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Relationships between Grain Physicochemical and Mechanical Properties of Some Iranian Wheat Cultivars

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ABSTRACT

Physicochemical and mechanical properties of wheat grains can have a great impact on the quality of the final products (bread). Therefore, correct selection of wheat cultivar for specific applications seems to be crucial. In this study, the differences in the physicochemical and mechanical properties (under compression and impact loadings) of ten Iranian wheat cultivars (Azar2, Alamut, Bam, Bahar, Chamran, Shiraz, Falat, Keras Adl, Marvdasht, and Nicknejad) were studied. Moreover, the relationship between these properties was investigated. The results indicated that the type of cultivar had significant influences on physicochemical and mechanical properties. The results of regression analysis between physicochemical and mechanical properties showed a significant correlation between protein content and particle size index (r^2= 0.6). Moreover, the protein content could be significantly correlated with the parameters obtained from mechanical tests (r^2> 0.50). Among the mechanical parameters obtained from compression and impact loading, the apparent elastic modulus and the specific breakage energy established maximum correlation (r^2= 0.77 and 0.78, respectively) with the protein content. Similarly, significant correlations were found between particle size index and mechanical parameters (r^2>0.60). Hence, the wheat protein content and particle size index, which have great impacts on quality of the final product, can be estimated by a few simple mechanical tests on the wheat kernels.

Keywords: Compression test, Impact test, Particle size index, Protein, Toughness.

INTRODUCTION

Wheat is the leading cereal crop in the world, consumed as food and feed in many different ways throughout the globe. Wheat is one of the most important sources of calorie and protein in human nutrition. It also provides essential vitamins and minerals such as vitamins B and E, magnesium, and phosphorous as well as fiber (Ranhotra, 1994). Wheat is mainly milled to flour before being used as a food component. However, whole-wheat grains or grits may also be used to make foods. Bread, pasta, noodles, biscuits, and cakes are the most common foods made basically from wheat flour. Breakfast cereals, curries, soups, and porridge are examples of the foods in which whole-wheat grains or grits may be used as an ingredient (Eliasson and Larson, 1993; Hoseney, 1994). In many parts of the world, the main application of wheat is to make bread as the major staple food. The need for production of economic and nutritive foods in developing countries such as Iran has made wheat and other cereals an important source of raw material in food industry.

In order to produce high quality products from wheat, an important step is to select the appropriate wheat variety in accordance with the characteristics of the final product. Therefore, it is necessary to determine the quality of the wheat in advance. Wheat

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quality criteria are mainly based on the physicochemical properties such as grain weight, grain hardness, and protein content (Sissons *et al.*, 2006). Grain hardness is used as a grading factor to determine the type of wheat (Morris, 2002). It is a key determinant for classification of wheat and end product quality (Campbell *et al.*, 1999). Grain hardness is important for the flour industry because it has significant impacts on milling, baking and qualities of wheat (Bettge *et al.*, 1995). One of the most important methods of grain hardness measurement is particle size index (PSI), which has a great impact on the quality of final product (especially bread). The soft wheat kernels fracture more easily, release many integral starch granules and produce finer textured flours with less starch damage, whereas, the hard wheat kernels produce coarser textured flours in which fracture planes produce broken starch granules (Morris and Rose, 1996). Since broken starch granules absorb more water, hard wheats are better suited for yeast-leavened bread, while soft wheats are preferred for cookies, cakes, and pastries (Farooq *et al.*, 2001).

Protein content is the best single test that can be applied to determine the quality of flour, because it has a direct correlation with baking quality (Stone and Savin, 1999; Matz, 1996).Wheat having high protein content tends to be hard, have strong gluten and produce good quality bread. Wheat of low protein content tends to be soft, have weak gluten and produce small loaves of inferior crumb structure (Bushuk, 1998; Tipples *et al.*, 1994), but produce better quality cookies. Majzoobi *et al.* (2011) investigated chemical properties of 14 Iranian wheat cultivars. Their results showed that the protein content varied significantly (7.83-14.98%) in different cultivars. In a similar study, Anjum and Walker (2000) reported protein contents in six most prevalent Pakistani wheat cultivars that ranged from 11.99 to 13.80%. Qarooni *et al.* (1993) confirmed that the most suitable value of wheat protein content for bread preparation should be 11-13%. Moreover, they concluded that there is a positive and significant correlation between protein content and quality parameters of bread.

Conducted studies by different researchers confirm that the grain hardness (PSI) of wheat is correlated significantly with protein content, moisture content, and kernels size (Pasha *et al.*, 2009; Abo-Shatala and Abdel Gewad, 2000; Yamazaki and Donelson, 1983). The protein content and the *PSI* relationship exhibits that *PSI* increases with increasing protein content in some cultivars, while in some other cultivars it is the opposite (Symes, 1965). Moisture content plays an important role in measuring the wheat kernel texture (Pomeranz and Williams, 1990) and has a very strong effect on grinding time, particularly for soft wheats (Williams and Sobering, 1988). All methods used for measuring wheat kernel texture have been reported to be affected by kernel moisture content (Newton *et al.*, 1927). Moisture content (6-18%) showed highly positive correlation with *PSI* for soft wheat cultivars (Obuchowski and Bushuk, 1980; Yamazaki and Donelson, 1983). The correlation between kernel size and the *PSI* has shown varying results. *PSI* and kernel weight are strongly correlated for hard cultivars while negatively correlated for soft cultivars (Williams and Sobering, 1984).

