Australian Journal of
Crop Science

AJCS

AJCS 5(10):1239-1246 (2011) ISSN:1835-2707

Rupture strength of brown rice varieties as affected by moisture content and loading rate

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Abstract

In this research, the mechanical strength of 12 varieties of brown rice grain was investigated. The brown rice grains at four levels of moisture content (8, 10, 12 and 14% w.b.) were quasi-statically loaded at two rates of 10 and 15 mm/min in horizontal orientation. The results revealed that the rupture force of brown rice grain decreased by increasing the moisture content and loading rate. For all varieties evaluated, the highest values of rupture force was obtained at the moisture content of 8% (w.b.) and loading rate of 10 mm/min; while the lowest rupture force corresponded to the moisture content of 14% (w.b.) and loading rate of 15 mm/min. The 12 varieties were divided into three groups based on the slenderness ratio of the grains, namely, local short grain varieties (LSGV), local long grain varieties (LLGV), and improved long grain varieties (ILGV). This classification is used in Iranian rice trade markets. The means groups were contrasted through the general linear model (GLM) procedure. It was observed that the rupture strength of the three groups were statistically different from each other ($P<0.01$). It was revealed that the brown rice rupture at lower levels of moisture content was in the form of sudden failure with less deformation; while at higher levels of moisture content the grain rupture was in the form of gradually crushing with more deformation. The results proved that some other characteristics such as textural properties might exist in the grains which influence the rheological behaviour and mechanical strength of the grains. So, it is recommended that the design and adjustment of rice processing equipments must be performed based on the mechanical and textural properties of rice varieties.

Keywords: Brown rice, Rupture force, Moisture content, Loading rate, Variety.
Abreviations: ILGV_Improved long grain varieties; LLGV_Local long grain varieties; LSGV_Local short grain varieties; LR_ Loading rate (mm/min); MC_Moisture content (wet basis); V_Variety.

Introduction

Rice (*Oryza sativa* L.) is the staple food for more than three billion people, more than half of the world's population. It provides 27% of dietary energy and 20% of dietary protein in the developing world. Rice is cultivated in at least 114, mostly developing, countries and is the primary source of income and employment for more than 100 million households in Asia and Africa. In Iran, rice is grown on an area of about 615000 ha with an annual paddy production of about 3.5 million ton and yields 5.56 t/ha (FAO, 2007). Main areas of rice cultivation of Iran are located in the north provinces, namely, Guilan and Mazandaran, producing 75 percent of Iran's rice product. During rice milling processes, in which rough rice hull is removed from brown rice, the occurrence of mechanical damage due to intensive forces and stresses cannot be neglected. The extent of these stresses could be induced by changes in materials properties such as moisture and texture. If the stresses exceed the rupture strength of the material, it will lead to cracks or breakage. The most important difference between rice and other cereal is the economic and qualitative aspects of rice production. In contrast with other cereals, rice is preferably consumed as whole grains. Therefore, the percentage of whole and unbroken kernels is an important quality criterion in rice trade (Siebenmorgen, 1994). In addition, the breakage of rice grains does adversely effect the seed germination, storability and cooking quality (Li *et al*., 1999). Thus, proper design and adjustment of the processing equipments for harvested rice is essential to reduce further probable losses in the crop production. In order to accurately design equipments used in different stages of rice processing, knowledge of mechanical properties is necessary to predict the extent of rupture for lowering the final crop damages and to improve and optimise the crop production. Recently, the rheological properties of several grains have been reported in the literature. Kamst *et al*. (2002) investigated the effect of deformation rate and moisture content on the mechanical properties of rice grains. They reported that at moisture contents of 8.87% (w.b.) and lower, the values of Young's modulus and tensile and compressive strength were not significantly different from each other, whilst at higher moisture contents the properties declined with moisture content. They also declared that the Young's modulus and compressive strength values decreased with a decrease in strain rate and reached a constant value at a strain rate of 7.1×10^{-3} min^{-1}. Chattopadhyay *et al.* (1981) carried out two types of uniaxial compression loading (constant displacement rate and sinusoidal varying stress) on brown rice to determine its rheological behavior over a widely-varying time period. They found that with a time decrease from 120 s to 0.00016 s the viscoelastic relaxation modulus increased 15, 25, 16 and 20 folds at moisture contents of 12, 17, 22 and 27% (d.b.), respectively. The results also showed the significant influence of moisture content on the mechanical properties of the high starch grain. The stress, strain, modulus of deformability and energy to yield point were found to be a function of loading rate and moisture content for different varieties of wheat kernels (Kang *et al*., 1995). The maximum compressive stress for wheat and canola decreased linearly with an increase in moisture content (Bargale *et al*., 1995). In a study, Isik and Unal (2007) observed that the shelling resistance of white speckled red kidney bean grain decreased as the moisture content increased from 98.26 to 53.67 N. Lately, a similar study was done by Altuntas and Karadag (2006) in which the mechanical properties of sainfoin, grass pea, and bitter vetch seeds were determined in terms of average rupture force, specific deformation and rupture energy. There were also multitudes of papers on mechanical characteristics of different agricultural commodities and by-products (Singh and Goswami, 1998; Gupta and Das, 2000; Ogunjimi *et al*., 2002; Saiedirad *et al*., 2008; Siebenmorgen *et al*., 2009; Gorji *et al*., 2010; Zareiforoush *et al*., 2010b; Fos'hat *et al*., 2011). In the current research the mechanical strength of brown rice grain was investigated. Study of mechanical behavior of brown rice grain is very important specially at whitening and de-husking processes, because in these stages brown rice is subjected to intensive forces and stresses. White rice is the final product of rice processing and there is no major external force to damage the grain after obtaining the final product compared with brown rice. Hence, the objective of this research was to determine the rupture strength of brown rice grain in quasi-static compressive loading as a function of grain variety, moisture content and loading rate. The information presented in this study could be helpful to optimise the design and adjustment of the machines used in rice processing operations.

