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Determination of Strength Properties of Chickpea Kernel in Relation to Splitting

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ABSTRACT

Chickpea grain damage in various forms, in which splitting is more important than other aspects, because of quantitative losses. This paper investigates the mechanical strength of chickpea kernels in relation to splitting. In this relation, three varieties (Bivanij, ILC482 and Philip 93-93) of chickpea at three levels of moisture content (15.5, 20.8 and 25.6 % wet bases) and three loading orientations (Length, Width and Thickness of kernel) were tested under quasi-static uni-axial compression. Measured and calculated parameters were including rupture force, maximum strain and deformation, rupture energy, maximum normal contact stress and apparent modulus of elasticity. Moisture content had a considerable effect on all mechanical parameters. In addition, the results showed that values of chickpea strength properties were lowest when loaded in the length direction. The minimum values of modulus of elasticity and rupture energy were equal to 6.75 MPa and 43.28 mJ, respectively, at 26%(w.b.). According to statistical results, Philip 93-93 variety had the highest resistance to damage and splitting in comparison to two other varieties. Several linear and nonlinear models were developed for prediction of chickpea strength parameters that presented in the article.

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Introduction

Chickpea has an important role in the population's diet as a source of protein. Approximately 0.8 million hectares of land in Iran is under chickpea cultivation which yielding around 0.3 million tons of product [7]. Recently demand for designing and manufacturing of harvesters, planters and sorters, necessitate determining basic mechanical properties of chickpea grain [6]. Chickpea kernels are very susceptible to mechanical damage during harvesting and processing, especially in form of splitting. In other hand, damaged grain, including those which are split or have checked seed coats, are of less commercial values. Fracture caused by forces exerted on a chickpea kernel can be analyzed with knowledge of the mechanical properties of the material, so, basic mechanical properties are a requirement to predict the behavior of the kernels under various types of loading. In this relation, force and energy to rupture usually considered as suitable parameters for design of agricultural and processing machines [5]. In spite of considerable studies about mechanical properties of wheat [4], barley [5] and other grains [13], there are limited data describing the mechanical properties of chickpea kernels in the scientific literatures. Konak and his coworker (2002) measured some physical properties of chickpea including rupture force. However, no direct study has been performed on chickpea strength properties in the case of grain splitting.

Therefore, the objectives of this research were to determine: (1) the strength properties of three varieties of chickpea under quasi-static loading in relation to splitting including minimum values of those parameters that can cause kernel damage in form of splitting and (2) mathematical modeling for predicting the strength properties of chickpea as a function of seed moisture content and kernel dimensions.

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Materials and Methods

Sample Preparation

Chickpea pods of three varieties (Bivanij, ILC482 and Philip 93-93) were harvested and separated from the pods manually. About 300 g of each variety was weighed, and then all samples were cleaned by hand to remove all foreign materials such as dust, dirt, stones, chaff, and broken seeds. The initial moisture content of samples was determined using a standard method [2]. The moisture content levels for the experiment were chosen on the basis of recommended harvest moisture content [6] thus, three levels of grain moisture content including: 15-16, 20-21 and 25-26% (wet basis) were considered in the study. Samples with the desired moisture levels were prepared by adding a calculated amount of distilled water, thoroughly mixing and then were kept at 4-5 C^o for three days to allow for uniform distribution of moisture. Due to anisotropic nature of agricultural material, loading orientation of kernels was considered as an independent factor affect on grain mechanical properties. Figure 1, shows the three chickpea kernel loading orientations.

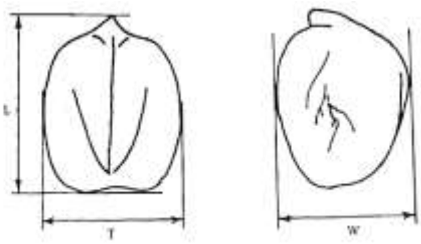


Fig. 1. *L*, *T*, and *W* indicating length, thickness and width of chickpea kernel, respectively

Uni-axial Compression Tests

All grain samples were subjected to compression test between two flat plates, as a most common material testing method, using TMU compression testing machine [11]. Prior to each test, the three dimensions of each kernel were measured using a 0.02 mm micrometer. Loading rate was constant at 7 mm/min, which provides the condition for quasi-static loading. For each test, the chickpea kernel was held in the desired position by laboratory tweezers until the compression plate began to exert force and then it was repeated 10 times in each treatment. Strain-gauge based loadcell was used with a dedicated data acquisition system to record the force values.

