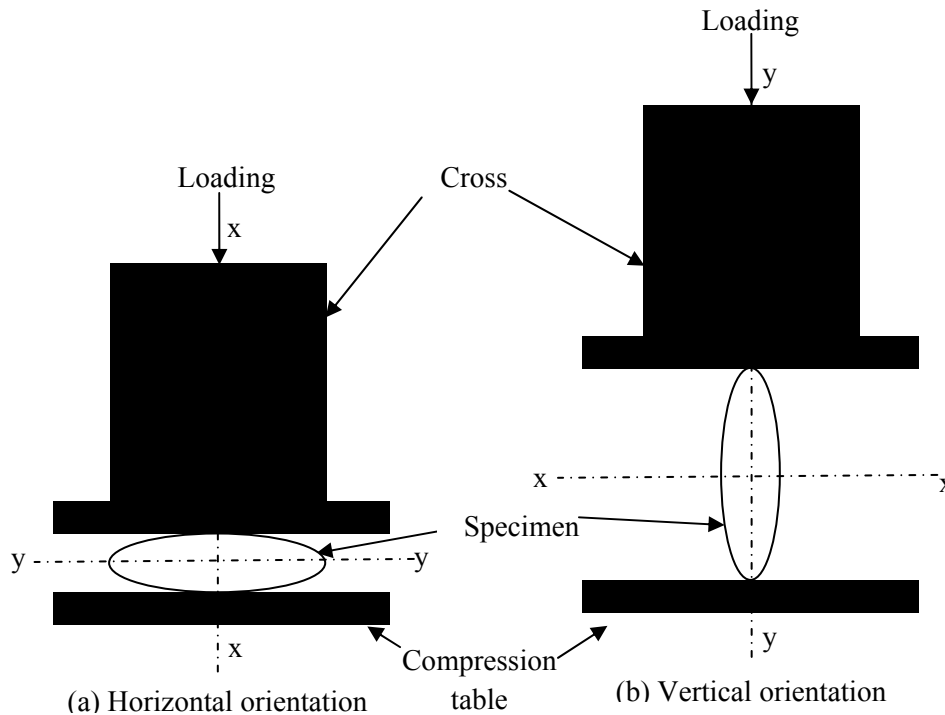
rupture force, specific deformation and rupture energy for bitter vetch seed were 57.60, 45.00, 87.00 N; 7.60%, 1.62%, 1.93%; 10.14, 4.42, 0.86 N mm for along X-, Y- and Z-axes, respectively. In a study, Işık and Ünal (2007) observed that the shelling resistance of white speckled red kidney bean grain decreased as the moisture content increased from 98.26 to 53.67 N. Saiedirad et al. (2008) studied Effects of moisture content, seed size, loading rate and seed orientation on force and energy required for fracturing cumin seed under quasi-static loading. Their results showed that the force required for initiating seed rupture decreased from 15.7 to 11.96 N and 58.2 to 28.8 N, and the energy absorbed at seed rupture increased from 1.8 to 8.6 mJ and 7.6 to 14.6 mJ, with increase in moisture content from 5.7% to 15% d.b., for vertical and horizontal orientations, respectively. They determined the fracture resistance of the cumin seed for loading rates of 2 and 5 mm min⁻¹, and showed that both rupture force and energy decreased as loading rate increased. Fathollahzadeh and Rajabipour (2008) found that the rupture force and toughness of barberry decreased from 47.238 to 19.669 (N) and 1.149 to 0.105 (J cm⁻³), respectively, as moisture content increased from 53.11 to 89.23% w.b.

Limited research has been conducted on the mechanical properties and fracture resistance of wheat grains. Bargale et al. (1995) reported that the maximum compressive stress for wheat decreased linearly with an increase in moisture content. Furthermore, the stress, strain, modulus of deformability and energy to yield point were found to be a function of loading rate and moisture content for different varieties of wheat kernels (Kang et al., 1995). The objective of this study was to determine fracture behavior of wheat grain by

Table 1. Analysis of the variance of parameters considered on rupture force and energy of wheat grain