Results and discussion

The results of ANOVA indicating the effects of variety, moisture content and compressive loading rate on the rupture force of brown grain is presented in Table 1. As shown, the main effects of variety, moisture content and loading rate on the rupture force of brown rice grain were significant ($P<0.01$). Also, the interaction effects of variety × moisture content, variety × loading rate, and moisture content × loading rate on the rupture force were significant ($P<0.01$). The average values of brown rice rupture force with respect to grain variety, moisture content and loading rate are shown in Table 2. It can be observed that the rupture force of brown rice grain increased independently with decreasing the loading rate and grain moisture content. The results also showed that there was a significant difference between the values of rupture force of brown rice varieties. An ANOVA was also performed on the experimental data according to the grouping of 12 varieties into three separate groups. The results are illustrated in Table 3. It can be seen that there was a significant difference ($P<0.01$) between the three groups of local short grain varieties (LSGV), local long grain varieties (LLGV), and improved long grain varieties (ILGV). This proves that the mechanical strength of local short grain varieties, local long grain varieties, and improved long grain varieties are different from each other and so the type and adjustment of the machines used for the crop processing should be selected accordingly. Some important dimensional properties of brown rice varieties at different moisture contents are shown in Table 4. As shown, the largest values of surface area in LSGV, LLGV and ILGV groups were attributed to the Hasani, Khazar and Dorfak varieties, respectively. Theoretically, it is expected that the highest values of grain rupture force should be obtained for grains with largest dimensions; because the grains surface area (that is to say the area of the grain which is subjected to the compressive loading force) is larger and therefore higher strength for the grains could be anticipated. However, the information obtained from experiments does not confirm this hypothesis. For example, in the LSGV group, although the largest dimensional properties were observed in the case of Hasani variety, but the highest value of rupture force was obtained for Binam variety (Table 5). This result shows that some other characteristics such as textural properties might exist in the grains which influence the rheological behaviour and mechanical strength of the grains. Perhaps, the higher rupture force in the case of Binam variety as compared with Hasani and Gharib varieties is due to the fact that Binam variety had stiff texture which could be due to present of more bran layer surrounding the grain; whilst Hasani and Gharib varieties were observed to have a soft and chalky texture. The mean values of rupture force for 12 varieties of brown rice at different levels of compressive loading rate and grain moisture content are given in Table 5. In the case of local short grain varieties (LSGV) the highest value of rupture force (161.60 N) was obtained for Binam variety at the moisture content of 8% (w.b.) and loading rate of 10 mm/min; whilst the lowest value of rupture force (43.28 N) was attributed to Gharib variety at the moisture content of 14% (w.b.) and loading rate of 15 mm/min. For local long grain varieties (LLGV) the highest value of rupture force (150.88 N) was obtained for Khazar variety at the moisture content of 8% (w.b.) and at the loading rate of 10 mm/min; while the lowest value of rupture force (52.48 N) belonged to Hashemi variety at the moisture content of 14% (w.b.) and loading rate of 15 mm/min. Finally, in the case of improved long grain varieties (ILGV) the highest value of rupture force (155.70 N) belonged to Kadoos variety at the moisture content of 8% (w.b.) and loading rate of 10 mm/min; and the lowest value of rupture force (58.05 N) was attributed to Sepidrood variety at the moisture content of 14% (w.b.) and loading rate of 15 mm/min. The effect of evaluated factors on the rupture force of brown rice grain is discussed in the following paragraphs. Fig. 2 presents the interaction effect of grain variety and moisture content on fracture resistance of brown rice for three groups of local short grain varieties (LSGV), local long grain varieties (LLGV) and improved long grain varieties (ILGV) as obtained through ANOVA. As shown, for the three groups evaluated, increasing the moisture content caused the rupture force to decrease that was most likely due to the softer structure of grain as a result of higher water present in the grain at higher levels of moisture contents. During the experiments it was observed that the brown rice rupture at lower levels of moisture content was in the form of sudden failure with less deformation; while at higher levels of moisture content the grain rupture was in the form of gradually crushing with more deformation. Altuntas and Yildiz (2007) studied the effect of moisture content on some mechanical properties of faba bean (*Vicia faba* L.) grains and reported that as the moisture content increased from 9.89% to 25.08%, the rupture force values ranged from 314.17 to 185.10 N; 242.2 to 205.56 N and 551.43 to 548.75 N for X-, Y-, and Z-axes, respectively. The results of this study were consistent with the findings of Konak *et al*. (2002) and Saiedirad *et al*. (2008) who had reported the highest rupture force at lower levels of moisture

