Physico-mechanical properties of rough rice (*Oryza sativa* L.) grain as affected by variety and moisture content

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Abstract: Rice varieties in Isfahan Province (central Iran) have high breakage losses during processing. In order to optimize the design of machinery used for milling of these varieties it is quite important to determine their engineering properties. In this study, physical and mechanical properties of Sorkheh and Sazandegi varieties were determined at three moisture content levels. To determine the mechanical properties, compression and three-point bending tests were conducted. It was observed that, by increasing moisture content, geometric mean diameter, sphericity, true density, and angle of repose were all increased, whereas bulk density decreased. In contrary to the moisture content at the tested range, variety had a significant effect on rough rice mechanical properties. For Sorkheh, the average fracture force, fracture energy, modulus of elasticity, and toughness obtained by compression test, were 169.1 N, 44.2 J×10^{-3}, 996.1 MPa, and 1.88 MJ/m^3, respectively. The corresponding values for Sazandegi were 125.1 N, 24.4 J×10^{-3}, 555.6 MPa, and 1.11 MJ/m^3. In three-point bending test, the average fracture force, fracture energy, and bending strength of Sorkheh were 24.2 N, 5.1 J×10^{-3}, and 23.4 MPa, respectively. For Sazandegi, these values were 19.1 N, 3.7 J×10^{-3}, and 17.7 MPa, respectively. Comparison of obtained mechanical properties with the literature revealed that the high milling losses of Isfahan province rice varieties could be due to the methods and devices used for their processing operations.

Keywords: mechanical characteristic, milling, moisture content, physical property, Iran

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1 Introduction

Rice (*Oryza sativa* L.) is one of the commonly consumed cereals and food staples for more than half of the world’s population. It is an important source of energy, vitamins, mineral elements, and rare amino acids. World rice production increased from 520 million tonnes in 1990 to 605 million tonnes in 2004, while Iran’s rice production increased from 1.3 million tonnes in 1980 to 3.4 million tonnes in 2004 (FAO, 2005).

The knowledge of physical and mechanical properties of the agricultural products is of fundamental importance for proper storage procedure and for design, dimensioning, manufacturing, and operating different equipments used in post harvest and processing operations of these products (Corrêa et al., 2007). Some post harvest operations are threshing, handling, cleaning, drying, and milling.

For rice grain, milling is the process of applying the load to the kernels in order to remove the bran layers and germ (Lu and Siebenmorgen, 1995). Principal dimensions of rough rice are used for calculating the power requirement during this process. Also physical properties of rough rice could affect its milling quality parameters like head rice yield (HRY) and degree of milling (DOM). Liu et al. (2009) investigated the relationships between physical properties (length, width, thickness, aspect ratio, equivalent diameter, sphericity, surface area, volume, bulk density, true density, porosity, and thousand-seed weight) and DOM of brown rice varieties during milling process. During rice milling, kernels are exposed to different compressive, bending,

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shear and frictional forces, and breakage can consequently occur (Shitanda, Nishiyama and Koide, 2002). This breakage causes HRY reduction and economic losses. The correlation of HRY to mechanical properties has been used by researchers to show the susceptibility of rice varieties to breakage during processing. Lu and Siebenmorgen (1995) studied the correlation of HRY to select physical and mechanical properties of rice kernels. Zhang et al. (2005) reported mechanical properties of sound and fissured rice kernels and their implications for rice breakage. Their results revealed that fissuring caused a rice kernel to stand less force and absorb less deformation energy before it broke. Hence, determination of physical and mechanical properties of rice varieties has always been investigated by specialists.

Corrêa et al. (2007) measured physical characteristics of rice kernel including dimensions, true and bulk densities, and porosity in rough, brown, and milled states at moisture content of 12% (w.b.). Their results showed a reduction in kernel's bulk density from rough to milled condition. They also considered other characteristics such as porosity and density as main parameters in heat and mass transfer phenomena and projected area and volume as basic parameters in crop drying and storage. Ghasemi Varnamkhasti et al. (2008) determined various physical properties of rough rice at moisture content of 10% (w.b.). Lee and Kunze (1972) inspected the effect of two factors of temperature and moisture content on rice kernels mechanical properties. Their results indicated that the mechanical properties are affected by moisture content and temperature factors. Shitanda, Nishiyama and Koide (2002) investigated compression resistance of three rough rice varieties under quasi-static loading.

