Australian Journal of Agricultural Engineering
AJAE
AJAE 2(5):132-139 (2011) ISSN:1836-9448

Comparison of mechanical and thermal properties between two varieties of barley (*Hordeum vulgare* L.) grains

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Abstract

In this research, the effect of moisture content and grain orientation on the mechanical properties of two barley grain varieties is investigated. For this purpose, the barley grains were quasi-statically loaded in horizontal and vertical orientations with moisture content in four levels ranging from 7.3 to 21.6% d.b. and 6.7 to 21.2% d.b. for Nosrat and Kavir varieties, respectively, and loading rate of 10 mm min^{-1}. Some thermal properties of the grains were also determined at moisture content of 7.3 and 6.7% d.b. for Nosrat and Kavir varieties, respectively, and at temperature of 25°C. For both varieties, with increasing moisture content the rupture force decreased while the rupture energy increased. Furthermore, for both varieties the rupture force and energy of the grain were higher under horizontal loading direction than under vertical loading. The rupture force of Nosrat variety was greater than that of Kavir variety, while in the case of the rupture energy, it was vice versa. This means higher flexibility and resistance of Kavir variety during compressive loading. There were no significant differences between the varieties in the thermal properties.

Keywords: barley, grain processing, rupture force, thermal conductivity.

Abbreviations:

c_c	specific heat of calorimeter, J kg^{-1} K^{-1}
c_s	specific heat of sample, J kg^{-1} K^{-1}
c_w	specific heat of water, J kg^{-1} K^{-1}
D	thermal diffusivity, m^2 s^{-1}
k	thermal conductivity, W m^{-1} K^{-1}
m_c	mass of calorimeter, kg
M_f	final desired moisture content of sample, % d.b.
M_i	initial moisture content of sample, % d.b.
m_s	mass of sample, kg
m_w	mass of water, kg
Q	mass of water added to sample, kg
R^2	determination coefficient
T_e	equilibrium temperature, K
T_{si}	Initial temperature of sample, K
T_{wi}	Initial temperature of water, K
W_i	Initial mass of sample, kg
ρ_b	bulk density, kg m^{-3}

Introduction

Barley (*Hordeum vulgare* L.) is an ancient and important cereal grain crop in the world. It is of the genus, *Hordeum*, which is a cereal from the grass family, Poaceae. In Iran, barley is widely cultivated on approximately 1,675,650 ha with an annual production of 3,446,230 tonnes (FAO, 2009). 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) (Baik and Ullrich, 2008). Complete knowledge of physical properties of agricultural materials has a decisive importance for the realization of many technological processes, especially for monitoring of their qualities and health harmlessness during their production and storage. The quality assessment and guarantee of the safety of foodstuff belong to the main priorities in food industry. The physical and mechanical properties of barley grain, like those of other grains and seeds, are essential for the design of equipment and the analysis of the behavior of the product during agricultural process operations such as handling, planting, harvesting, threshing, cleaning, sorting and processing. Agricultural materials and food products deform in response to the applied forces. The nature of the response varies widely among different materials. The amount of force and energy required to produce a given amount of deformation can be used to study the damage which occurs during harvesting and handling of grains and seeds. Such information often gives insight into the specific circumstances that lead to failure (i.e.

cracking or splitting) and how such a failure can be prevented (Stroshine and Hamann, 1994).

The awareness of thermal properties such as specific heat, thermal conductivity and thermal diffusivity as well as such physical properties as density, shape and size is essential for design of the equipment and predicting the relevant processes. To define the magnitude and location of a temperature that denotes the heat content of the material at any time during a heating or cooling process, knowledge of the thermal properties of the material is required (Mohsenin, 1970).