The mechanical properties of grain are important in the grinding and milling processes, and for designing machines for these tasks (Kang *et al.*, 1995; Saiedirad *et al.*, 2008; Yucel *et al.*, 2009). These properties are also important in order to design machines for harvesting, cleaning, separating, and processing. The effect of a wheat grain’s mechanical properties on grinding energy is greater than that of its other physical properties (Dziki, 2008). Rupture force, energy absorbed, and hardness are important mechanical properties of a wheat grain. Rupture force (N) is the minimum force needed to rupture the individual grain. Energy absorbed (J) is the energy required during the loading to rupture the individual grain (Sirisomboon *et al.*, 2007). Hardness (Nmm^{-2}) is the resistance of the individual grain to deformation under applied forces (Kang *et al*., 1995; Dobraszczyk *et al*., 2002; Turnbull and Rahman, 2002). Hardness is also defined as the ratio of the rupture force to the deformation at the rupture point of the grain (Sirisomboon *et al*., 2007). Several studies have been conducted that consider the moisture-dependent physical and mechanical properties of wheat, such as those by Delwiche (1993), Kang *et al*. (1995), Dobraszczyk *et al*. (2002), Dursun and Guner (2003), Tabatabaeefar (2003), Karimi *et al*. (2009), Kalkan (2009), Kalkan and Kara (2011), and Babic *et al*. (2011). However, Tabatabaeefar (2003) and Karimi *et al*. (2009) did not investigate the mechanical properties of wheat grains. Delwiche (1993) measured the hardness of individual wheat kernels using near-infrared transmittance. Kang *et al*. (1995) analyzed the mechanical properties of wheat such as yield stress, yield strain, modulus of deformability, and energy to yield point. Dobraszczyk *et al*. (2002) studied the fracture properties of endosperm machined from individual wheat kernels from several wheat varieties. The mechanical behavior of different wheat varieties was determined by Dursun and Güner (2003) using compression loading between two parallel plates. They reported that the rupture force decreased and the rupture energy increased as the wheat moisture content increased. Kalkan (2009) reported that the rupture force of wheat grains decreased as the moisture content increased, whereas, the deformation at rupture point, energy absorbed, and grain hardness did not show any regular variation. Babic *et al*. (2011) analyzed the physical and stress strain properties of 3 wheat varieties.

Despite the numerous previous studies on the mechanical properties and physicochemical characteristics of wheat grains, there is no published study on the relationships between the mechanical properties and the physicochemical characteristics. Therefore, the objectives of this study were:

(1) To determine the mechanical properties under static and dynamic loadings of single kernels of wheat and the physicochemical characteristics of wheat grains and,

(2) To describe the relationships between the mechanical parameters and the physicochemical characteristics of wheat grains.

MATERIALS AND METHODS

Wheat Samples

Ten samples of the most widely cultivated Iranian wheat were selected as study materials, namely, Azar2, Alamut, Bam, Bahar, Chamran, Shiraz, Falat, Keras Adl, Marvdasht, and Nicknejad. The wheat samples came from Seed Research Institute located in Agricultural College, Shiraz University, Shiraz, Iran. The grains were cleaned and sieved to remove broken, shrunken, and damaged kernels. Since the mechanical properties of wheat are affected by moisture content (Dziki, 2008), the moisture content of the wheat varieties was adjusted to approximately 11.5±0.5% (wb) based on the AACC method No. 55-30. Samples were placed inside separate perforated boxes, kept in a large plastic bag, and refrigerated at 4°C for 3 days to allow moisture to distribute uniformly throughout the samples. All tests were conducted at room temperature (24°C).

Physicochemical Measurements

The axial dimensions, namely length (L), width (W), and thickness (T) of 30 randomly selected grains for each variety were measured based on the guidelines of Jain and Bal (1997) using digital calipers to an accuracy of 0.01 mm. The thousand kernels weight was calculated by the method of Farooq *et al*. (2001). A 100 g sample of each wheat cultivar was taken and thousand kernels weight were recorded by counting clean, sound, and unbroken kernels. The kernel weight was calculated as grams per thousand kernels. To calculate *PSI*, a 50 g sample of wheat grain from each variety was ground by a laboratory hammer mill at its finest setting (AACC 2000, N0. 55-30). Then 10 g of meal was weighed, separated and transferred to a Tyler No. 70 sieve and sifted by a percussion shaker for ten minutes. To increase the shaking performance, each time 10 g of whole kernels was added to the meal. Then, all the fine materials collected in the pan, along with any fines adhering to the bottom of the sieve, were weighed to the nearest 0.01 g (W). The *PSI* was then calculated using Equation (1).

$$\mathrm{PSI}(\%)= \frac{\mathrm{W}}{\text{Sample weight}} \times 100 \qquad (1)$$

The chemical compositions, including crude protein, fiber, fat, and ash contents were estimated at each wheat variety as the respective procedures described in AACC method No. 46-10, 32-10, 30-10 and 08-01, respectively (AACC, 2000).