In spite of good aroma and flavor, rice varieties in Isfahan province (central Iran) have high breakage losses during milling process. In order to optimize the design of machinery used for milling of these varieties and obtain some simple and quantitative criteria to detect the susceptible varieties to breakage, their engineering properties should be determined. So far, only some physical characteristics of Isfahan rough rice at moisture content of 10% (w.b.) have been reported (Ghasemi Varnamkhasti et al., 2008). In the research reported here, the physical and mechanical properties of two common rough rice varieties namely, Sorkheh and Sazandegi were investigated over a wider range of moisture content.

2 Materials and methods

2.1 Sample preparation and procurement

Two common rough rice varieties called Sorkheh and Sazandegi, which are grown in Isfahan province (central Iran), were prepared from Isfahan Center for Agricultural and Natural Resources Research. The samples were cleaned manually to remove stones, straw, and dirt and then sieved to remove broken and damaged kernels. Initial moisture content (MC) of samples was determined by drying them in an oven according to ASAE (2001b). Initial MC of Sorkheh and Sazandegi were 20.5 and 21.2% (w.b.), respectively. The samples were then air-dried under sunlight at mean day temperature of 26.2℃ until they reached to desirable MC levels of 11% – 13%, 13% – 15% and 15% – 17% (w.b.) (henceforth referred to as 12%, 14%, and 16% (w.b.), respectively). These MC levels were selected since the milling operations in the region were performed in this range (Abedi, 1997). The rough rice samples were finally sealed in double plastic bags and stored at approximately 4℃ before conducting the experiments.

2.2 Physical properties measurement

The measured physical properties were dimensions (major, intermediate and minor diameters, geometric mean diameter and sphericity), mass, bulk and true densities, porosity, static coefficient of friction and angle of repose. Principal dimensions of rough rice kernel and its mass were determined by selecting 100 kernels randomly and measuring the kernels' length (a), width (b) and thickness (c) at different MCs using a digital caliper with accuracy of 0.01 mm and a digital balance with accuracy of 0.001 g, respectively. Then, geometric mean diameter (GMD) and sphericity (ϕ) were calculated as follows (Mohsenin, 1986):

$$GMD = (abc)^{\frac{1}{3}} \tag{1}$$

$$\varphi=\frac{GMD}{a} \tag{2}$$

True density (ρ_p) was determined by toluene displacement method (Stroshine and Hamann, 1998) and bulk density (ρ_b) was determined accordingly to Amin et al. (2004). Then porosity (ε) was computed using the following equation (Mohsenin, 1986):

$$\varepsilon=\frac{\rho_p-\rho_b}{\rho_p}\times 100\% \tag{3}$$

The static coefficient of friction of rice kernels was determined against the surfaces of plywood, glass, galvanized iron sheet and concrete with the slope controller mechanism. A hollow woody box of 150 mm × 100 mm × 40 mm was filled with kernels. The inclined surface was raised gradually until the filled box started to slide down. By measuring the angle of surface (θ) at this state, static coefficient of friction was considered as $\tan\theta$.

The angle of repose was considered from two aspects: emptying and filling. To determine the emptying angle of repose, a specific constructed box of 440 mm × 440 mm × 210 mm having a removable front panel was used. The box was filled with rice kernels and then the front panel was quickly removed, allowing the kernels to flow to their natural slope. To determine the filling angle of repose another constructed box of 1,250 mm × 110 mm × 750 mm was used. The box was filled with kernels by dropping them from a height as equal as the height of the box by a funnel.

All physical experiments including measurement of densities, coefficient of friction, and angles of repose were conducted in five replications.

2.3 Mechanical properties measurement

The parallel-plate compressive and three-point bending tests were carried out to determine the mechanical properties of rice kernels. Both tests were conducted using a universal testing machine (Hounsfield, model H50 K-S).

Compressive tests were performed at deformation rate of 1.25 mm/min (quasi-static loading). In order to have a good contact between the rice kernel and the compressive flat plates, the kernel was placed in its natural rest position and then the compressive load was applied. A typical force-deformation curve is shown in Figure 1. As it is shown, the force-deformation curve exhibited two peak points. The first peak corresponds to the yield point at which kernel damage was initiated. The second peak corresponds to the maximum compressive force. The rupture energy was calculated from the area under the curve up to the fracture point. The toughness was calculated as the rupture energy at failure divided by the kernel volume. Volume (V) of each seed itself was calculated as follows:

$$V=\frac{\pi}{6}abc \tag{4}$$

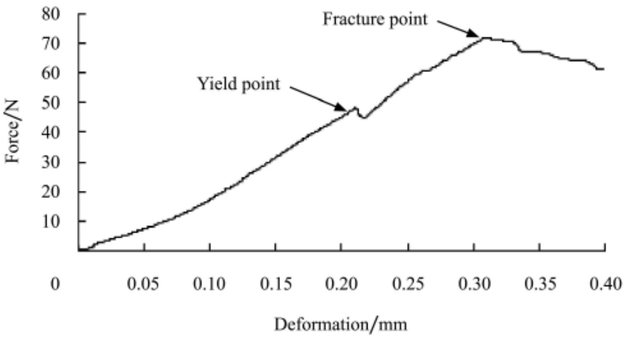

Figure 1 A typical force-deformation curve for rough rice kernel under compressive loading

Apparent modulus of elasticity (E) was computed by using Hertz contact stresses theory for parallel-plate contact geometry (ASAE, 2001a):

$$E=\frac{0.338K^{\frac{3}{2}}F_c(1-\nu^2)}{\delta^{\frac{3}{2}}}\left[\left(\frac{1}{R_1}+\frac{1}{\acute{R}_1}\right)^{\frac{1}{3}}+\left(\frac{1}{R_2}+\frac{1}{\acute{R}_2}\right)^{\frac{1}{3}}\right]^{\frac{3}{2}} \tag{5}$$

The compressive force (F_c) was considered at deformation (δ) of kernel at about half of inflection point and the Poisson's ratio (ν) was taken to be 0.28 (Shitanda et al., 2002). The compression test was conducted on 20 randomly selected kernels per treatment.

In three-point bending test, low loading speed can minimize the stored elastic energy remaining when fracturing is completed (Zhang, Yang and Sun, 2005). Therefore, the tests were conducted at loading rate of 0.5 mm/min. In this test, mechanical properties were determined similar to Zhang, Yang and Sun (2005). In the experiments, 100 sound rough rice kernels were randomly selected for mechanical property measurements. Rice kernels were naturally oriented over the support with major diameter horizontal. After contact between machine probe and kernel surface, bending force-deformation curves were plotted until the rupture took place. Then, all desired attributes were determined from each curve. Specific fracture energy (G) is defined by:

$$G = \frac{\int F_b d\delta}{A} \tag{6}$$

The numerator at the right hand of equation 6 is fracturing energy and was computed numerically by measuring the area under the force-deformation curve up to the breakage point. F_b and δ are bending force and kernel deformation, respectively. The fracture surface was assumed as an ellipse and the breakage surface bisected the rice kernel perpendicularly to the longitudinal axis. Therefore, the area of fracture surface (A) was calculated by:

$$A = \frac{\pi bc}{4} \tag{7}$$

Maximum bending stress (σ) a material can sustain before it is ruptured by a flexural load is calculated by the following equation:

$$\sigma = \frac{F_b LS}{4I} \tag{8}$$

The peak bending force (breakage force) was used for calculating the maximum bending stress. The beam span (L) was 3.5 mm in accordance with average length of rice kernels. The distance from the neutral axis to the outer layer of the rice kernel (S) was considered as half of the rice kernel thickness. Considering the aforementioned fracture surface, the moment of inertia (I) was calculated as follows:

$$I = 0.049bc^3 \tag{9}$$

2.4 Data analysis

The experimental design was randomized complete design with factorial layout in which two varieties and three levels of MC were the independent variables and the physical characteristics and mechanical properties were the dependent variables. Treatment effects were analyzed using ANOVA PROC of SAS software. When the F-value was significant (P<0.05), the least significant difference (LSD) test was used for means comparison of data.

3 Results and discussion

3.1 Dimensions, Mass, GMD, Sphericity, True Density, Bulk Density, and Porosity

The dimensions, mass, GMD, and sphericity of the kernels were significantly affected by variety (P<0.001). Except for the length, other physical characteristics including width, thickness, mass, GMD and sphericity of Sazandegi were significantly lower than their values for Sorkheh (Table 1). Sorkheh had a significantly higher aspect ratio; the ratio of width to length as defined by Maduako and Faborode (1990); as compared to Sazandegi. This characteristic could affect the kernel behavior during milling operation and consequently, the HRY might be affected.