In recent years, the mechanical properties have been determined for various crops such as sunflower seed and kernel (Gupta and Das, 2000); locust bean seed (Ogunjimi et al., 2002); almond nut and kernel (Aydin, 2003); peanut and kernel (Aydin, 2007); faba bean grain (Altuntaş and Yildiz, 2007); edible beans (Correa et al., 2008); cumin seed (Saiedirad et al., 2008); corn grain (Seifi and Alimardani, 2010) and sunflower seed (Tarighi et al., 2011). The thermal properties of grains and seeds were also considered by some researchers (Alagusundaram et al., 1991; Aviara and Haque, 2001; Ogunjimi et al., 2002; Yang et al., 2002; Razavi and Taghizadeh, 2007). Regarding to the comparison of mechanical and thermal properties of two varieties of barley grain no report was seen in the literature. Therefore, the objective of this study was to determine the mechanical properties, namely, force and energy required for fracturing barley grain varieties under quasi-static loading at different moisture contents. In addition, the thermal properties of the grains, including, specific heat, thermal conductivity and thermal diffusivity were determined.

Results and discussion

The mean values for the physical characteristics of the investigated grain varieties are presented in Table 1. Variance analysis of the data indicated that the effect of moisture content on the rupture force of Nosrat and Kavir varieties and the rupture energy of Nosrat variety was significant at the 1% probability level, while the effect on the rupture energy of Kavir variety was significant at the 5% probability level. The grain orientation had significant effect ($P<0.01$) on the rupture force and energy of Nosrat and Kavir varieties. The interaction effect of moisture content × orientation on the rupture force of Nosrat variety was significant at 1% probability level, while the effect on the rupture energy of Nosrat and Kavir varieties and the rupture force of Kavir variety was not significant ($P>0.05$). In addition, the variety had not have significant effect on the thermal properties. Results obtained are discussed in details as presented in the followings.

Rupture Force

The force required to initiate grain rupture at different moisture contents and compression orientations for Nosrat and Kavir varieties is presented in Table 2. It can be observed that the force required to initiate grain rupture decreased for both varieties as the moisture content increased. In addition, the rupture force of both grain varieties was greater under horizontal loading direction than under vertical loading (Table 1). The interaction effect of moisture content and grain orientation on the rupture force is shown in Fig. 2. The average force to rupture the grain was obtained as 104.28 N varying from 53.11 to 172.39 N for Nosrat variety, while the value was obtained as 71.76 N ranging from 40.88 to 111.72 N for Kavir variety. Therefore, the force required to initiate rupture of Nosrat variety was greater than that of Kavir variety. For two orientations studied of both varieties, lower forces were necessary to rupture the grains at higher moisture contents. This may be due to the fact that at an 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 became more sensitive to cracking at an 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. They 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. 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 and Gorji et al. (2010) for wheat grain. 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 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.

Rupture Energy

The results of the rupture energy are presented in Table 2 and Fig. 3. The rupture energy values for both varieties increased as moisture content increased. The average rupture energy of the grain was calculated as 54.38 mJ varying from 29.10 to 78.24 mJ for Nosrat variety, while the value was calculated as 60.65 mJ ranging from 40.33 to 77.43 mJ for Kavir variety. Therefore, the rupture energy of Kavir variety was greater than that of Nosrat variety, indicating higher flexibility of Kavir variety during compressive loading. The energy absorbed at the grain rupture was a function of both force and deformation up to the rupture point. At low moisture content, the grain required 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 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 and Gorji et-

Table 1. Physical characteristics of barley grain varieties in different moisture contents (N=100)

	Moisture Content (% dry basis)							
	Nosrat				Kavir			
Characteristic	7.3	12.1	16.8	21.6	6.7	11.6	15.4	21.2
Length (mm)	8.91 (0.67)*	9.29 (0.66)	9.47 (0.64)	9.64 (0.57)	9.18 (1.04)	9.66 (0.95)	9.72 (0.90)	9.84 (0.83)
Width (mm)	3.29 (0.28)	3.45 (0.26)	3.65 (0.22)	3.73 (0.22)	3.16 (0.33)	3.39 (0.29)	3.56 (0.28)	3.68 (0.28)
Thickness (mm)	2.58 (0.23)	2.71 (0.23)	2.90 (0.18)	2.98 (0.18)	2.45 (0.32)	2.63 (0.28)	2.77 (0.27)	2.87 (0.22)

*Figures in parentheses are standard deviations; N – number of observations.