Mechanical Testing

Impact Test

A tester for grain resistance to impact, developed at the ‘‘Agriculture Machinery Laboratory” of mechanics of agricultural machinery school, University of Shiraz, was used to determinate breakage energy of wheat kernel (Figure 1). A single grain was vertically placed in the kernel holder unit so that half of the kernel length was out of the holder. The pendulum was elevated to contact the hammer with the magnetic holder. The magnetic holder kept the pendulum at specific height h_1 (Figure 2). When the tester was adjusted in the start mood, the pendulum was released due to elimination of the magnetic property of the magnetic holder. After contact with the center of the kernel, the released pendulum broke the kernel, and climbed up to h_2. The rotary encoder measured the corresponding angle (β) with height h_2, and displayed it on the screen. The breakage energy (mJ) could be calculated by the following equation:

$$E_b = mgr_g(\cos\beta - \cos\alpha) \qquad (2)$$

Where, α is the angle between pendulum and vertical line at the start of motion (see Figure 2), β is maximum angle between pendulum and vertical line after kernel breakage, m is mass of pendulum (0.193 kg), r_g is center of gravity length (133.156 mm), and g is acceleration due to gravity (m s^{-2}). The specific breakage energy and dynamic toughness were calculated using the following equations (Zhang *et al*., 2005):

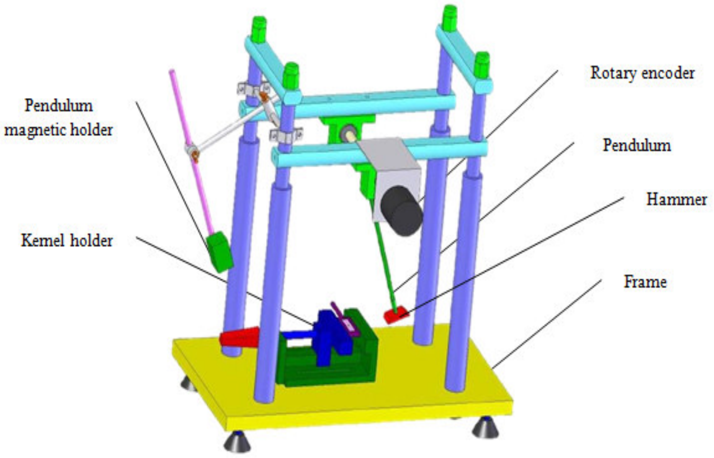


Figure 1. Lay out of tester for grain resistance to impact.

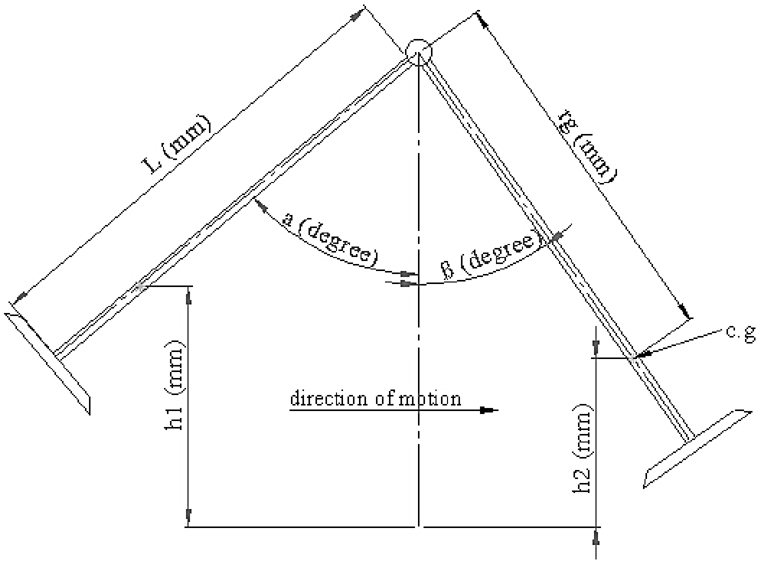


Figure 2. Schematic diagram of motion of pendulum including some parameters specified about dimensions of pendulum: (L) Length of pendulum; (c.g) Center of gravity; (r_g) Length of center of gravity; (h_1) Distance of c.g from the horizontal line at initial position of pendulum; (h_2) Maximum distance of c.g from the horizontal line after breakage of sample; (α) The angel between pendulum at initial position and vertical line, and (β) The maximum angle between pendulum and vertical line after breakage of sample.