Variation source	DF	Rupture force (N)	Rupture energy (mJ)
Treatment	14	9708.52 ^b	144.60 ^b
Moisture content	2	40825.07 ^b	505.25 ^b
Loading rate	1	7179.18 ^b	673.98 ^b
Grain orientation	1	33822.57 ^b	156.03 ^{ns}
Moisture content × Loading rate	2	72.68 ^{ns}	21.10 ^{ns}
Moisture content × Grain orientation	2	5645.61 ^a	10.32 ^{ns}
Loading rate × Grain orientation	1	897.62 ^a	62.22 ^{ns}
Moisture content × Loading rate × Grain orientation	5	186.71 ^{ns}	11.77 ^{ns}
Error	75	162.48	42.40

ns: Corresponding to no significant difference, ^a Corresponding to confidence of interval, 95%, ^b Corresponding to confidence of interval, 99%

**Fig 1.** Orientations of wheat grain under compressive loading.

examining the effect of moisture content, loading rate and grain orientation on rupture force and energy of the grain.

Materials and methods

The wheat grains (cv. *Shiroody*) used for the present study were from one of the prevalent varieties of wheat in Iran and were obtained from the Seed and Seedling Research Institute, Karaj, Iran. The samples were manually cleaned to remove foreign matter, dust, dirt, 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 7.8% d.b.

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 is the mass of water added, kg, W_i is the initial mass of the sample in kg, M_i is the initial moisture content of the

sample in d.b.% and M_f is the final moisture content of the sample in d.b.%.

The samples were then transferred to separate plastic bags and the bags sealed tightly. The samples were kept at 5 °C in a refrigerator for a week to enable the moisture to be distributed uniformly throughout the sample. Before starting a 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 properties of the grains were assessed at moisture levels of 7.8, 15, and 20% d.b. The mechanical properties of wheat grain were determined in terms of average rupture force and energy at horizontal and vertical orientations (Fig. 1) with moisture contents of 7.8, 15, and 20% d.b. The experiments were also conducted at two loading rates of 5 and 10 mm min⁻¹. 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 grain was loaded between two parallel plates of the machine and compressed at the preset condition until rupture occurred as is denoted by a bio-yield point in the force–

Table 2. Mean comparison of rupture force and energy of wheat grain in different moisture contents, loading rates and grain orientations

Moisture content (%)	Rupture force (N)	Rupture energy (mJ)
7.8%	127.303 ^{a*}	18.812 ^a
15%	80.255 ^b	22.887 ^b
20%	54.561 ^c	27.019 ^c
Loading rate (mm min ⁻¹)		
5	96.304 ^a	25.643 ^a
10	78.442 ^b	20.170 ^b
Grain orientation		
Horizontal	101.081 ^a	23.837 ^a
Vertical	59.957 ^b	21.044 ^a

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

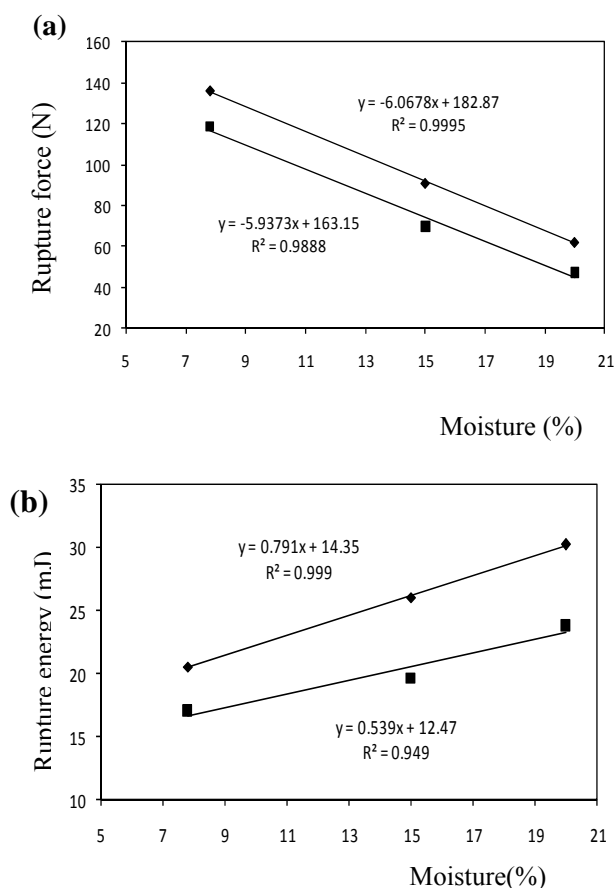


Fig 2. Effect of moisture content and loading rate on a: rupture force and b: rupture energy of wheat grain; (♦) 5 mm min⁻¹; (■) 10 mm min⁻¹.