Due to the irregular shape of chickpea kernel it was not possible to use the direct equations of stress-strain. Therefore, the apparent modulus of elasticity was estimated using force-deformation curve, according to Hertz theory in contact stress between two solids with convex body [3].

For determining apparent modulus of elasticity and maximum compressive contact stress, the flat parallel plate method was used, which resembles the actual loading conditions. Equations (1) and (2) were used to calculate the modulus of elasticity and maximum compressive contact stress, respectively:

$$E=\frac{0.338k^{3/2}F\left(1-\mu^2\right)}{D_e^{3/2}}\left[\left(\frac{1}{R_{\min_1}}+\frac{1}{R_{\max_1}}\right)^{1/3}+\left(\frac{1}{R_{\min_2}}+\frac{1}{R_{\max_2}}\right)^{1/3}\right]^{3/2} \quad (1)$$

$$\sigma_{\max}=\frac{1.5\,F}{\pi a_e b_e} \quad (2)$$

In the above equations, E is the modulus of elasticity for chickpea kernel in MPa; k is a dimensionless factor which depends on the geometric properties of chickpea kernel; F is compressive force in N; D_e is the deformation of kernel in m; μ is the Poisson's ratio which is dimensionless and its value is taken to be 0.4 for chickpea kernel; R_{max} and R_{min} are major and minor radii of curvature of the kernel and the compression plate at the point of contact in m; σ_{max} is maximum contact stress occurring at the center of the elliptical contact area in MPa; a_e and b_e are semi-major and semi-minor axes of the elliptical contact area in m. For a kernel, the minimum and maximum radii of curvature at the point of contact can be approximated as follows:

$$R_{\min}=\frac{W+T}{4} \quad (3)$$

$$R_{\max}=\frac{(W+T)^2-L^2}{4(W+T)} \quad (4)$$

In which W, T and L are width, thickness and length of kernel, respectively. When a convex body is in contact with a flat plate, axes of elliptical contact area, ae and be can be calculated using equations:

$$a_e=m\left[\frac{3F\left(k_1+k_2\right)}{2}\left(\frac{1}{R_{\min_1}}+\frac{1}{R_{\max_1}}+\frac{1}{R_{\max_2}}+\frac{1}{R_{\min_2}}\right)^{-1}\right]^{1/3} \quad (5)$$

$$b_e=n\left[\frac{3F\left(k_1+k_2\right)}{2}\left(\frac{1}{R_{\min_1}}+\frac{1}{R_{\max_1}}+\frac{1}{R_{\max_2}}+\frac{1}{R_{\min_2}}\right)^{-1}\right]^{1/3} \quad (6)$$

In which m, n (based on cosθ) and k value in equation (1) can be determined using the appropriate table [14]. The value of cosθ can be calculated from Eq. (7):

$$Cos\theta=\frac{R_{\max}-R_{\min}}{R_{\max}+R_{\min}} \quad (7)$$

The values of k1 and k2 are dependent upon the modulus of elasticity and Poisson's ratio, as follows.

$$K_1=\frac{1-\mu_1^2}{E_1} \quad (8)$$

$$K_2=\frac{1-\mu_2^2}{E_2} \quad (9)$$

In which subscripts 1 and 2 refer to the contact bodies. Obviously, Elasticity modulus of the loading probe (E2) is much greater than that of the kernels (E1), and in k2 is assumed to be zero.

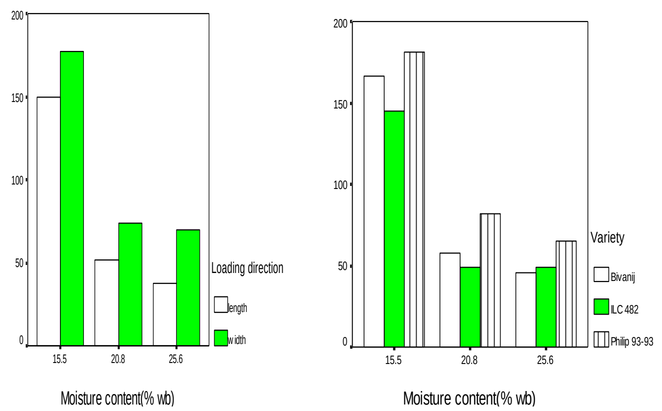
In this experiment, multivariable factorial test was utilized for determination of the effect of independent variables on the dependent parameters and Minitab statistical software was used for analysing the data.

