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Mechanical test suitable for detection of bug-damage wheat grains abstract

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Abstract

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Considering the fact that the presence of bug-damaged wheat in the bulk results in a decrease of the flour quality and its final product, which is bread, it is necessary to differentiate the bug-damaged wheat grains from the healthy ones. Therefore, the present study investigated the mechanical properties of bug-damaged and healthy wheat grains of the Azar cultivar. By making use of these mechanical properties, it would be possible to provide a more precise texture identification of the bug-damaged wheat grains compared to the healthy ones. In this study, the mechanical properties (rupture energy, toughness and apparent elastic coefficient) were determined under compressive loading, with four levels of loading velocity (5, 15, 25 and 35 mm·min^{-1}) and four levels of moisture content (9, 11.5, 14 and 16.5% wet basis) in both bug-damaged and healthy wheat grains. Due to the significant difference in the mean value of apparent elastic coefficient between the bug-damaged grains (74.779 MPa) and the healthy ones (289.071 MPa), this parameter can be employed as the most appropriate factor to distinguish the bug-damaged wheat grains from the healthy ones.

Keywords: mechanical properties; wheat; bug-damaged; apparent elastic coefficient; toughness

Wheat is a very valuable food product: it is richer than rice in protein (by 1.5–2 times), much of it is presented with unique viscoelastic gluten (Krupnov 2011). The major wheat product is bread. Pests are the most important factors that lead to a decreasing efficiency and quality of baked bread. In the Middle East, Central Asia and North Africa, as well as East and South-eastern Europe, Sunn pest causes great harm to crops and the grain quality of wheat (Krupnov 2011). Sunn pest causes severe quantitative and qualitative damage by feeding on leaves, stems and wheat grains.

Feeding on grain is the most destructive (Saadati, Bandani 2011). By injecting salivary enzymes into the grain during feeding, enzymes destroy proteins and prevent the formation of strong gluten (Every et al. 2005; Tosi et al. 2009; Saadati, Bandani 2011). The shape of damaged bug-damaged grains is thin and wrinkled with a dark spot related to the insect bite and a pale area around it (Tischler 1939; Critchley 1998). Fig. 1 shows samples of wheat grains damaged by Sunn pest. Attacks on grain are manifested in three ways: (a) reductions in actual yield; (b) reductions in seed germination; and (c) reductions in the gluten index. (Shurovenkov et al. 1984; Critchley 1998). Because of degradation, gluten cannot store the carbon dioxide from the fermentation of

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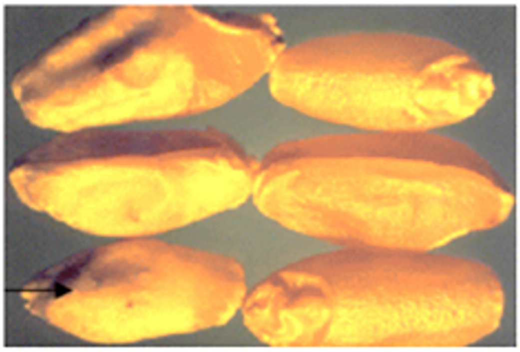

Fig. 1. Sample of bug-damaged wheat

starch. Therefore, the porosity cannot be produced in bread and the prepared bread is not as brittle as the bread prepared of healthy wheat (Paulian, Popov 1980). Finally, the bread prepared from bug-damaged wheat has low volume, poor sensory properties, unacceptable texture and abnormal shape (Kostyukovsky, Zohar 2004; Vaccino et al. 2006). Thus, a reduction in the quality of bread increases the waste caused by it.

Therefore, identifying bug-damaged and healthy grain wheat to determine the grading of wheat in terms of a bug-damage is important.