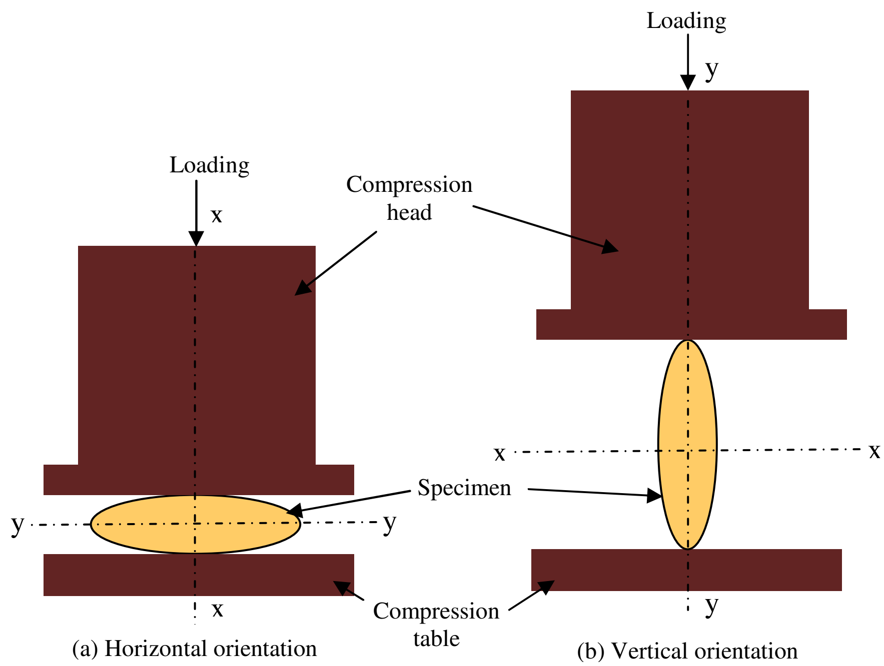

Fig 1. Orientations of barley grain under compressive loading

al. (2010) for wheat grain. This attribute caused the broken grain percentage to be reduced during dynamic loading (Kirk and McLeod 1967). In addition, the values of the rupture energy for horizontal orientation were statistically higher (P<0.01) than those of the vertical orientation at different moisture contents for both varieties as seen in Table 2. Therefore, the grains were more flexible in the horizontal loading direction. 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. 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.

Thermal Properties

The thermal properties of the barley grain varieties at moisture content of 7.3 and 6.7% d.b., for Nosrat and Kavir varieties, respectively, and temperature of 25 °C are presented in Table 3. It can be observed that there are no significant differences (P>0.05) between the varieties in the thermal properties. The average of specific heat of the grains was found to be 1631.6 and 1392.0 J kg^{-1} K^{-1} for Nosrat and Kavir varieties, respectively. These values were lower than those of various sizes of oil bean seed (2.14–5.32 kJ kg^{-1} K^{-1}) (Oje and Ugbor, 1991; Ogunjimi et al., 2002). This means that it needs less energy to heat barley grains to reach drying temperatures during the drying process. The specific heat will be useful in thermal processing of the grains, and especially in predicting its thermal behaviour. Mandas and Habte (2002) conducted a study entitled "numerical simulation state-bed drying of barley". They suggested that in calculation of heat transfer equation (energy balance of grain), the equation of:

$$\rho_g (c_g + c_w M) \frac{\partial \theta}{\partial t} = h_a (T - \theta) + h \frac{\partial M}{\partial t} \rho_g$$

where c_g is the specific heat of dry grain c_w is specific heat

Table 2. Mean comparison of rupture force and energy of barley grain varieties in different moisture contents and grain orientations