$$E_{s.b} = \frac{E_b}{A} \qquad (3)$$

$$T_d = \frac{E_b}{V} \qquad (4)$$

In the above equations, $E_{s.b}$ is specific breakage energy (mJ mm^{-2}), A is breakage area of kernel (mm^2), T_d is dynamic toughness (mJ mm^{-3}) and V is volume of kernel (mm^3). Equations (5) and (6) were used to calculate the breakage area (A) and volume of kernel (V), based on elliptical volume of kernel, respectively as follows (Zhang *et al.*, 2005).

$$A = \frac{\pi WT}{4} \qquad (5)$$

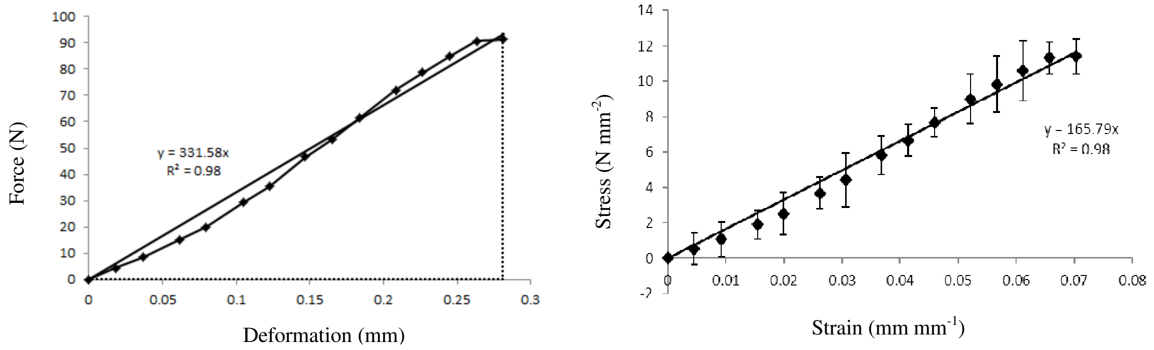
$$V = \frac{1}{4}\left[\left(\frac{\pi}{6}\right)L(W+T)^2\right] \qquad (6)$$

Where, *L, W* and *T* are the length, width and thickness of the wheat kernel in mm, respectively.

This experiment was conducted for each variety such that, in total, 300 tests (10 varieties by 30 replications) were conducted.

Compression Test

In this experiment, single wheat grains were placed between two parallel plates of the lower and upper heads of a compression-testing machine (Instron, Model: Santam STM-20) with an accuracy of 0.01% of load cell capacity (20 KN). The upper head compressed the kernel with constant loading rate of 7 mm min^{-1} till rapture was occurred. For each test, force-deformation values were measured by Instron, recorded in the computer. Figure 3-a shows a typical force-deformation curve in this study. The force-deformation curve was used to extract mechanical properties of kernels. The mechanical properties consisted of maximum force at rapture point, apparent elastic modulus and static toughness. The apparent elastic modulus, E_{app} (N mm^{-2}) was obtained from stress-strain curve. The slope of the fitted line through the stress-strain data points at linear limit was considered as apparent elastic modulus (Figure 3-b):



(a) (b)

Figure 3. A typical force-deformation curve of wheat grain: (a) Fitted line and the approximate triangular shaped area for calculating static toughness, and (b) Fitted line through the stress-strain data point for calculating the apparent elastic modulus.

$$E_{app} = \frac{\sigma_{\max}}{\varepsilon} \tag{7}$$

Where, σ_{max} is the maximum axial stress at rapture point on the fitted line (N mm^{-2}) and ε is the strain at rapture point (mm mm^{-1}).

Besides, the static toughness, T_s (mJ mm^{-3}) was calculated from dividing the area under the force-deformation curve by kernel volume as follows:

$$T_s = \frac{A_{under\ curve}}{V} \tag{8}$$

The area under the force-deformation curve (mJ) was considered as a triangular shaped area and estimated with a good approximation from the following equation:

$$A_{under\ curve} = \frac{1}{2} F_{\max} x \tag{9}$$

Where, F_{max} and x are the maximum force (N) and deformation (mm) at the rapture point, respectively.

This experiment was conducted for each variety such that, in total, 300 tests (10 varieties by 30 replications) were conducted.

Statistical Analysis

All experiments were conducted in a randomized complete design with 10 treatments (variety) and 30 replications for mechanical and physical properties, and 3 replications for chemical properties. The data were analyzed using the ANOVA procedure of SPSS followed by the comparison of means using the Duncan multiple range test ($P < 0.05$). The relationships between physicochemical characteristics and mechanical properties were calculated using stepwise regression analysis.