To pay attention to post-harvest processing operations and related machinery design is very important in development of the food industry. This requires a further research to understand the engineering properties of agricultural products; mechanical properties of the material and a better understanding of the characteristics of the texture of the material are important. So, the basic concept is to identify the tissue properties of biological materials. Mechanical properties of the damaged and healthy wheat grains should be considered for determining the wheat quality. Among the different identification methods of grain properties, the mechanical methods are considered to be the easiest and most reliable ones. The mechanical properties of materials are defined as any feature that presents its behaviour under the forces applied. In general, the "stress-strain" single axial compression test is employed to determine and describe the mechanical behaviour (Mohsenin 1986). The compression test is an objective method for determining the mechanical properties of cereal seeds and also one of the best techniques for determining the modulus of elasticity by studying their behaviour at the compression stress, using force-deformation curve (ASAE Standards 2008). Despite many studies were conducted to determine the mechanical properties of grain crops (Prasad, Gupta 1973; Liu et al. 1990; Bargale et al. 1995; Kang et al. 1995; Gupta, Das 2000; Molenda, Stasiak 2002; Afkari-Sayyah, Minaei 2004; Tavakoli et al. 2006; Gorji et al. 2010; Zareiforoush et al. 2010; Babic et al. 2013; Voicu et al. 2013), due to a special structure of bio-materials, these characteristics may change under different conditions (moisture, temperature and difference in variety), necessitating more data collection in this field (Afkari-Sayyah, Minaei 2004). Thus, the aim of the current study was the extraction of mechanical properties of healthy and bug-damaged wheat grains (such as rupture energy, toughness and apparent elastic coefficient) at 4 moisture content levels and 4 levels of loading velocity. In addition, it is expected that by determining the mechanical properties of healthy and damaged wheat grains, valid and scientific criteria would be presented to discriminate the damaged wheat grains from the healthy ones. Achieving this aim can assist to increase the quality of the flour prepared. In addition, the results of this research can be employed in wheat silos for identifying the bug-damaged grains from the healthy ones and determining the percentage of bug-damaged wheat grains by sampling.

MATERIAL AND METHODS

After preparing an Iranian variety of wheat grains (the Azar cultivar), the samples were sent to the Bio-Physics Laboratory at the Bio-Systems Department of the Mohaghegh-Ardabili University, Ardabil, 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 130°C for 19 h based on the standard method (ASAE Standards 2002). The initial moisture content of the grains was found to be 9% wet basis. The experiments were done at four moisture content levels of 9, 11.5, 14 and 16.5% (w.b.). The samples at the desired moisture levels were prepared by adding the calculated amounts of distilled water calculated from Eq. (1) (Mohsenin 1986):

$$Q = \frac{w(M_f - M_i)}{100 - M_f} \tag{1}$$

where: Q – mass of the added water (kg); W – initial

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mass of the sample (kg); M_f – initial moisture content of the sample (%, wet basis); M_i – final moisture content of the sample (%, wet basis)

After adding the water calculated to the given weight of samples, the samples were poured into separate polyethylene bags, sealed tightly and kept at 5°C in refrigerator for a week to enable the moisture content distribute uniformly throughout the samples. Before starting the tests, the required quantities of the samples were taken out of the refrigerator and were allowed to warm up to room temperature for approximately 2 h (Aydin et al. 2002; Konak et al. 2002). Quasi-static compression tests were performed using a proprietary tension/compression testing machine (Universal Testing Machine/STM 20, Santam Company, Tehran, Iran). The tension/compression testing machine was equipped with the Bongshin load cell (model DBBP-100; Korea) with the capacity of 100 kg. The compressive tests were performed in a way that the wheat grain in its most stable state was loaded quasi-elastically between two parallel plates (Fig. 2) and compressed under the pre-set conditions until the rupture occurred as denoted by the rupture point in the force-deformation curve. Once a sudden decrease in force occurred, as the rupture point was detected, the loading was stopped, and then the data were transferred to Excel software. By considering the effect of loading velocity on the desirable efficiency of processing machines, four different loading speeds with uniform distances of 5, 15, 25 and 35 mm·min^{-1} were selected. After performing each experiment, the force-deformation curve and its related data were saved in Excel Software. Subsequently, the rupture energy and toughness were calculated from the data. To do this, the area under force-formation curve from the loading moment to the rupture time of samples, which is equal to rupture energy (E_b), was calculated. Toughness (T_n) was obtained through Eq. (2) (Mohsenin 1986):

$$T_n = \frac{E_b}{V} \qquad (2)$$

where: E_b – rupture energy (J); V – volume of wheat grain (m^3)