Table 1 Mean comparison of size, mass, shape, bulk and true densitities, and porosity of Sorkheh and Sazandegi varieties as affected by moisture content

Experimental factor	Length/ mm	Width/ mm	Thickness/ mm	Mass/ g	GMD/ mm	Sphericity	Bulk density/ kg · m^{-3}	True density/ kg · m^{-3}	Porosity/ %
Variety									
Sorkheh	8.27^{b*}± 0.54**	2.85^{a}± 0.26	1.98^{a}± 0.17	0.026^{a}± 0.003	3.596^{a}± 0.22	0.435^{a}± 0.026	598^{a}± 2.00	1136^{a}± 23.50	47.41^{b}± 0.99
Sazandegi	8.68^{a}± 0.61	2.47^{b}± 0.29	1.88^{b}± 0.19	0.024^{b}± 0.003	3.422^{b}± 0.21	0.400^{b}± 0.028	576^{b}± 1.88	1131^{a}± 24.83	48.85^{a}± 1.01
MC (% w.b.)									
12	8.53^{a}± 0.56	2.63^{a}± 0.26	1.89^{c}± 0.18	0.026^{b}± 0.003	3.465^{b}± 0.21	0.412^{b}± 0.029	594^{a}± 1.94	1114^{c}± 21.01	46.70^{b}± 1.00
14	8.53^{a}± 0.52	2.68^{a}± 0.30	1.93^{b}± 0.17	0.026^{b}± 0.003	3.525^{a}± 0.20	0.415^{ab}± 0.025	584^{c}± 2.01	1136^{b}± 24.87	48.65^{a}± 0.94
16	8.47^{a}± 0.64	2.68^{a}± 0.28	1.96^{a}± 0.17	0.028^{a}± 0.004	3.538^{a}± 0.21	0.419^{a}± 0.028	587^{b}± 1.89	1152^{a}± 21.38	49.04^{a}± 1.07

Note: * For each factor, the means in the same column followed by the common lowercase superscript letters do not differ statistically at 5% probability level using LSD test. ** Table values show the mean ± one standard deviation.

For both varieties, the kernel length was more than twice of its width (Table 1). When the kernel major diameter (length) is no more than twice its intermediate diameter (width), the grading is satisfactory even on sieves having a horizontally reciprocating motion (Klenin et al., 1986). Therefore, for both varieties the grading could be performed with horizontally vibrating sieves.

The MC had a significant effect on thickness, mass and GMD ($P<0.05$). Among three diameters, only the thickness was significantly affected by MC. As the MC increased from 12% to 16% (w.b.) the average kernel thickness was increased from 1.89 to 1.96 mm. It should be mentioned that the mean values of sphericity for Sorkheh (0.435) and Sazandegi (0.400) fall within the range of 0.32-1 reported for most agricultural products (Mohsenin, 1986).

The bulk density and porosity were significantly affected by variety ($P<0.001$). The effect of MC on bulk and true densities, and porosity was significant ($P<0.001$). This finding is in line with the results presented for Brazilian rice (Corrêa et al., 2007). As Table 1 shows Sorkheh had significantly higher bulk density than Sazandegi (598 vs. 576 kg/m^3). This could be due to higher sphericity of the Sorkheh. The higher the sphericity of the kernels, the more regular is array of them together. Consequently, there would be smaller cavities between the kernels which in turn results in a higher bulk density.

The mean values of true density for Sorkheh and Sazandegi varieties were 1,136 and 1,131 kg/m^3, respectively, and did not show a significant difference. The true density of cereal grains is important to separate various impurities from them as the true density of cereal crops and most impurities widely differ. According to Table 1, as the MC increased the true density was increased significantly.

The mean values of porosity for Sorkheh and Sazandegi were 47.41% and 48.85%, respectively, which were lower than the values of 64 to 66% for three Brazilian varieties as reported by Corrêa et al. (2007). This difference is due to the inherent characteristics of varieties. Similarly to the Paksoy and Aydin (2004), the porosity was increased by increasing MC.

3.2 Static coefficient of friction

The effects of variety, MC and surface type on static coefficient of fiction were significant ($P<0.001$). Similar result has been reported by Corrêa et al. (2007) for three Brazilian varieties at MC of 12% (w.b.). Table 2 shows that the mean values of static coefficient of friction against the tested surfaces decreased significantly in order of concrete (0.432), galvanized iron sheet (0.363), plywood (0.276) and glass (0.082). It was also observed that, Sorkheh had significantly higher static coefficient of friction (0.303) than Sazandegi (0.237). Table 2 also indicates that as MC increased from 12% to 16% (w.b.), this attribute was significantly increased. Amin et al. (2004) reported similar results on frictional properties of lentil seeds over concrete, galvanized iron sheet, wood and glass surfaces. In their study, static coefficient of friction was increased from 0.458 to 0.490 as MC increased.