RESULTS AND DISCUSSION

Physicochemical Properties

The physicochemical properties of ten wheat cultivars are shown in Table 1. The results for various varieties showed that the physical properties varied significantly. The kernel length for various cultivars varied from 6.49 mm (for Falat) to 7.75 mm (for Keras Adl). The kernel width was in the range of 2.92 mm (Keras Adl) to 3.22 mm (Bam). The kernel thickness of the cultivars studied were significantly different and in the range of 2.57 mm for Shiraz to 2.92 mm for Chamran. The length-width ratio of samples among different wheat cultivars ranged from 1.95 (Chamran) to 2.67 (Keras Adle). The thousand kernel weight showed significant variation among different wheat cultivars; Chamran and Nicknejad had the highest (38.91 g) and lowest (27.98 g) values of 1,000 kernel weight, respectively. The significant differences observed in physical properties among wheat varieties may be due to the differences in the genetic make-up of the varieties. However, these differences may be partly attributed to different growing and environmental conditions that prevailed during growing periods.

PSI (as an indicator of wheat hardness) values ranged from 12.17% in Keras Adle to 26.63% in Bam (Table 1). Lower values of the *PSI* for wheat kernels indicate that the wheat kernels are harder. The findings of the present study depicted that two wheat varieties fall in the category of semi-hard, three varieties are semi-soft, three varieties fall in the category of hard, one variety is soft, and only one variety falls in the class of very hard wheat as according to the hardness scale given in AACC (2000). Anjum *et al.* (2005) evaluated six Pakistani wheat varieties and observed that they fell into the category of semi- hard group. Butt *et al.* (2001) found *PSI* of 30 Pakistani wheat varieties ranging from 17.32 to 24.41%. As mentioned earlier, the wheat hardness has a significant impact on the end product quality. The soft wheat kernels fracture more easily, release many integral starch granules, and produce finer textured flours with less starch damage. On the other hand, hard wheats produce coarser textured flours in which fracture planes produce broken starch granules. Because broken starch granules absorb more water, hard wheats are better suited for yeast-leavened bread, while soft wheats are preferred for cookies, cakes, and pastries (Morris and Rose, 1996). Therefore, in this study, the harder varieties such as Keras Adl, Shiraz, and Bahar are recommended for preparation of flat bread, while the softer wheat such as Bam, Chamran, and Marvdasht are preferred for cookies, and cakes.

The protein content varied significantly among the cultivars studied: Keras Adl had the highest protein content (12.01%), while Bam had the lowest (10.63%). Wheat having high protein content tends to be hard, have

Table 1. Physicochemical properties of different wheat cultivars.[a]

Cultivars	Length (mm)	Width (mm)	Thickness (mm)	Length/width	1000 kernel weight (g)	PSI[b] (%)	Hardness scale	Protein (%)	Fiber (%)	Fat (%)	Ash (%)
Alamut	6.97±0.07 c	3.00±0.01ab	2.64±0.07ab	2.33±0.04d	33.33±0.58cd	23.00	Semi-soft	10.72±0.20de	3.26±0.09f	2.04±0.04ab	1.12±0.001e
Azar2	7.51±0.06 d	3.07±0.01bc	2.73±0.07bc	2.45±0.04e	35.47±0.02de	18.67	Semi-hard	11.68±0.16c	2.03±0.04a	2.16±0.09abcd	1.04±0.040d
Bahar	6.55±0.08ab	2.88±0.02ab	2.89±0.07de	1.96±0.04a	36.12±0.57def	15.97	Hard	11.83±0.34de	1.85±0.08a	1.97±0.07a	0.980±0.001bc
Bam	7.08±0.05c	3.22±0.03e	2.78±0.07cde	2.21±0.04c	37.85±0.53ef	26.63	Soft	10.63±0.10e	2.36±0.07b	2.27±0.01cd	0.95±0.030b
Chamran	6.66±0.09ab	3.43±0.01f	2.92±0.07f	1.95±0.04a	38.91±0.67f	23.13	Semi-soft	10.87±0.24d	2.73±0.04d	2.24±0.03bcd	1.02±0.010cd
Falat	6.49±0.07a	3.16±0.03cd	2.81±0.07cde	2.07±0.04b	30.64±0.58abc	15.50	Hard	11.53±0.22b	2.00±0.04a	2.06±0.01abc	0.99±0.010c
Keras Adl	7.75±0.06e	2.92±0.02a	2.61±0.07a	2.67±0.04f	33.45±0.71cd	12.17	Very hard	12.01±0.26a	2.92±0.09e	2.37±0.09de	0.94±0.050b
Marvdasht	6.63±0.05ab	3.05±0.01bc	2.74±0.07bc	2.19±0.04c	29.16±0.68ab	22.43	Semi-soft	10.71±0.19c	2.47±0.09bc	3.00±0.02f	1.16±0.010e
Nicknejad	6.70±0.05b	2.96±0.04ab	2.64±0.07ab	2.27±0.04cd	27.98±0.53a	20.37	Semi-hard	11.26±0.14c	3.08±0.03ef	2.57±0.09e	1.25±0.001f
Shiraz	6.59±0.06ab	3.06±0.05bc	2.57±0.07a	2.17±0.04c	31.14±0.67bc	16.70	Hard	11.78±0.24c	2.65±0.03cd	3.15±0.09f	0.87±0.001a