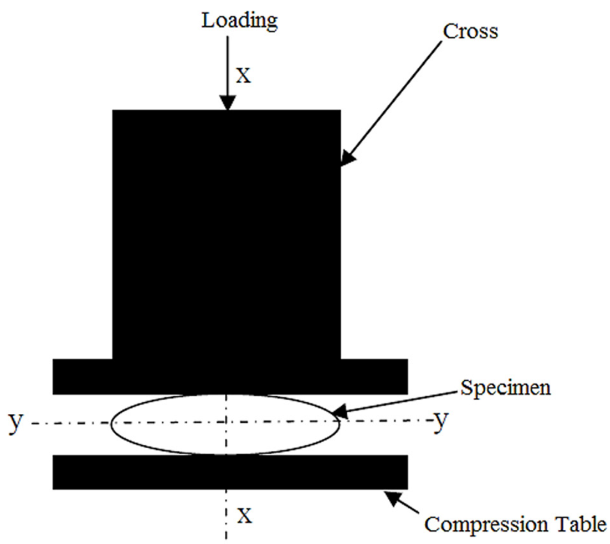

Fig. 2. Wheat grain under compressive loading
y, *x*– coordinate axes vertical and horizontal, respectively

Volume of wheat grain was calculated using the equivalent elliptical volume as shown in Eq. (3):

$$V = \frac{\pi}{6} abc \qquad (3)$$

where *a*, *b* and *c* – grain length, width and thickness (m), respectively

Based on the standard method (ASAE Standards 2008), Eq. (4) was employed to calculate the apparent elastic coefficient of wheat grain:

$$E = \frac{0.338 K^{3/2} F (1-\theta^2)}{D^{3/2}} \left[\frac{1}{R'} + \frac{1}{R'_1} \right]^{1/2}$$
$$E = \frac{0.338 K^{3/2} F (1-\vartheta^2)}{D^{3/2}} \left[\frac{1}{R'} + \frac{1}{R'_1} \right]^{1/2} \qquad (4)$$

where: F – force (N); D – deformation (m); R' – minimum curvature radiu (m); R'_1 – maximum curvature radius (m), q – poison's ratio; K – constant coefficient

Based on the above-mentioned standard, the force F and deformation D are related to the point on the linear section of force-deformation curve (PC in Fig. 3). The deformation D is equivalent to $D_{L/2}$ where D_L is the grain deformation from the beginning of the curve to the linear limit (Voicu et al. 2013). In general, D is a point in the elastic region that has to be lower than the curve yield point (Afkari-Sayyah, Minaei 2004).

In order to calculate the values of R' and R'_1 (Fig. 4), Eqs (5 and 6) were used, respectively (Mohsenin 1986; Bargale et al. 1995; Afkari-Sayyah, Minaei 2004; Voicu et al. 2013):

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$$R' \cong \frac{H}{2} \quad (5)$$

$$R_1' \cong \frac{H^2 + \frac{L^2}{4}}{2H} \quad (6)$$

where: L – the large diameter of the grain (m); H – the mean of average and small diameters (m)

The poison's ratio (was considered to be 0.3 for wheat grains (Bargale et al. 1995; Afkari-Sayyah, Minaei, 2004; Voicu et al. 2013). In order to determine K, the term cosq was calculated from Eq. (7) (Bargale et al. 1995; Afkari-Sayyah, Minaei 2004). Afterwards, the K value was extracted based on the value of (refer to Mohsenin 1986 for K values):

$$\cos\theta = \frac{\frac{1}{R'} - \frac{1}{R_1'}}{\frac{1}{R'} + \frac{1}{R_1'}} \quad (7)$$

The experimental data were analysed by factorial randomized complete design and the mean

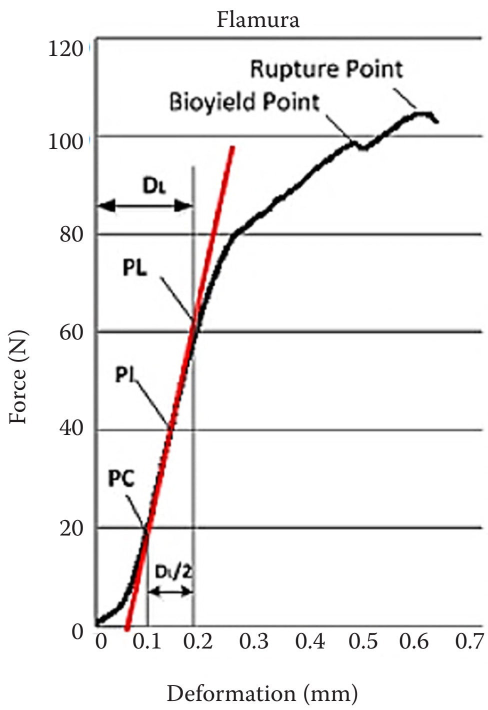

Fig. 3. Force-deformation curve for wheat grain. PL: proportional limit, PE: turning point and PC: calculated point (Voicu et al. 2013)
DL – deformation in the proportionality limit; PL – proportional limit; PI – turning point; PC – calculated point