Table 1. Analysis of variance indicating the effects of variety (V), moisture content (MC) and compressive loading rate (LR) on the rupture force of brown rice grains

Source	DF	Sum of Squares	"F" value
V	11	223556.78	428.76**
MC	3	477793.60	3360.01**
LR	1	50046.58	1055.84**
V × MC	33	24490.93	15.66**
V × LR	11	3417.98	6.56**
MC × LR	3	5754.17	40.47**
V × MC × LR	33	4380.08	2.80ns
Coefficient of variation		7.62	

**: Significant at 1% probability level, ns: not significant

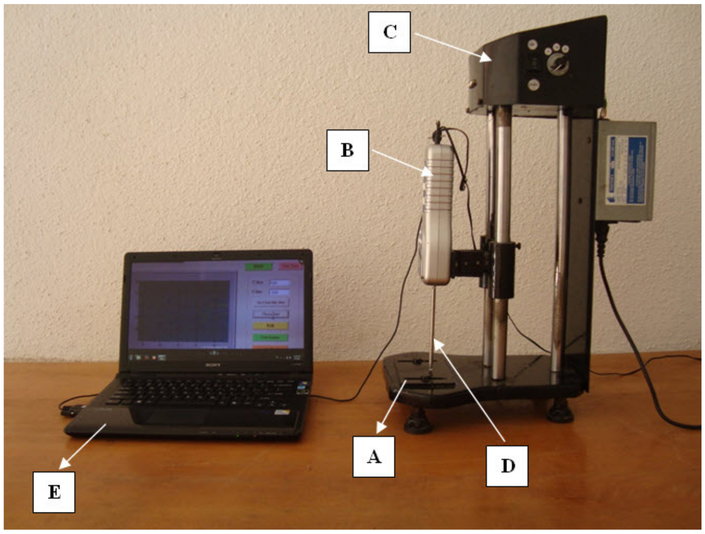

Fig 1. Biological material test apparatus. A) loading platform, B) digital force gauge, C) drive and transmission unit, D) loading probe, E) PC

contents for chick pea and cumin seeds. However, there were some conflicting reports on the effect of moisture content on rupture force. Paulsen (1978) and Liu *et al*. (1990) reported a decrease in rupture force values for soybean with a decrease in moisture content. In the case of local short grain varieties, the highest and lowest values of rupture force were obtained for Binam and Gharib varieties, respectively (Fig. 2a). The highest and lowest values of rupture force in the case of local long grain varieties were respectively attributed to Khazar and Hashemi varieties (Fig. 2b). Finally, for improved long grain varieties, the highest and lowest values of rupture force were observed for Kadoos and Hybrid varieties, respectively (Fig. 2c). The equations representing the relationship between the brown rice grains rupture force and moisture content for the different varieties evaluated is tabulated in Table 6. The interaction effect of grain variety and compressive loading rate for the three brown rice groups of local short grain varieties, local long grain varieties, and improved long grain varieties is given in Fig. 3. It can be seen that for the three groups evaluated and all of the varieties included in the groups, the rupture force of brown rice grain decreased with increasing the rate of compressive loading. This could be due to the fact that at higher rates of compressive loading, there is less time for the grain to react to the incoming force. Saeidirad *et al*. (2008) Studied the effects of moisture content, seed size, loading rate and seed orientation on force and energy required for fracturing cumin seed (*Cuminum cyminum* Linn.) under quasi-static loading. They reported that the highest mechanical strength of cumin seed (60 N) was obtained for small seed with a moisture content of 5.7% under horizontal loading and the lowest (10.8 N) was attributed to large seed with a moisture content of 15% under vertical loading. Singh and Goswami (1998) indicated that the force required for initiating the rupture in cumin seed decreased from 50 to 40 N and 31 to 20.3 N with an increase in moisture content from 7% to 13% (d.b.), for the horizontal and vertical orientations, respectively. Zoerb (1967) reported that most agricultural materials are elastic during the first portion of a load–deformation curve, but have viscoelastic properties with increased loading. Thus, once the elastic region is extended, properties are time-dependent and the effect of loading rate becomes more noticeable.

Materials and methods

Sample preparation

The brown rice varieties used in this research are cultivated in Guilan province, north of Iran. The varieties were obtained from the Rice Research Institute of Iran (RRII), Rasht, Iran. The samples were cleaned to remove all foreign materials such as dust, dirt, broken and immature grains. The initial moisture content of the samples was determined by oven drying at 103 °C for 48 h (Zareiforoush *et al*., 2010a). The initial moisture content of the 12 varieties was in the range of 14.5 to 16% (w.b.).