deformation curve. The bio-yield point was detected by a break in the force–deformation curve. Once the bio-yield was detected, the loading was stopped. To determine the effect of the orientation of loading, the grain was positioned horizontally (Fig. 1a), with the major axis of the grain being normal to the direction of loading, or lengthwise. For vertical loading (Fig. 1b), 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 load cell deflection under load was found to be negligible for

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 grain rupture. The latter procedure was done by the utilization of computing software installed on the apparatus used.

This study was planned as a completely randomized 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 software (vers. 13, SPSS, Inc., Chicago, IL, USA).

Results and Discussion

Based on variance analysis of data, as shown in Table 1, moisture content and loading rate created a significant effect on rupture force and energy ($P<0.01$). Grain orientation also had a significant effect on rupture force ($P<0.01$) but did not have significant effect on rupture energy ($P>0.05$). The average force to rupture the grain was obtained as 87.37 N varying from 30.48 to 162.60 N, while the average rupture energy of the grain was calculated as 22.90 mJ ranging from 16.87 to 32.40 mJ. According to Table 1, interaction effects of loading rate \times grain orientation and moisture content \times grain orientation were significant at 5% level on rupture force but the effects were not significant on rupture energy ($P>0.05$). Based on the statistical analyses, the effects of moisture content \times loading rate and moisture content \times loading rate \times grain orientation were not significant on rupture force and energy of the wheat grain. In the following paragraphs, the effects of each factor on the rupture force and energy are comprehensively discussed. The force required for initiating grain rupture at different moisture contents is presented in Table 2. It is observed that the rupture force decreased with an increase in moisture content. This may be due to the fact that at higher moisture content, the grain becomes softer and requires less force. This conclusion was consistent with the findings of Konak et al. (2002), who reported the highest rupture force of chick pea seeds was obtained as 210 N with a moisture content of 5.2% d.b. It was also stated that the seeds became more sensitive to cracking at higher moisture contents; hence, they required less force to rupture. Altuntaş and Yildiz (2007) conducted a research to study the effect of moisture content on some physical and mechanical properties of faba bean grains (*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; 242.2 to 205.56 N and 551.43 to 548.75 N for X-, Y-, and Z-axes, respectively. Saiedirad et al. (2008) reported that as the moisture content increased from 5.7% to 15%, the rupture force decreased from 36.977 to 20.358 N. Energy absorbed at grain rupture increased from 18.81 to 27.01 mJ with an increase in moisture content from 7.8 to 20% d.b. (Table 2). Energy absorbed at grain rupture was a function of both force and deformation up to rupture point. At low moisture content, the grain requires high force to be ruptured and its deformation was low but at high moisture content, the rupture force was low and the deformation was high. This fact showed that energy absorbed at grain rupture increases as the moisture content of the grain increases indicating high resistance to grain rupture during compressive loading. The latter result has been documented by Khazaei (2002), who investigated energy absorbed in pea rupture under quasi-statistically loading and reported that with an increase in seed moisture content, the energy absorbed increases significantly. The interaction effects of moisture content \times loading rate and moisture content \times grain orientation on the rupture force and energy of the wheat

Table 3. Mean comparison of rupture force and energy of wheat grain considering interaction effect among moisture content, loading rate and grain orientation

Moisture content (%)	Seed orientation							
	Rupture force (N)				Rupture energy (mJ)			
	Horizontal		Vertical		Horizontal		Vertical	
Loading rate (mm min ⁻¹)	5	10	5	10	5	10	5	10
7.8%	162.61 ^{a*}	139.70 ^b	82.63 ^{cde}	74.45 ^{def}	21.76 ^{ab}	16.97 ^b	18.21 ^b	16.19 ^b
15%	101.43 ^c	70.90 ^{def}	69.73 ^{def}	63.27 ^{ef}	27.31 ^{ab}	20.13 ^{ab}	23.64 ^{ab}	18.35 ^b
20%	72.70 ^{def}	55.30 ^{fg}	40.90 ^{gh}	30.48 ^h	32.40 ^a	24.31 ^{ab}	25.96 ^{ab}	22.72 ^{ab}