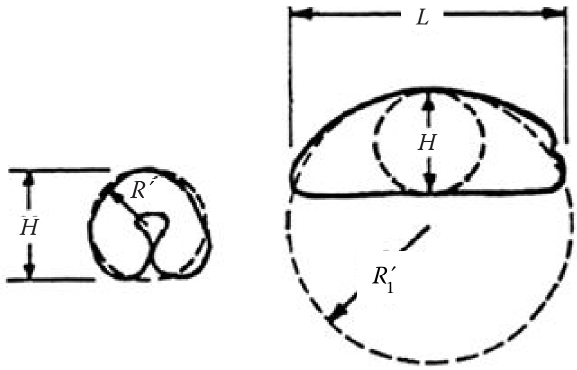

Fig. 4. The min. curvature radius (R') and the max. curvature radius (R'_1)
R´ – minimum curvature radius; R_1' – maximum curvature radius; H – grain thickness; L – grain length

values of mechanical parameters were compared by applying the Duncan's multiple range tests in the MSTAT-C statistical software. In this research, 32 treatments were considered: moisture content at four levels: 9, 11.5, 14 and 16.5% (w.b.), loading velocity at four levels: 5, 15, 25 and 35 mm/min and grain type at two levels: healthy grains and the bug-damaged ones. The experiments were conducted using factorial randomized complete design with eight replications.

RESULTS AND DISCUSSION

The results of the analysis of variance are shown in Table 1. As it can be observed, there is a significant difference ($P < 0.01$) between the healthy wheat grains and the bug-damaged ones in terms of the 3 independent variables including rupture energy, toughness and apparent elastic coefficient. The results revealed that the grain moisture has a significant effect on all mechanical properties ($P < 0.01$). Nevertheless, the main effect of loading velocity was not significant. Furthermore, the effect of interaction between moisture content and the type of wheat grain was considerable in all 3 mechanical properties. The effect of the interaction between loading velocity and the type of wheat grain was significant only for the apparent elastic coefficient ($P < 0.05$). Moreover, the effect of the interaction between moisture content, loading velocity, and the type of wheat grain was considerable only for the parameter of toughness ($P < 0.05$).

Fig. 5 compares the means of double interactive effects of moisture content and wheat type on rup-

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Table 1. Results of the analysis of variance of wheat grain mechanical properties

Source of variation	Degree of freedom	Mean squares		
		rupture energy (mJ)	toughness (mJ·mm^{-3})	apparent elastic coefficient(MPa)
Moisture content	3	2,712.565**	2.227**	645,013.732**
Loading velocity	3	165.359^{ns}	0.267^{ns}	52,575.55^{ns}
Moisture content × loading velocity	9	125.917^{ns}	0.22^{ns}	28,491.687^{ns}
Wheat type	1	5,090.466**	7.293**	2,938,938.084**
Moisture content × wheat type	3	512.352*	0.625**	425,892.652**
Loading velocity × wheat type	3	176.746^{ns}	0.247^{ns}	70,072.055*
Moisture content × loading velocity × wheat type	9	242.367^{ns}	0.273*	27,947.955^{ns}
Error	224	138.677	0.129	24739.032
Total	255			

** – significant effect at the probability level of 1%; * – significant effect at the probability level of 5%; ns – non-significant effect

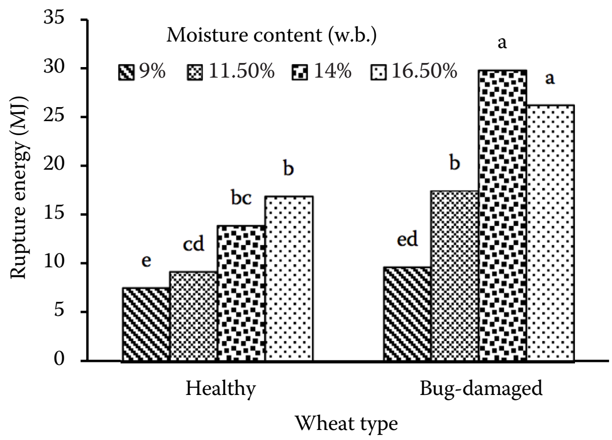

Fig. 5. Comparison of the means of double interactive effect of moisture content and wheat type on rupture energy (LSD = 5.80)