Table 2. Mean comparison of rupture force of brown rice considering the main effects of grain variety, grain moisture content and loading rate

Variety	NO. of Observations	Rupture force (N)	Duncan Grouping
Binam	80	110.916	A
Kadoos	80	102.435	B
Khazar	80	99.974	C
Dorfak	80	99.039	DC
Domsiah	80	95.909	DE
Sepidrood	80	96.294	E
Tarom	80	92.367	F
Hybrid	80	91.786	F
Alikazemi	80	88.950	G
Hashemi	80	87.269	G
Hasani	80	60.115	H
Gharib	80	57.989	H
Moisture content (% w.b.)			
8	240	124.331	A
10	240	94.532	B
12	240	77.890	C
14	240	64.594	D
Loading rate (mm/min)			
10	480	97.557	A
15	480	83.117	B

For each test, the means followed by the same capital letter are not statistically different at 5% probability level through the Duncan test

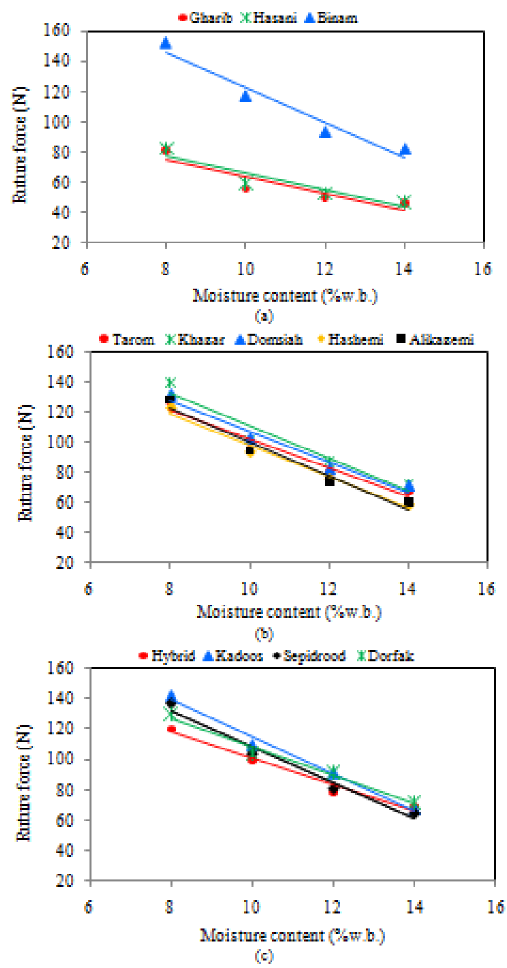

Fig 2. The interaction effect of grain variety and moisture content on the rupture force of brown rice for: a) Local short grain varieties (LSGV), b) Local long grain varieties (LLGV) and c) Improved long grain varieties (ILGV) as obtained through ANOVA

Table 3. Analysis of variance indicating the contrast of means of local short grain varieties (LSGV), local long grain varieties (LLGV) and improved long grain varieties (ILGV)

Contrast source	DF	Contrast SS	"**F**" value
LSGV vs LLGV	1	42102.34	501.03**
LSGV vs ILGV	1	60759.32	723.05**
LLGV vs ILGV	1	3279.26	39.02**
Coefficient of variation		10.15	

**: Significant at 1% probability level

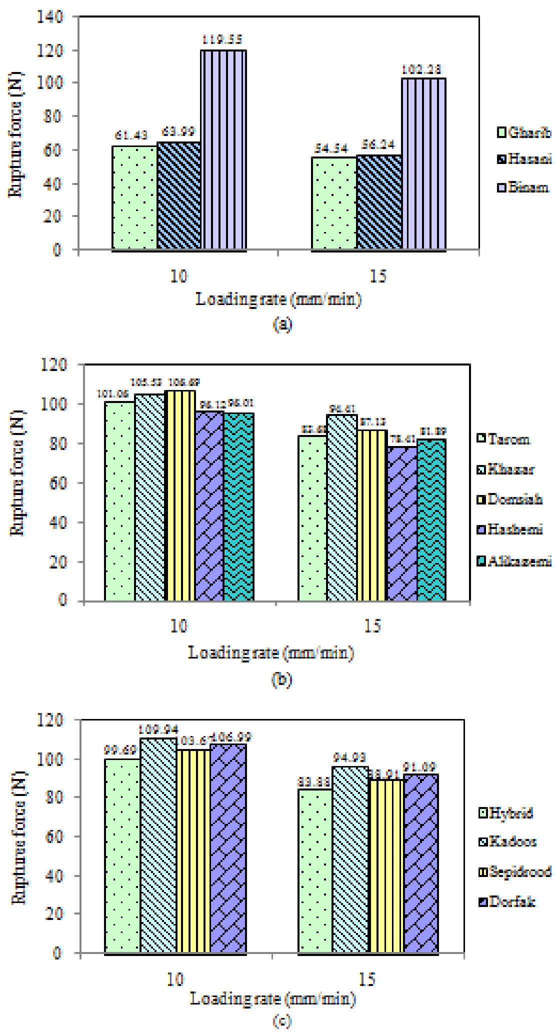

Fig 3. The interaction effect of grain variety and loading rate on fracture resistance of brown rice for: a) Local short grain varieties (LSGV), b) Local long grain varieties (LLGV) and c) Improved long grain varieties (ILGV) as obtained through ANOVA