Moisture content (% d.b.)	Rupture force (N)	Rupture energy (mJ)
Nosrat variety		
7.3	128.04 a*	34.37 d
12.1	116.49 b	47.42 c
16.8	96.95 c	63.54 b
21.6	75.66 d	72.20 a
Grain orientation		
Horizontal	141.09 a	60.67 a
Vertical	67.49 b	48.11 b
Kavir variety		
6.7	85.74 a	52.17 b
11.6	76.07 ab	57.07 ab
15.4	65.22 bc	64.04 ab
21.2	59.98 c	69.34 a
Grain orientation		
Horizontal	93.76 a	71.39 a
Vertical	49.75 b	49.91 b

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

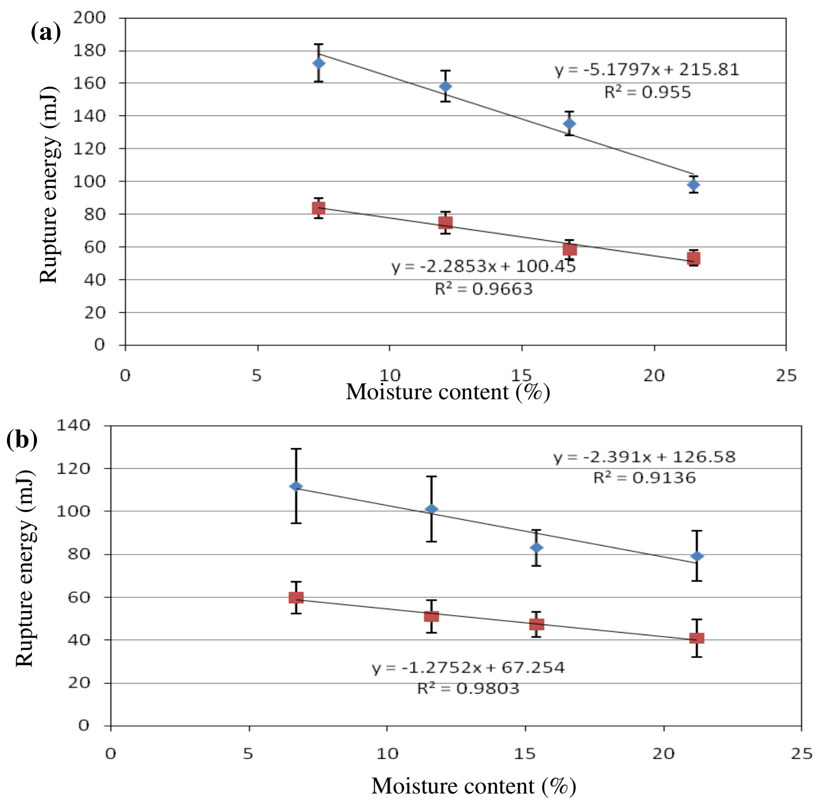

Fig 2. Effect of moisture content on rupture energy of barley grain varieties; a) Nosrat and b) Kavir; (♦) horizontal, (■) vertical.

of water, h is heat of water adsorption, θ is barley grain temperature, T is the air temperature, h_a is the grain bed volumetric heat transfer coefficient and ρ_g is the barley gain density) is considered. Therefore, knowing the specific heat of barley gain is useful in designing of the drying process. Also, for obtaining the empirical drying rate equations for barley grain, by which the rate of moisture loss from the grain kernel as a function of barley grain temperature is described, some information on barley thermal properties such as specific heat is required (Sharp, 1982; Sun and Woods, 1997).