ture energy. As Fig. 5 clearly indicates, the rupture energy of bug-damaged grains was higher than of the healthy grains at each level of moisture content. Due to the higher elasticity of bug-damaged grains, the area under the force-deformation curve (rupture energy) would be much higher than that of the healthy grains; however, the rupture force of bug-damaged grains is lower than that of healthy grains. In addition, the deformation in the rupture point of bug-damaged grains is higher than that of the healthy grains (Rasekh et al. 2007). The rupture energy of healthy grain increased from 7.476 to 16.856 mJ with moisture content increase from 9 to 16.5% (w.b.). In addition, the value of rupture energy of bug-damaged grains increased from 9.602 to 29.802 mJ with increasing grain mois-

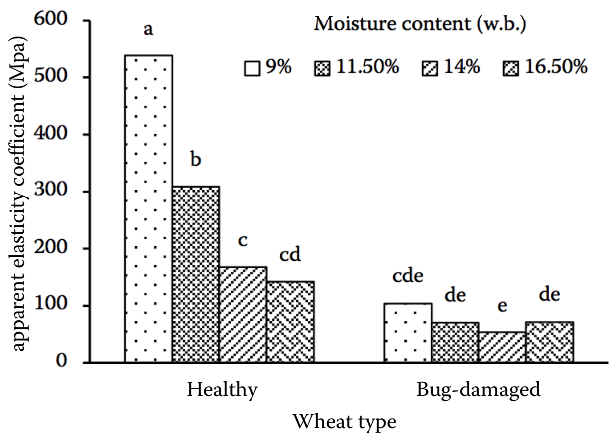

Fig. 6. Comparison of the means of double interactive effect of moisture content and wheat type on apparent elastic coefficient (LSD = 77.4)

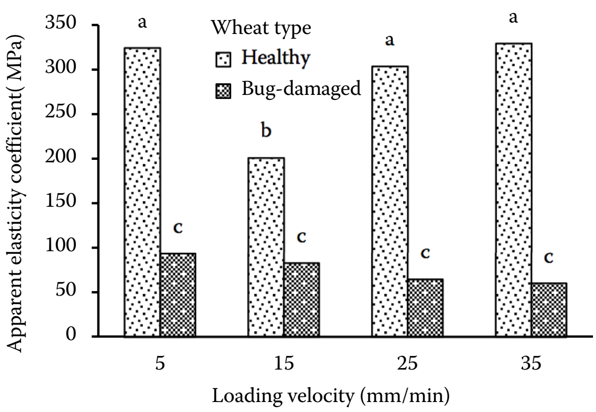

Fig. 7. Comparison of the means of double interactive effect of loading velocity and wheat type on apparent elastic coefficient (LSD = 77.46)

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Table 2. Comparison of the mean of triple interactive effect of moisture content, loading velocity and wheat type on toughness

Loading velocity (mm·min^{-1})	Moisture content (% w.b.)	Wheat type	
		healthy grains	bug-damaged grains
5	9.0	0.255^{hi}	0.378^{ghi}
	11.5	0.281^{hi}	0.430$^{f–i}$
	14.0	0.313^{hi}	0.569$^{c–i}$
	16.5	0.332^{ghi}	0.909^{bcd}
15	9.0	0.135^{i}	0.280^{hi}
	11.5	0.234^{hi}	0.569$^{c–i}$
	14.0	0.411^{fghi}	0.869^{bcde}
	16.5	0.559$^{c–i}$	0.486$^{d–i}$
25	9.0	0.250^{hi}	0.348^{ghi}
	11.5	0.255^{hi}	0.754$^{b–g}$
	14.0	0.260^{hi}	1.052^{ab}
	16.5	0.356^{ghi}	0.981^{bc}
35	9.0	0.225^{hi}	0.231^{hi}
	11.5	0.243^{hi}	0.518$^{d–i}$
	14.0	0.463$^{e–i}$	1.401^{a}
	16.5	0.612$^{c–h}$	0.811$^{b–f}$

Values marked by small letters are significant ($P < 0.05$)

ture content from 9 to 14% (w.b.); it decreased to the mean value of 26.175 mJ at moisture content 16.5% (w.b.). The minimum value of rupture energy (7.476 mJ) was related to the healthy grain with the moisture content of 9% while its maximum amount (26.802 mJ) was related to bug-damaged wheat grains with the moisture content of 14%.