Experimental procedure

The 12 varieties of brown rice grains were divided into three groups, namely, local short grain varieties (Hasani, Gharib and Binam), local long grain varieties (Khazar, Tarom, Hashemi, Alikazemi and Domsiah) and improved long grain varieties (Sepidrood, Dorfak, Kadoos, and Hybrid), based on the slenderness ratio of the grains. This classification is used in Iranian rice trade markets. The slenderness ratio (S_r) of grain is defined as following (Firouzi *et al*., 2010):

$$S_r = \frac{L}{W}$$

Where L and W are the length and width of the grain, respectively. The mechanical properties of brown rice grain were determined in terms of the grain rupture force. The effect of moisture content on the failure strength of brown rice grains were studied by creating four levels of moisture below the initial moisture content, namely, 8, 10, 12 and 14% (w.b.). For this purpose, rough rice grains were dried in an oven at a constant temperature of 43 °C to lower the initial moisture contents to the desired levels (Zareiforoush *et al*., 2010a). The moisture content of the brown rice grains during the moisture lowering process was measured by means of a digital grain moisture meter (GMK model 303RS, Korea). The samples were then poured into separate polyethylene

Table 4. Dimensional properties of 12 varieties of brown rice grains at different levels of moisture content

Varieties Group	Variety	Moisture content (%w.b.)	Length (mm)	Width (mm)	Thickness (mm)	Surface area (mm^2)	Sphericity (%)	Slenderness ratio
LSGV*	Gharib	8	$6.25_{\pm0.29}$	$2.45_{\pm0.10}$	$1.67_{\pm0.60}$	$23.37_{\pm1.42}$	$47.18_{\pm1.38}$	$2.55_{\pm0.13}$
		10	$6.31_{\pm0.16}$	$2.49_{\pm0.09}$	$1.70_{\pm0.06}$	$24.38_{\pm1.09}$	$47.35_{\pm1.08}$	$2.54_{\pm0.10}$
		12	$6.36_{\pm0.16}$	$2.52_{\pm0.09}$	$1.71_{\pm0.06}$	$24.80_{\pm1.10}$	$47.38_{\pm1.07}$	$2.53_{\pm0.11}$
		14	$6.42_{\pm0.29}$	$2.55_{\pm0.13}$	$1.73_{\pm0.06}$	$25.38_{\pm1.55}$	$47.47_{\pm1.23}$	$2.52_{\pm0.12}$
	Hasani	8	$6.24_{\pm0.51}$	$2.55_{\pm0.23}$	$1.80_{\pm0.12}$	$25.34_{\pm1.75}$	$49.14_{\pm1.58}$	$2.44_{\pm0.14}$
		10	$6.32_{\pm0.41}$	$2.67_{\pm0.47}$	$1.87_{\pm0.11}$	$26.94_{\pm1.27}$	$50.03_{\pm1.32}$	$2.36_{\pm0.10}$
		12	$6.37_{\pm0.48}$	$2.70_{\pm0.19}$	$1.89_{\pm0.12}$	$27.53_{\pm1.18}$	$50.29_{\pm1.77}$	$2.35_{\pm0.13}$
		14	$6.40_{\pm0.33}$	$2.71_{\pm0.23}$	$1.90_{\pm0.12}$	$27.78_{\pm1.54}$	$50.31_{\pm1.48}$	$2.36_{\pm0.11}$
	Binam	8	$6.64_{\pm0.31}$	$2.34_{\pm0.09}$	$1.76_{\pm0.08}$	$25.01_{\pm1.48}$	$45.39_{\pm1.65}$	$2.84_{\pm0.12}$
		10	$6.71_{\pm0.31}$	$2.37_{\pm0.09}$	$1.78_{\pm0.08}$	$25.55_{\pm1.45}$	$45.41_{\pm1.64}$	$2.83_{\pm0.12}$
		12	$6.74_{\pm0.30}$	$2.39_{\pm0.09}$	$1.79_{\pm0.09}$	$25.86_{\pm1.37}$	$45.54_{\pm1.69}$	$2.82_{\pm0.10}$
		14	$6.76_{\pm0.30}$	$2.40_{\pm0.08}$	$1.80_{\pm0.08}$	$26.07_{\pm1.39}$	$45.60_{\pm1.68}$	$2.81_{\pm0.11}$
LLGV	Tarom	8	$7.06_{\pm0.35}$	$1.77_{\pm0.16}$	$1.53_{\pm0.09}$	$20.67_{\pm1.75}$	$37.88_{\pm1.71}$	$3.98_{\pm0.13}$
		10	$7.09_{\pm0.43}$	$1.80_{\pm0.21}$	$1.56_{\pm0.09}$	$21.13_{\pm1.60}$	$38.23_{\pm1.84}$	$3.94_{\pm0.15}$
		12	$7.13_{\pm0.40}$	$1.84_{\pm0.17}$	$1.59_{\pm0.13}$	$21.80_{\pm1.92}$	$38.64_{\pm1.97}$	$3.87_{\pm0.14}$
		14	$7.16_{\pm0.45}$	$1.86_{\pm0.20}$	$1.61_{\pm0.12}$	$22.19_{\pm2.03}$	$38.83_{\pm2.02}$	$3.85_{\pm0.16}$
	Khazar	8	$7.60_{\pm0.43}$	$1.92_{\pm0.12}$	$1.67_{\pm0.13}$	$24.23_{\pm2.09}$	$38.19_{\pm1.82}$	$3.96_{\pm0.12}$