The thermal conductivity of barley grain is a measure of its ability to transmit heat. The average values of the thermal conductivity for the grains were 0.175 and 0.161 W m^{-1} K^{-1}, for Nosrat and Kavir varieties, respectively. This is in good agreement with the fact that thermal conductivities of food materials vary between that of water (k_{water} = 0.614 W/m$^{\circ}$C at

Table 3. Mean comparison of thermal properties of barley grain varieties (N=5)

Variety	Thermal properties		
	C_s (J kg^{-1} K^{-1})	k (W m^{-1} K^{-1})	D (m^2 s^{-1}×10^{-8})
Nosrat	1631.6 a*	0.175 a	14.67 a
	(56.52)	(0.006)	(5.92)
Kavir	1392.0 a	0.161 a	15.70 a
	(36.57)	(0.019)	(3.29)

*The means with minimum common letter are not significantly different (P>0.05) according to Duncan's multiple ranges test; Figures in parentheses are standard deviations.

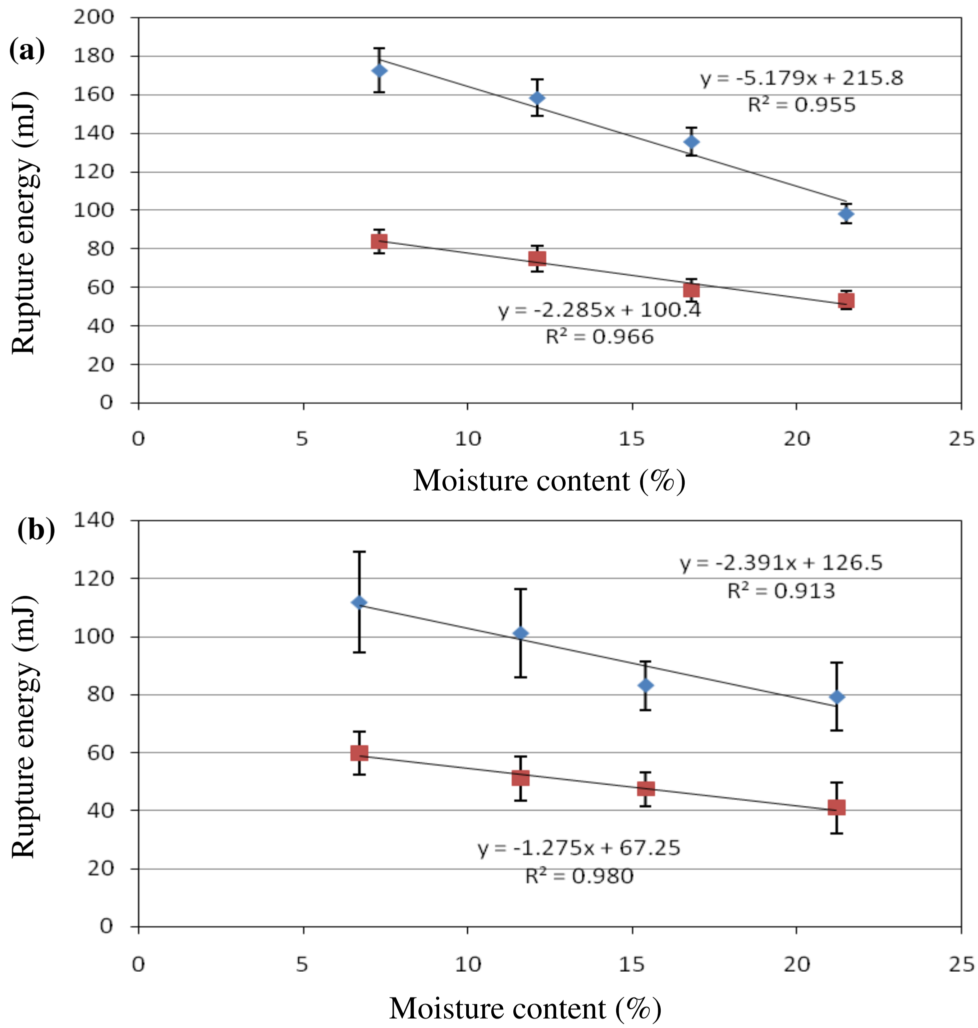

Fig 3. Effect of moisture content on rupture energy of barley grain varieties; a) Nosrat and b) Kavir; (♦) horizontal, (■) vertical.