Fig. 6 compares the mean of double interactive effects of moisture content and wheat type on the apparent elasticity coefficient. The mean value of healthy and bug-damaged grains was observed at moisture content of 9% (w.b.). The apparent elastic coefficient of healthy wheat grains decreased significantly from 538.5 to 142 MPa with the moisture content increasing from 9 to 16.5% (w.b.), This finding agrees well with other researchers' results (Afkari-Sayyah, Minaei 2004; Voicu et al. 2013). Bargale et al. (1995) showed that with increasing moisture content, the apparent elastic coefficient of wheat grain decreased. The mean value of the apparent elastic coefficient of bug-damaged wheat grains decreased from 103.9 to 53.26 MPa with the grain moisture content increasing from 9 to 14% (w.b.), but it increased to the mean value 71.62 MPa at moisture content 16.5% (w.b.). Since the apparent elastic coefficient is the representative of material hardness in outer surface of an object and healthy grains are much harder than the bug-damaged ones, the mean apparent elastic coefficient of healthy grains is higher than that of the bug-damaged ones at each level of moisture content.

Fig. 7 compares the means of double interactive effects of loading velocity and wheat type on the apparent elastic coefficient. There is a significant difference between apparent elastic coefficient of healthy and bug-damaged wheat grains at each level of loading velocity. The results showed that the mean apparent elastic coefficient in all four levels of loading velocity is higher in healthy grains compared to the bug-damaged ones. The minimum and maximum amounts of apparent elasticity coefficients (64.3 and 328.8 MPa) were obtained in loading velocity of 35 mm/min for bug-damaged and healthy wheat grains, respectively.

Table 2, compares the means of triple interactive effect of moisture content, loading velocity and wheat type on toughness. Since the deformation under the loading force is higher for bug-damaged grains compared to the healthy ones, the area under the force-deformation curve for the bug-damaged grains is greater than that of the healthy grains. As a result, due to the lower volume of bug-damaged

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grains (because of their shrinkage) and by considering Eq. 2, the mean value of toughness at all four levels of moisture content for bug-damaged grains (0.662 mJ·mm^{-3}) is higher than that of healthy grains (0.324 mJ·mm^{-3}). Rasekh et al. (2007) also concluded that the bug-damaged wheat grains (Sardari cultivar) are tougher than the healthy ones. With regard to Table 2, by increasing the moisture content, the toughness of healthy grains increased in each loading velocity. This finding is in agreement with other researchers' results (Afkari-Sayyah, Minaei 2004; Rasekh et al. 2007). The maximum and the minimum mean values of toughness were found to be equal to 0.612 and 0.135 mJ·mm^{-3} in moisture contents of 16.5 and 9 % (w.b.) at loading velocities of 35 and 15 mm·min^{-1} for healthy grains, respectively. In the case of bug-damaged grains, by increasing the moisture content at each loading velocity, the toughness increases until the moisture content reaches 14% (w.b.). However, the toughness has a decreasing trend between the moisture contents of 14 and 16% (w.b.). The maximum and the minimum mean values of toughness were calculated to be equal to 1.401 and 0.231 mJ·mm^{-3} in moisture contents of 14 and 9 % at loading velocity of 35 mm/min for bug-damaged grains, respectively. As it can be observed, loading velocity does not have a significant effect on the toughness values and other mechanical properties. If the velocity interval changes were considered, their effect on mechanical properties would be more evident.

CONCLUSION

– There was a significant difference (P < 0.01) between healthy and bug-damaged wheat grains in terms of their mechanical properties (toughness, apparent elastic coefficient and rupture energy).
– The rupture energy of bug-damaged grains was higher than that of the healthy ones at each level of moisture content. The rupture energy of healthy grains increased with increasing moisture content (from 9 to 16.5% (w.b.)). This increasing trend in bug-damaged grains is also observed until they reach the moisture content of 14% (w.b.).
– Healthy grains were harder bug-damaged grains. Thus, the apparent elastic coefficient of healthy grains was higher than that of the bug-damaged ones at each level of moisture content and loading velocity.
– The mean toughness value of bug-damaged grains (0.662 mJ·mm^{-3}) was higher than of the healthy ones (0.342 mJ·mm^{-3}). This observation is mainly attributed to the porous texture of bug-damaged wheat grains and their lower volume.

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