[a] Mean±SD; different letters within each column show significant difference at $P < 0.05$. [b] Particle Size Index.

strong gluten, and produce good quality bread. Wheat of low protein content tends to be soft, have weak gluten, and produce small loaves of inferior crumb structure (Tipples *et al*., 1994), but produce better quality cookies. To produce bread with better quality from Iranian wheat cultivars, the protein content should be 11-13% (Samiee, 2004). The fiber content of the samples varied from 1.85% (for Bahar) to 3.26% (for Alamut). The fat content of the samples was in the range of 1.97% (Bahar) to 3.15% (Shiraz). The ash content of the samples were significantly different and in the range of 0.87% for Shiraz to 1.25% for Nicknejad. In this regard, Majzoobi *et al.* (2011) reported the range of protein, fat, and ash compositions of different Iranian wheat cultivars as 10.74-14.98, 1.48-2.95 and 0.54-2.96%, respectively, which agree with the present study. The correlation analysis results of physicochemical properties showed that there was a significant and negative correlation (r^2= 0.59) between the *PSI* and the protein content. No significant correlation was found between the other parameters. The variation of protein content with the *PSI* is shown in Figure 4, which depicts that the protein content increases with the decrease of *PSI* value. In other words, wheat having low *PSI* value tend to be hard and have higher protein content.

Mechanical Properties

The mean values of mechanical parameters for ten Iranian wheat cultivars under compression and impact loadings are presented in Table 2. The results indicated that the mechanical properties were significantly different among various cultivars. The maximum force at rapture, apparent elastic modulus, and toughness of different varieties were in the range of 48.51-88.96 N, 173.5 -267.73 N mm^{-2}, and 0.155 -0.297 mJ mm^{-3}. The maximum and minimum values of these parameters belonged to Keras Adl and Bahar varieties. The results investigated in the present study are in line with earlier work conducted by Rasekh *et al.* (2007) who reported the range of the maximum force at rapture and static toughness in different wheat varieties as 31.8-66.29 N and 0.15-0.41 mJ mm^{-3}, respectively. Wide range of these parameters in this study may be due to genetic and environmental effects.

Similar results were obtained for the mechanical parameters under impact loading. The breakage energy varied from 36.33 to 50.19 mJ. The specific breakage energy was in range of 4.75 to 8.38 mJ mm^{-2}. The dynamic toughness in different cultivars varied from 1.08 to 1.61 mJ mm^{-3}. As expected, the maximum and minimum of these parameters corresponded to Keras Adl

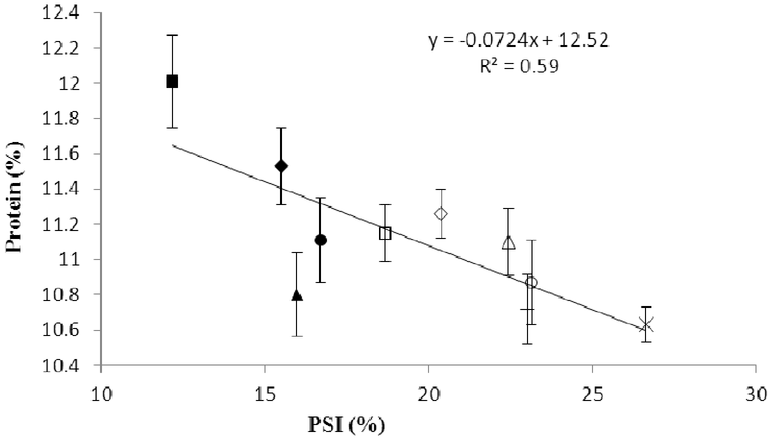


Figure 4. Correlation between particle size index (PSI) and protein for ten wheat cultivar; (■) Keras Adl, (♦) Falat, (▲) Bahar, (●) Shiraz, (□) Azar 2, (◊) Nicknejad, (Δ) Marvdasht, (+) Alamut, (○) Chamran, (×) Bam.

Table 2. Mechanical characteristics of ten Iranian wheat cultivars.[a]