Table 2 Mean comparison of frictional static coefficient of Sorkheh and Sazandegi varieties as affected by surface material and moisture content

Experimental factor	Static coefficient of friction
Frictional surface	
Plywood	$0.276^{c*} \pm 0.12^{**}$
Glass	$0.082^{d} \pm 0.14$
Concrete	$0.432^{a} \pm 0.12$
Galvanized iron sheet	$0.363^{b} \pm 0.15$
Variety	
Sorkheh	$0.303^{a} \pm 0.14$
Sazandegi	$0.273^{b} \pm 0.13$
MC (% w.b.)	
12	$0.262^{c} \pm 0.13$
14	$0.292^{b} \pm 0.14$
16	$0.310^{a} \pm 0.14$

Note: * For each factor, the means in the same column followed by the common lowercase superscript letters do not differ statistically at 5% probability level using LSD test.

** Table values show the mean ± one standard deviation.

3.3 Angle of repose

The effects of variety and MC on emptying and filling angles of repose were significant ($P<0.001$). Sorkheh variety had higher mean values for both angles than Sazandegi (35.6° and 29.6° versus 31.7° and 26.1°, respectively; Table 3). For each variety and at each MC, the mean value of emptying angle of repose was higher than that of filling angle. Both angles were increased as

MC increased (Table 3). Angle of repose is a useful parameter for optimum design of hoppers. The inclination angle of hopper wall should be larger than the grain angle of repose to ensure the continuous flow of grain by gravitational force.

Table 3 Mean comparison of angle of repose of Sorkheh and Sazandegi varieties as affected by moisture content

Experimental factor	Angle of repose / (°)	
Variety	Emptying	Filling
Sorkheh	$35.6^{a*} \pm 0.39^{**}$	$29.6^{a} \pm 0.30$
Sazandegi	$31.7^{b} \pm 0.24$	$26.1^{b} \pm 0.28$
MC (% w.b.)		
12	$32.6^{c} \pm 0.27$	$27.2^{c} \pm 0.27$
14	$33.7^{b} \pm 0.33$	$27.8^{b} \pm 0.22$
6	$34.6^{a} \pm 0.36$	$28.5^{a} \pm 0.32$

Note: * For each factor, the means in the same column followed by the common lowercase superscript letters do not differ statistically at 5% probability level using LSD test.

** Table values show the mean ± one standard deviation.

3.4 Mechanical properties

Variety showed a significant effect on mechanical properties ($P<0.01$). Sorkheh had significantly higher values in all properties (Table 4). The average values of rupture force for Sorkheh (169.06 N) and Sazandegi (125.10 N) were lower than the corresponding values (174.4 to 188.8 N) for Lemont rough rice variety (Lu and Siebenmorgen, 1995), but higher than the values (98.10 to 101.18 N) for three Brazilian varieties (Corrêa et al., 2007). The discrepancy could be due to the inherent characteristics of varieties and different compression speeds. Corrêa et al. (2007) used the loading rate of 8.4 mm/min, and Lu and Siebenmorgen (1995) used the speed of 2 mm/min. As mentioned earlier, the loading speed in the present study was 1.25 mm/min which more exactly simulates the quasi-static loading.

The average apparent modulus of elasticity of Sazandegi (555.6 MPa) falls within the range of 501 – 598 MPa for three rough rice varieties reported by Shitanda, Nishiyama and Koide. (2002). However, the corresponding value for Sorkheh (996.1 MPa) lies within the range of 930 – 3,380 MPa for seven varieties of Australian wheat reported by ASAE (2001a).

Table 4 Mechanical properties of Sorkheh and Sazandegi varieties obtained by compression test

Experimental factors	Bio-yield force/N	Fracture force/N	Fracture energy/$\times 10^{-3}$ J	Apparent modulus of elasticity/MPa	Toughness/MJ · m^{-3}
Variety					
Sorkheh	$80.32^{a*} \pm 32.34^{**}$	$169.06^{a} \pm 31.89$	$44.18^{a} \pm 0.22$	$996.1^{a} \pm 101.09$	$1.88^{a} \pm 0.69$
Sazandegi	$60.48^{b} \pm 45.00$	$125.10^{b} \pm 28.01$	$24.45^{b} \pm 0.31$	$555.6^{b} \pm 120.41$	$1.11^{b} \pm 0.50$

Note: * For each factor, the means in the same column followed by the common lowercase superscript letters do not differ statistically at 5% probability level using LSD test. ** Table values show the mean ± one standard deviation.