		10	$7.67_{\pm0.56}$	$1.98_{\pm0.19}$	$1.68_{\pm0.15}$	$24.94_{\pm2.16}$	$38.38_{\pm2.19}$	$3.87_{\pm0.15}$
		12	$7.73_{\pm0.59}$	$2.02_{\pm0.17}$	$1.74_{\pm0.16}$	$25.90_{\pm2.17}$	$38.89_{\pm2.05}$	$3.83_{\pm0.15}$
		14	$7.76_{\pm0.45}$	$2.04_{\pm0.16}$	$1.75_{\pm0.12}$	$26.22_{\pm2.03}$	$38.99_{\pm2.02}$	$3.80_{\pm0.13}$
	Domsiah	8	$7.04_{\pm0.48}$	$1.59_{\pm0.13}$	$1.54_{\pm0.12}$	$19.51_{\pm1.93}$	$36.77_{\pm1.82}$	$4.43_{\pm0.15}$
		10	$7.07_{\pm0.55}$	$1.62_{\pm0.16}$	$1.56_{\pm0.15}$	$19.89_{\pm2.16}$	$36.98_{\pm2.19}$	$4.36_{\pm0.11}$
		12	$7.13_{\pm0.48}$	$1.64_{\pm0.19}$	$1.57_{\pm0.14}$	$20.25_{\pm1.87}$	$37.00_{\pm1.94}$	$4.35_{\pm0.10}$
		14	$7.15_{\pm0.41}$	$1.67_{\pm0.12}$	$1.59_{\pm0.13}$	$20.65_{\pm1.91}$	$37.31_{\pm2.01}$	$4.28_{\pm0.14}$
	Hashemi	8	$7.43_{\pm0.43}$	$1.86_{\pm0.16}$	$1.57_{\pm0.13}$	$22.51_{\pm2.21}$	$37.52_{\pm1.90}$	$3.99_{\pm0.13}$
		10	$7.48_{\pm0.46}$	$1.90_{\pm0.14}$	$1.61_{\pm0.09}$	$23.30_{\pm2.15}$	$37.99_{\pm1.93}$	$3.93_{\pm0.10}$
		12	$7.53_{\pm0.46}$	$1.92_{\pm0.18}$	$1.63_{\pm0.08}$	$23.75_{\pm2.02}$	$38.14_{\pm1.99}$	$3.92_{\pm0.12}$
		14	$7.57_{\pm0.42}$	$1.95_{\pm0.19}$	$1.67_{\pm0.11}$	$24.42_{\pm2.12}$	$38.54_{\pm2.08}$	$3.88_{\pm0.11}$
	Alikazemi	8	$7.13_{\pm0.38}$	$1.89_{\pm0.14}$	$1.63_{\pm0.12}$	$22.41_{\pm1.73}$	$39.28_{\pm2.13}$	$3.77_{\pm0.11}$
		10	$7.16_{\pm0.42}$	$1.92_{\pm0.17}$	$1.65_{\pm0.12}$	$22.86_{\pm1.77}$	$39.53_{\pm1.38}$	$3.73_{\pm0.10}$
		12	$7.18_{\pm0.46}$	$1.94_{\pm0.18}$	$1.67_{\pm0.08}$	$23.21_{\pm2.02}$	$39.76_{\pm1.99}$	$3.70_{\pm0.16}$
		14	$7.21_{\pm0.53}$	$1.97_{\pm0.18}$	$1.68_{\pm0.10}$	$23.58_{\pm1.93}$	$39.93_{\pm1.52}$	$3.66_{\pm0.14}$
ILGV	Hybrid	8	$9.03_{\pm0.59}$	$1.85_{\pm0.11}$	$1.64_{\pm0.09}$	$27.38_{\pm2.22}$	$33.45_{\pm1.54}$	$4.88_{\pm0.13}$
		10	$9.08_{\pm0.54}$	$1.87_{\pm0.12}$	$1.66_{\pm0.08}$	$27.83_{\pm1.08}$	$33.52_{\pm2.01}$	$4.85_{\pm0.10}$
		12	$9.11_{\pm0.46}$	$1.89_{\pm0.18}$	$1.67_{\pm0.08}$	$28.17_{\pm1.35}$	$33.63_{\pm1.21}$	$4.82_{\pm0.15}$
		14	$9.15_{\pm0.53}$	$1.90_{\pm0.18}$	$1.69_{\pm0.10}$	$28.55_{\pm1.65}$	$33.72_{\pm1.17}$	$4.81_{\pm0.15}$
	Kadoos	8	$8.73_{\pm0.43}$	$1.75_{\pm0.12}$	$1.62_{\pm0.11}$	$25.54_{\pm1.80}$	$33.41_{\pm1.56}$	$4.99_{\pm0.14}$
		10	$8.85_{\pm0.57}$	$1.81_{\pm0.13}$	$1.64_{\pm0.09}$	$26.53_{\pm1.08}$	$33.64_{\pm1.77}$	$4.89_{\pm0.14}$
		12	$8.88_{\pm0.44}$	$1.83_{\pm0.13}$	$1.65_{\pm0.08}$	$26.88_{\pm1.72}$	$33.75_{\pm1.41}$	$4.85_{\pm0.11}$
		14	$8.92_{\pm0.56}$	$1.92_{\pm0.14}$	$1.66_{\pm0.10}$	$27.87_{\pm1.48}$	$34.29_{\pm1.58}$	$4.64_{\pm0.10}$
	Sepidrood	8	$8.72_{\pm0.62}$	$1.87_{\pm0.18}$	$1.65_{\pm0.08}$	$26.80_{\pm1.47}$	$34.43_{\pm2.01}$	$4.66_{\pm0.11}$
		10	$8.74_{\pm0.55}$	$1.91_{\pm0.16}$	$1.67_{\pm0.07}$	$27.35_{\pm2.01}$	$34.76_{\pm1.94}$	$4.57_{\pm0.14}$
		12	$8.75_{\pm0.67}$	$1.92_{\pm0.16}$	$1.68_{\pm0.10}$	$27.53_{\pm1.36}$	$34.90_{\pm1.27}$	$4.61_{\pm0.16}$
		14	$8.78_{\pm0.63}$	$1.95_{\pm0.15}$	$1.69_{\pm0.08}$	$28.01_{\pm2.04}$	$35.12_{\pm1.13}$	$4.50_{\pm0.14}$
	Dorfak	8	$9.26_{\pm0.58}$	$1.79_{\pm0.18}$	$1.63_{\pm0.09}$	$27.32_{\pm2.16}$	$32.41_{\pm1.90}$	$5.17_{\pm0.15}$
		10	$9.33_{\pm0.62}$	$1.83_{\pm0.15}$	$1.65_{\pm0.12}$	$28.09_{\pm2.41}$	$32.68_{\pm1.94}$	$5.10_{\pm0.12}$
		12	$9.42_{\pm0.55}$	$1.86_{\pm0.16}$	$1.66_{\pm0.08}$	$28.72_{\pm2.20}$	$32.70_{\pm1.76}$	$5.06_{\pm0.11}$
		14	$9.44_{\pm0.58}$	$1.89_{\pm0.19}$	$1.68_{\pm0.08}$	$29.17_{\pm2.37}$	$32.95_{\pm1.84}$	$4.99_{\pm0.15}$