	Parameters obtained from compression test			Parameters obtained from Impact test		
Cultivars	Maximum force (N)	Apparent elastic modulus (N mm^{-2})	Static toughness (mJ mm^{-3})	Breakage energy (mJ)	Specific breakage energy (mJ mm^{-2})	Dynamic toughness (mJ mm^{-3})
Alamut	62.17±4.40cd	188.70±11.56b	0.184±0.06cd	37.13±2.65cd	5.98±2.65cde	1.28±0.34def
Azar2	60.96±5.60cd	215.77±10.98ab	0.193±0.09cd	36.52±2.54cd	5.52±0.84de	1.13±0.29f
Bahar	48.51±3.34bcd	173.50±10.54ab	0.155±0.05ab	36.33±2.45b	4.75±0.87bcd	1.08±0.31f
Bam	57.93±3.80d	190.67±9.87b	0.164±0.05d	41.18±3.15d	5.82±0.93f	1.22±0.24g
Chamran	65.96±4.50cd	216.97±12.24ab	0.198±0.05bcd	41.67±4.67cd	5.42±0.95e	1.18±0.36ef
Falat	73.32±4.45bc	230.73±11.30ab	0.289±0.06a	47.91±4.22b	6.85±0.91b	1.58±0.33b
Keras Adl	88.96±4.25a	267.73±10.78a	0.297±0.08a	50.19±3.78a	8.38±0.92a	1.61±0.30a
Marvdasht	71.44±5.20bc	224.27±9.96b	0.250±0.09abc	42.86±3.95bc	6.51±0.88bc	1.46±0.29bc
Nicknejad	69.73±4.45bcd	222.97±10.65b	0.231±0.09abcd	38.37±2.98c	6.25±0.79bcd	1.39±0.36cd
Shiraz	79.78±5.24ab	238.77±11.35ab	0.201±0.06bcd	36.83±2.56cd	5.97±0.86cde	1.35±0.27cde

[a] Mean±SD; different letters within each column show significant difference at $P < 0.05$.

and Bahar varieties. The results reported by Afkari *et al*. (2006) support our findings who found the breakage energy in different wheat varieties in the range of 33-72 mJ as the impact test was applied with a different method. As mentioned before, the mechanical properties are correlated with some wheat quality specifications, therefore, the results of this section can be useful for determining the quality of the wheat in advance, as discussed in the following sections.

Relationship between Physicochemical and Mechanical Parameters

Values of the simple coefficient of determination (r^2), for the relationship between the physicochemical and mechanical properties of wheat grain are summarized in Table 3. The coefficient of determination is the ratio of explained variation to total variation. For example, the r^2 value of 0.7 means that 70% of the total

Table 3. Correlation values calculated between physicochemical properties and mechanical parameters.

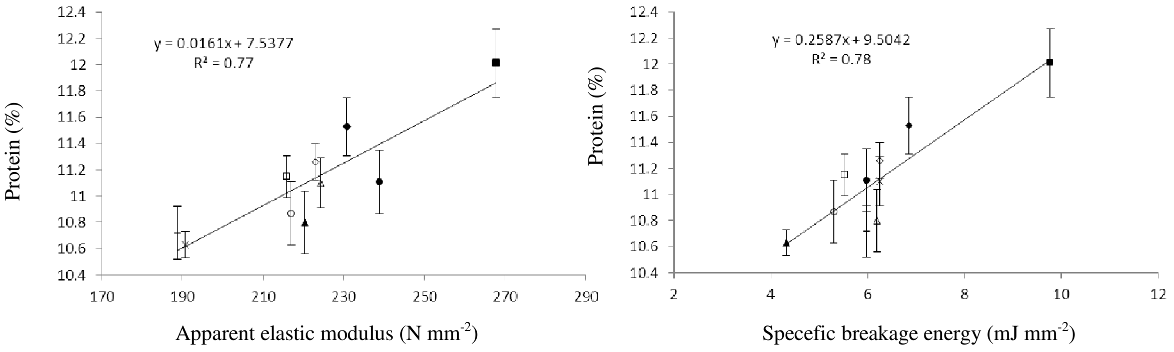
	Length	Width	Thickness	Length /Width	1000 kernel weight	PSI[a]	Protein	Fiber	Fat	Ash
Maximum force	0.01^{NS}[b]	0.14^{NS}	0.20^{NS}	0.11^{NS}	0.18^{NS}	0.62 **	0.70**	0.18^{NS}	0.18^{NS}	0.09^{NS}
Apparent elastic modulus	0.04^{NS}	0.09^{NS}	0.09^{NS}	0.11^{NS}	0.11^{NS}	0.70**	0.77**	0.00^{NS}	0.12^{NS}	0.09^{NS}
Static toughness	0.00^{NS}	0.20^{NS}	0.00^{NS}	0.00^{NS}	0.15^{NS}	0.60**	0.54*	0.05^{NS}	0.00^{NS}	0.00^{NS}
Breakage energy	0.03^{NS}	0.12^{NS}	0.00^{NS}	0.05^{NS}	0.01^{NS}	0.60**	0.57**	0.00^{NS}	0.00^{NS}	0.00^{NS}
Specific breakage energy	0.15^{NS}	0.27^{NS}	0.15^{NS}	0.32^{NS}	0.13^{NS}	0.62**	0.78**	0.05^{NS}	0.00^{NS}	0.01^{NS}
Dynamic toughness	0.01^{NS}	0.26^{NS}	0.08^{NS}	0.11^{NS}	0.26^{NS}	0.64**	0.70**	0.02^{NS}	0.01^{NS}	0.00^{NS}

[a] Particle Size Index, [b] NS: Not Significant. **: Significant at $P < 0.01$.