27°C) and that of air (k_{air} = 0.026 W/m°C at 27°C), which are the most and the least conductive components in foods, respectively. The thermal conductivity values of the other food components fall between these limits. When the barley grains are dried, thermal conductivity value diminished remarkably so that it can be stated that dry porous solids are very poor heat conductors because the pores are occupied by air. For porous materials, the measured thermal conductivity is an apparent one, called the effective thermal conductivity. It is an overall thermal transport property assuming that heat is transferred by conduction through the solid and the porous phase of the material. The value obtained was comparable with those of barley (0.17–0.23 W m^{-1} K^{-1}), lentils (0.19–0.24 W m^{-1} K^{-1}) and peas (0.19– 0.26 W m^{-1} K^{-1}) for moisture contents within 9–23 % and temperature range from –28 to 29 ºC (Alagusundaram et al., 1991). It is clear that the lower thermal conductivity results in the slower drying process. In the work of Emami et al. (2007), a direct linear relationship between bulk density and thermal conductivity was found that this trend can be predicted for barley grain in the current research. This can be attributed to the presence of pores and air pockets among the powder particles. Since air has low thermal conductivity, higher porosity (lower bulk density) would result in lower thermal conductivity.

Thermal conductivity data for more than 100 food materials in the recent literature were classified and analyzed by Krokida et al. (2001). The thermal conductivity of different food materials was also given by Rahman and Chen (1995), Saravacos and Maroulis (2001), and Sweat (1995).

Thermal diffusivity quantifies a material's ability to conduct heat relative to its ability to store heat (Stroshine and Hamann, 1994). The average thermal diffusivity for barley grains was found to be 14.67×10^{-8} and 15.70×10^{-8} m^2 s^{-1}, for Nosrat and Kavir varieties, respectively. Knowing this value for barley grain as thermal diffusivity is required in heat and mass transfer computations applied in drying process design. This is due to the fact that one of the topics is heat and mass transfer in porous media like cereals grains (specifically herein barley grain) is mass diffusion. Under steady state condition, the diffusion of moisture and nutrients in food may be described by Fick's First Law as defined $m_a = -DA\frac{dC_a}{dy}$ (where m_a is the mass flow of the grain on kgs^{-1}, D is the diffusion coefficient in m^{2}s^{-1}, and C_a is the concentration of the diffusing materials in kgm^{-3}) as discussed by Basmadjian (1980). The values obtained in the current study for barley grains, were close to that of cumin seed (6.53 × 10^{-8}–16.64 × 10^{-8} m^2 s^{-1}) at temperatures from –50 °C to 50 °C and moisture content of 7.8 % d.b. (Singh and Goswami, 2000). The results on thermal properties on barley grains presented in this paper can be used in food industry in such processes where heat transport and storage properties of granular agricultural materials are indispensable. They can be applied for instance, for the adjustments of drying rate, for the calculations of the economical drying time and for the determination of energetic balances of drying processes.

Materials and methods

Preparing the materials

The barley grains (Nosrat and Kavir varieties) used in the current research, are from the prevalent varieties in Iran which were obtained from the Seed and Seedling Research Institute, Karaj, Iran. The samples were manually cleaned in order to remove foreign matters, 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 contents of Nosrat and Kavir varieties were 7.3 and 6.7% d.b., respectively. The samples of the studied moisture contents were prepared by adding the amount of distilled water, Q, as calculated from the following relationship (Sacilik et al., 2003):

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

The samples were transferred to separate polyethylene bags and then 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 an experiment, 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. The rewetting technique to attain the desired moisture content in the grains has frequently been used (Sacilik et al., 2003; Garnayak et al., 2008). All the mechanical properties of the grains were assessed at moisture levels of 7.3, 12.1, 16.8 and 21.6% d.b. for Nosrat variety and 6.7, 11.6, 15.4 and 21.2% d.b. for Kavir variey. For each moisture content, the length, width and thickness of barley grain were measured in randomly selected 100 grains. The length, width and thickness of materials were measured using a digital caliper with an accuracy of 0.01 mm.