*LSGV: Local short grain varieties; LLGV: Local long grain varieties; ILGV: Improved long grain varieties

bags and the bags sealed tightly. Before starting each experiment, rough rice grains were selected randomly from the samples and their hulls were separated manually; then the brown rice grains were placed on a crack detecting device (MAHSA, IRAN) and the presence of cracks in the grains was investigated. Only the sound brown rice grains which were not immature or cracked were selected for conducting the experiments. Some physical properties of brown rice grains including, axial dimensions (length, width and thickness), surface area and sphericity were also measured before each experiment for further analysis. The length (*L*), width (*W*) and thickness (*T*) of grains were measured using a digital caliper with an accuracy of 0.01 mm (Mytutoyo, JAPAN). Grain surface area (*S*) was calculated using (Jain and Bal, 1997):

$$S = \frac{\pi B L^2}{(2L - B)} \tag{1}$$

Table 5. The mean values of rupture force for 12 brown rice varieties at different levels of compressive loading rate and grain moisture content

Varieties Group	Moisture content (%w.b.)	8		10		12		14	
	Loading rate (mm/min)	10	15	10	15	10	15	10	15
	Variety	Rupture force (N)							
LSGV*	Gharib	85.95±5.12	76.38±4.19	58.96±2.97	51.64±4.42	52.82±5.65	46.86±6.11	48.00±4.84	43.28±3.13
	Hasani	87.18±8.44	77.53±8.84	63.68±5.88	54.79±7.18	55.31±7.17	48.97±8.73	49.78±6.01	43.65±6.03
	Binam	161.60±8.59	142.05±8.09	128.34±8.63	105.12±6.65	101.27±6.97	85.12±7.31	86.97±5.32	76.84±5.51
LLGV	Tarom	144.73±7.88	109.23±6.95	99.75±6.58	90.40±6.50	84.55±6.50	74.98±6.17	75.19±6.59	60.09±5.75
	Khazar	150.88±8.95	128.07±7.58	104.78±5.77	97.64±4.02	90.48±6.77	83.63±6.26	75.98±6.52	68.30±4.46
	Domsiah	149.01±7.07	114.79±8.43	111.28±6.12	94.01±7.41	89.26±6.21	75.02±5.17	77.21±4.20	64.67±5.35
	Hashemi	138.70±6.63	106.07±6.48	99.06±7.01	87.23±7.58	82.57±6.05	67.85±7.38	64.16±5.69	52.48±6.90
	Alikazemi	141.69±6.90	114.45±8.30	100.84±5.43	87.87±5.79	77.89±7.93	69.72±9.07	63.58±6.37	55.54±7.26
HLGV	Hybrid	131.89±6.22	108.11±6.48	108.72±4.96	90.89±6.82	84.61±7.10	71.66±3.83	73.55±5.95	64.84±4.95
	Kadoos	155.70±7.87	127.54±6.56	113.31±7.16	105.59±6.96	97.35±6.92	85.23±6.05	73.40±5.01	61.33±4.30
	Sepidrood	143.80±8.91	129.40±6.75	109.94±9.18	96.88±7.43	90.16±8.98	71.31±8.77	70.78±5.39	58.05±5.81
	Dorfak	137.42±8.10	121.69±9.07	111.47±6.84	96.50±7.48	101.49±8.75	81.20±7.05	77.57±5.87	64.94±4.05