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

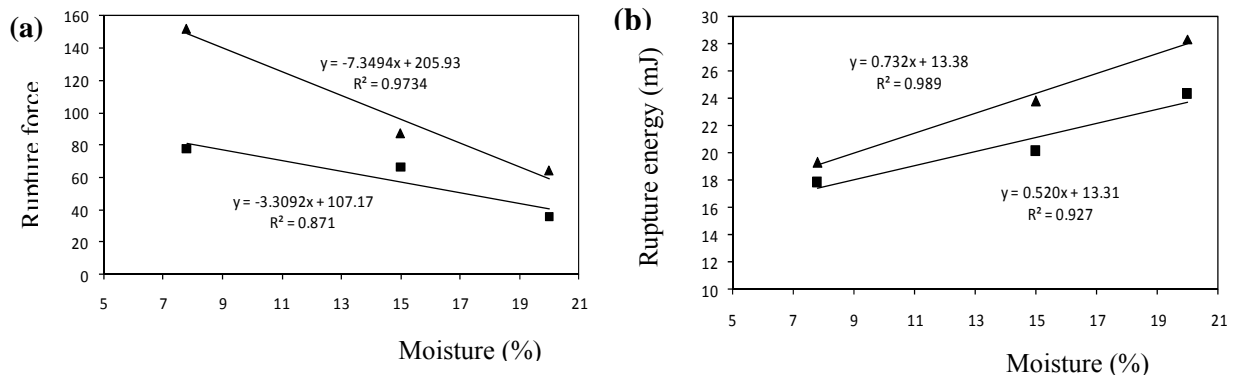


Fig 3. Effect of moisture content and grain orientation on a: rupture force and b: rupture energy of wheat grain; (▲) horizontal; (■) vertical.

grains are shown in Fig. 2 and 3, respectively. Considering the values presented in Table 2 and Fig. 3, the grains were more flexible in the horizontal loading direction, and 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, smaller contact area of the grain with the compressing plates results in the expansion of high stress in the wheat grain. Effect of moisture content and orientation of loading on rupture force and rupture deformation of safflower hull was studied by Baumler et al. (2006), who reported that no important difference in rupture force between both seed orientations was measured. They suggested the force required for the hull rupture decreases as the moisture content increased, and it attained a minimum value at around 11% (d.b.), followed by an increasing trend with further increase in moisture content. Gupta and Das (2000) reported a decrease in rupture force of sunflower hull, with an increase in moisture content. The effect of loading rate on rupture force and energy was determined for loading rate of 5 and 10 mm min⁻¹. Both rupture force and energy decreased as loading rate increased (Table 2). 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. The highest energy absorbed at grain rupture was as much as 32.40 mJ belonging to 5 mm min⁻¹ loading rate at 20% moisture under horizontal loading and the lowest one was determined as 16.19 mJ associated with 10 mm min⁻¹ loading rate at 7.8% moisture under vertical loading direction (Table 3). Similar results of effect of loading rate on rupture force and energy were reported by Saiedirad et al. (2008).

Conclusions

In this study, the effects of moisture content, loading rate and grain orientation on the rupture force and energy of wheat grain were investigated.

1. Mechanical strength and deformation capability of the wheat grain decreased and increased, respectively, as the moisture content increased according to the hypothesis that energy absorption capability of wet grains compared to dry ones is higher, leading to higher mechanical strength to rupture during compressive loading.
2. The wheat grains are more flexible in the horizontal loading direction and the rupture under vertical loading demanding less energy than under horizontal loading. This is due to decreasing contact area of seed with loading plate and probably the occurring buckling phenomenon.
3. The rupture force and energy of the grains decreased with an increase in loading rate.
4. The highest energy absorbed at grain rupture was calculated as 32.40 mJ concerned with 5 mm min⁻¹ loading rate at 20% moisture content under horizontal loading and the lowest one, namely 16.19 mJ was attributed to 10 mm min⁻¹ loading rate at 7.8% moisture under vertical grain orientation.

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