Determining the mechanical properties

The mechanical properties of barley grain were determined in terms of average rupture force and energy at horizontal and vertical orientations (Fig. 1). Quasi-static compression tests were performed using a proprietary tension/compression testing machine (Instron Universal Testing Machine /SMT-5, SANTAM Company, Tehran, Iran). The loading rate was 10 mm/min. 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 then compressed at the preset condition until rupture occurred which is 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 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 point. The latter procedure was done by the utilization of computing software installed on the apparatus used.

Determining the thermal properties

The thermal properties of barley grains, including, specific heat, thermal conductivity and thermal diffusivity were studied at moisture contents of 7.3% and 6.7% for Nosrat and Kavir varieties, respectively, and also temperature of 25°C for both varieties, with five replications. The specific heat of the grains was determined using a copper calorimeter placed inside a flask, by the method of mixtures as described by Ogunjimi et al. (2002). A sample of known weight and temperature was poured into the calorimeter containing water of known weight and temperature. The mixture was stirred with a copper stirrer until equilibrium was attained. The final temperature was noted and the specific heat, c_s, of the sample was calculated using the following equation:

$$c_s = \left[\frac{(m_c c_c + m_w c_w)(T_e - T_{wi})}{m_s (T_{si} - T_e)} \right] \qquad (2)$$

The thermal conductivity, *k*, was determined using a probe similar to that described by Alagusundaram et al. (1991). The apparatus consisted of a heat source, a calorimeter base and a Dewar vessel (to decrease heat losses due to radiation). The grains were compressed to ensure a good contact among them and placed in a polyvinyl chloride (PVC) tube. Two holes were provided in the tube for insertion of the thermocouples which were penetrated within the grain bulk. The sample was placed between the heating source and a clamp. The maximum temperature of the grain bulk was controlled by a thermostat during the measurements and steady state conditions of the equipment were provided before the measurements performed. For calculation of the thermal conductivity of the grain bulk, the amount of heat absorbed by water was determined. The thermocouple reading was taken to signify the temperature at the cross-section as there was no radial heat transfer (Alagusundaram et al., 1991).

The thermal diffusivity, *D*, was also calculated based on the measured values of the specific heat and thermal conductivity and using the following relationship:

$$D = \left[\frac{k}{c_s \rho_b} \right] \qquad (3)$$

Experimental data were analysed using analysis of variance (ANOVA) and the means were compared at the 5% level of significance using the Duncan's multiple range tests in SAS (vers. 9.1, SAS Institute Inc., Cary, NC, USA).

Conclusions

Based on this study on barley grain varieties, as moisture content increased, the rupture force of the grains decreased, while the rupture energy increased. The values of the rupture force and energy for the horizontal orientation were statistically higher than those of the vertical orientation, indicating higher resistance of the grain to rupture at horizontal orientation loading. The rupture energy of Kavir variety was greater than that of Nosrat variety, indicating higher flexibility and resistance of Kavir variety during compressive loading.

There were not significant differences between the varieties in the thermal properties. The average specific heat, thermal conductivity and thermal diffusivity of the grains were found to be 1631.6 and 1392.0 J kg^{-1} K^{-1}, 0.175 and 0.161 W m^{-1} K^{-1} and 14.67×10^{-8} and 15.70×10^{-8} m^2 s^{-1}, for Nosrat and Kavir varieties, respectively. Moisture content and temperature are the important factors affecting thermal properties of biological materials. This matter can be pursed in future as a research. Finally, it is recommended that the correlation of some physical characteristics such as bulk and true densities with the thermal properties of barley grain to be investigated by other researches.

Acknowledgments

The authors would like to thank the Seed and Seedling Institute Research for providing the test grains and the University of Tehran for providing the laboratory facilities for this project.

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