variation in the dependent variable can be explained by the linear relationship between the independent variable and the dependent variable. The other 30% of the total variation in the dependent variable remains unexplained. The protein content was significantly correlated with the mechanical parameters under compression test such as maximum force (r^2= 0.70), apparent elastic modulus (r^2= 0.77), and static toughness (r^2= 0.54). Besides, linear and significant relationships were found between protein content and mechanical parameters extracted from impact test such as breakage energy (r^2= 0.57), specific breakage energy (r^2= 0.78), and dynamic toughness (r^2= 0.70). Among the mechanical parameters obtained from compression test, the apparent elastic modulus established maximum correlation (r^2= 0.77) with protein content, whereas for impact test, the maximum correlation (r^2= 0.78) was obtained for the specific breakage energy. The variation of the protein content with apparent elastic modulus and the specific breakage energy are shown in Figure 5 (a and b), respectively. In the figure, it is found that increase in the protein content leads to increases in both of the parameters. The reason may be high resistance of grains to failure as a result of high protein content (Symes, 1965). Other results showed that the *PSI* was significantly correlated with the mechanical parameters obtained from compression test such as maximum force (r^2= 0.62), apparent elastic modulus (r^2= 0.70), and static toughness (r^2= 0.60). Besides, significant correlation was observed between *PSI* and parameters obtained from impact test including breakage energy, specific breakage energy, and dynamic toughness. The coefficients of determination (r^2) for the parameters were equal to 0.60, 0.62, and 0.64, respectively. The results of the present study are in agreement with the study conducted by Afkari *et al.* (2004) who reported r^2= 0.77 between apparent elastic modulus and *PSI*. No significant correlation was found between other physicochemical properties and mechanical parameters.

CONCLUSIONS

The physicochemical and mechanical properties for ten Iranian wheat cultivars were measured at moisture content of 11.5±0.5% (wb). The results indicate that the type of variety has significant influences on the physicochemical and mechanical properties. These properties can have a great impact on the quality of the final products. Therefore, correct selection of the wheat cultivar for specific applications seems to be crucial. For example, wheats having low protein content (in this study, Bam and Alamut) can be regarded as having weak flours. Therefore, it may be concluded that



(a) (b)

Figure 5 Relationships between protein and apparent elastic modulus (a) and specific breakage energy (b) of different wheat cultivars; (■) Keras Adl, (♦) Falat, (▲) Bahar, (●) Shiraz, (□) Azar 2, (◊) Nicknejad, (Δ) Marvdasht, (+) Alamut, (○) Chamran, (×) Bam.

for better application of wheat, the physicochemical properties of wheat should be considered as a quality criterion. A relatively strong correlation was found between the protein content and particle size index (r^2= 60). Moreover, the protein content could be significantly correlated with the parameters obtained from mechanical tests (r^2> 0.50). Among the mechanical parameters obtained from compression and impact loading, the apparent elastic modulus and the specific breakage energy established maximum correlation (r^2= 0.77 and 0.78, respectively) with the protein content. Similarly, significant correlations were found between particle size index and parameters extracted from mechanical tests (r^2> 0.60). Hence, the wheat protein content and particle size index, which are effective on quality of final product, can be estimated by several simple mechanical tests on wheat kernels.

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ارتباط بین خصوصیات فیزیکوشیمیایی و مکانیکی برخی ارقام گندم ایرانی

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چکیده

خصوصیات فیزیکو شیمیایی و مکانیکی گندم تأًثیر مهمی روی کیفیت محصول نهایی (نان) دارد. از اینرو، انتخاب صحیح گندم برای یک کاربرد خاص یک امر حیاتی می باشد. در این مطالعه خصوصیات فیزیکو شیمیایی و مکانیکی (تحت بارگذاری ضربه ای و فشاری) ۱۰ رقم گندم و همچنین ارتباط بین این خصوصیات مورد بررسی قرار گرفت. نتایج نشان داد که رقم تأًثیر معنی داری روی این خصوصیات دارد. نتایج حاصل از آنالیز رگرسیونی نشان دهنده وجود یک رابطه خطی بین محتوای پروتئین دانه و شاخص توزیع اندازه ذرات بود ($r^2= 0.6$). علاوه براین، محتوای پروتئین دانه ها به طور معنی داری با پارامترهای حاصل از آزمون مکانیکی همبسته شد ($r^2> 0.5$). در میان پارامترهای حاصل از بارگذاری فشاری و ضربه ای، بیشترین ضریب همبستگی به ترتیب مربوط به مدول الاستیک ظاهری ($r^2= 0.77$) و انرژی ویژه شکست بود ($r^2= 0.78$). به طور مشابه، همبستگی های معنی داری بین شاخص توزیع اندازه ذرات و پارامترهای مکانیکی حاصل شد ($r^2> 0.6$). از اینرو محتوای پروتئین دانه ها و شاخص توزیع اندازه ذرات که تأًثیر مهمی روی کیفیت محصول نهایی دارند می تواند توسط چند آزمون ساده مکانیکی تخمین زده شود.