*LSGV: Local short grain varieties; LLGV: Local long grain varieties; ILGV: Improved long grain varieties

Table 6. Regressions representing relationship between the grain rupture force and moisture content for 12 brown rice varieties

Varieties group	Variety	Relationship	R^2
LSGV*	Gharib	$R_f = -5.602M_c + 119.62$	0.822
	Hasani	$R_f = -5.701M_c + 122.83$	0.880
	Binam	$R_f = -11.665M_c + 239.23$	0.950
LLGV	Tarom	$R_f = -9.666M_c + 198.70$	0.946
	Khazar	$R_f = -10.809M_c + 218.87$	0.933
	Domsiah	$R_f = -10.170M_c + 208.77$	0.962
	Hashemi	$R_f = -10.508M_c + 202.85$	0.981
	Alikazemi	$R_f = -11.304M_c + 213.29$	0.963
ILGV	Hybrid	$R_f = -8.705M_c + 187.54$	0.973
	Kadoos	$R_f = -12.046M_c + 234.93$	0.988
	Sepidrood	$R_f = -11.961M_c + 227.86$	0.975
	Dorfak	$R_f = -9.377M_c + 202.19$	0.984

*LSGV: Local short grain varieties; LLGV: Local long grain varieties; ILGV: Improved long grain varieties; R_f: Rupture force (N); M_c: Moisture content (%w.b.)

Where:

$$B = \sqrt{WT} \tag{2}$$

The sphericity (ϕ) defined as the ratio of the surface area of the sphere having the same volume as that of the grain to the surface area of the grain was determined using (Mohsenin, 1986):

$$\phi = \frac{(LWT)^{\frac{1}{3}}}{L} \tag{3}$$

The experiments were also conducted at two loading rates of 10 and 15 mm/min. The effect of loading rate on the rupture force of brown rice grain was determined using a biological material test apparatus (Fig. 1). The apparatus consisted of five major components, namely, a loading platform, a digital force gauge (Lutron model FG-5020, Taiwan) with a reading accuracy of 0.01N, a drive electric motor, the accompanied electronic circuits for creating the desired loading rates and a gearbox transmission system for converting the rotational motion of the drive electric motor to the linear motion in the loading probe. The digital force gauge was connected to a PC and the values of compressive force could be monitored on the PC using a software program. At each experiment, the individual brown rice grain was horizontally placed on the stable platform and pressed with a motion probe (Ø10.50 mm) that had been attached to the head of the digital force gauge. The grain was loaded at the preset condition until the rupture occurred and detected by a bio-yield point in the force–time curve. The bio-yield point was recognized by a break in the force–time curve. Once the bio-yield was detected, the loading process was stopped.

Experimental design and statistical analysis

This study was carried out based on a factorial statistical design. 96 treatments (12 varieties, 4 moisture contents and 2 loading rates) were evaluated based on the randomised complete blocks design (RCBD). At each treatment, the experiments were replicated ten times and the average values were reported. The mean values, standard deviation and correlation coefficient of the rupture force of brown rice grains were determined using Microsoft Excel 2007 software program. The effects of variety, moisture content and compressive loading rate on the grain mechanical strength were investigated using analysis of variance (ANOVA), and mean significant differences were compared using Duncan's multiple range test at 5% significant level using SAS 9.1 software. The 12 varieties were also divided into three groups, namely, local short grain varieties (Hasani, Gharib and Binam), local long grain varieties (Khazar, Tarom, Hashemi, Alikazemi and Domsiah), and improved long grain varieties (Sepidrood, Dorfak, Kadoos, and Hybrid). The mean groups were contrasted through the general linear model (GLM) procedure using SAS 9.1 software.

Conclusions

The rupture force of brown rice grains decreased by increasing the moisture content and loading rate ($P<0.01$). The values of rupture force obtained for the three groups of local short grain varieties (LSGV), local long grain varieties (LLGV), and improved long grain varieties (ILGV) were statistically different from each other ($P<0.01$). For all varieties evaluated, the highest values of rupture force was obtained at the moisture content of 8% (w.b.) and loading rate of 10 mm/min; while the lowest rupture force corresponded to the moisture content of 14% (w.b.) and loading rate of 15 mm/min. During the experiments it was observed that the rupture of brown rice at lower levels of moisture content was in the form of sudden failure with less deformation; while at higher levels of moisture content the grain rupture was in the form of gradually crushing with more deformation. It was concluded that the difference between the textures of brown rice varieties could be an effective parameter on the value of grain rupture force. Therefore, it is recommended that the design and adjustment of rice processing equipments must be performed based on the mechanical and textural properties of each variety.

Acknowledgements

The authors would like to thank the University of Guilan for providing the laboratory facilities and financial support for this research.

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