The effect of MC was not significant on any of the measured and computed mechanical properties obtained by the compression test. At the range of tested MC (12 to 16%, w.b), the mean of bio-yield force, fracture force, fracture energy, apparent modulus of elasticity, and toughness were 70.4 N, 147.1 N, 34.2 J×10^{-3}, 760.9 MPa, and 1.49 MJ/m^3.

Similar to the compression test, variety showed a significant effect ($P<0.01$) on mechanical properties obtained by the three-point bending test. Sorkheh had significantly higher values of mechanical properties (Table 5). The average value of bending fracture force for Sorkheh (24.23 N) was higher than the corresponding value (5 to 20 N) for Lemont rough rice variety at different harvest time (Lu and Siebenmorgen, 1995). However, the value for Sazandegi (19.04 N) falls within the reported range by these researchers.

Table 5 Mechanical properties of Sorkheh and Sazandegi varieties obtained by three-point bending test

Experimental factors	Fracture force/N	Fracture energy/$\times 10^{-3}$ J	Specific fracture energy/J · m^{-2}	Bending strength/MPa
Variety				
Sorkheh	$24.23^{a} \pm 4.79^{**}$	$5.07^{a} \pm 0.21$	$385.81^{a} \pm 98.01$	$23.39^{a} \pm 1.32$
Sazandegi	$19.04^{b} \pm 4.10$	$3.68^{b} \pm 0.16$	$277.48^{b} \pm 101.48$	$17.73^{b} \pm 1.50$

Note: * For each factor, the means in the same column followed by the common lowercase superscript letters do not differ statistically at 5% probability level using LSD test. ** Table values show the mean ± one standard deviation.

The values for specific fracture energy (385.81 J/m^2 for Sorkheh and 277.48 J/m^2 for Sazandegi), and bending strength (23.39 MPa for Sorkheh and 17.73 MPa for Sazandegi) were observed to be lower than those reported by Zhang et al. (2005) for Cypress brown rice variety. In their study, the specific fracture energy and the bending strength varied from 480 to 620 J/m^2 and from 50 to 58 MPa, respectively. This could be due to the inherent characteristics of varieties, as the same loading speed of 0.5 mm/min was used in both studies.

None of the mechanical properties obtained by three-point bending test were significantly affected by increasing MC from 12 to 16% (w.b.). The mean values of fracture force, fracture energy, specific fracture energy, and bending strength were 21.63 N, 4.37 J×10^{-3}, 341.64 J/m^2, and 20.56 MPa, respectively at the range of MC in this research (12% to 16%, w.b.).

4 Conclusions

In this research, various physical and mechanical properties of two rough rice varieties namely, Sorkheh and Sazandegi important to design of machinery used for milling of these varieties as well as understanding their susceptibility to breakage during processing were determined.

The following conclusions can be drawn from the performed experiments:

- The effect of variety and moisture content on most physical properties was significant. Sorkheh variety showed higher mechanical strength than Sazandegi variety. In contrary to the variety, moisture content did not show a significant effect on mechanical properties obtained by both parallel-plate and three-point bending tests.
- The mechanical properties of tested varieties fell within the ranges reported in the literature. For Sorkheh some characteristics were even higher than the corresponding reported values. Hence, the high milling losses of Isfahan province rice varieties could be due to the methods and devices used for their processing operations, not because of their low strength.

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Nomenclature

a	length of kernel, mm
b	width of kernel, mm
c	thickness of kernel, mm
A	area of fracture surface, mm^2
E	apparent modulus of elasticity, MPa
F_b	bending force, N
F_c	compressive force, N
G	specific fracture energy, J/m^2
GMD	geometric mean diameter, mm
K	geometrical factor
L	beam span, m
R_1, R'_1	minor and major radii of curvature at upper contact surface, mm
R_2, R'_2	minor and major radii of curvature at lower contact surface, mm
V	volume of seed, mm^3
Greek letters	
δ	deformation of kernel, mm
θ	angle of surface, degree
σ	maximum bending stress, Pa
ε	porosity, %
ϕ	sphericity
ρ_p	true density, kg/m^3
ρ_b	bulk density, kg m^{-3}
Abbreviations	
DOM	degree of milling
GMD	geometric mean diameter
HRY	head rice yield
LSD	least significant difference
MC	moisture content

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