Results And Discussion

Damage to chickpea kernels can consist of breaking, scratching, damage to embryo, and splitting. Splitting damage is more important than other aspects, because of quantitative losses. Failure criteria in this study were kernel splitting and not breakage. According to this, no kernels split was observed in thickness orientation, as expected. Therefore, the strength properties were evaluated on length and width loading orientations only. According to analysis of variance, moisture content was the major factor affecting all dependent parameters in comparison to loading orientation and variety (Table 1).

Rupture Force

In most cases, the highest rupture force occurred when compression was applied in direction of thickness. This is in agreement with results obtained by other researchers [9, 10]. In this orientation at 15.5% mc(wb), rupture force often was over 300 N. However, the lowest rupture force was 28.29 N that obtained for Bivanij variety, at 25.6% mc (wb), and loaded on lengthwise direction. As it was mentioned, loading in the thickness orientation did not cause any kernel splitting (separation of cotyledons), but loading in the two other orientations resulted in kernel splitting. In this relation, the mean value of rupture force is 106.30 N at widthwise loading and only 78.15 N at the longwise direction. The effect of moisture content, loading orientation and variety on rupture force is significant at 0.01 statistical level. As figure 2 shows graphically, effect of moisture content on rupture force is more pronounced than that of loading direction and variety. The rupture force decreased significantly from 159.9 to 49.9 N, when moisture content increased from 15.5 to 25.6% mc (wb).



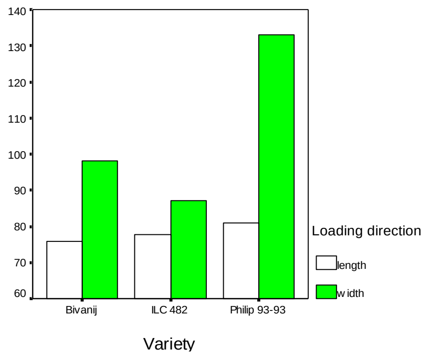


Fig. 2: Effect of moisture content and variety on chickpea rupture force.

The force required to rupture in Philip variety was more higher than that for other varieties probably, because of greater kernel size. In this relation, Kazaei (2003) and Minaei, *et al.*, (2003) observed that the higher size of kernel results in more resistance to rupture.

In addition, several regression models were manipulated to obtain the best relationship between rupture force and independent parameters or physical properties. The best regression model with high value of R^2 was found in exponential form that can be expressed mathematically as equation 10.

$$F = M_C{}^m \times D_G{}^n \qquad (10)$$

In which, F is rupture force in N, M_c is moisture content in % wb, and D_G is Geometric mean diameter in mm. Coefficients of exponential regression model for estimation of rupture force, based on moisture content and geometric mean diameter, are indicated in Table 2 for two loading orientations.

Table 2: Exponential regression models of rupture force (Eq. 13)

Loading orientation	m	n	R^2
W	-2.24	5.26	0.99
L	-2.58	5.61	0.98

Apparent Modulus of Elasticity

For most samples, the force-deformation curve was essentially a part of third-order polynomial (Fig. 3) and the modulus of elasticity was determined based on the slope from origin to rupture point. This is true, because most of food grains show a similar trend in their force-deformation curve, even with high amount of moisture contents. Values of elasticity modulus for chickpea are close to those of the cowpea kernels determined by Allen and Watts (1997). The minimum and maximum values of elasticity modulus was found to be 2.66 and 43.45 MPa for Bivanij variety at moisture content of 25.6% loaded in the lengthwise orientation, and Philip variety at moisture content of 15.5 % loaded in the width orientation, respectively.

Based on the analysis of variance, chickpea variety had a significant effect on elasticity modulus at the 0.05 level, but effects of moisture content and loading orientation were quite significant at the 0.01 level. Increasing moisture content resulted a significant decrease in elasticity modulus. Also, the value of elasticity modulus found in the longitudinal loading orientation to be less than the other orientations (Fig 4).

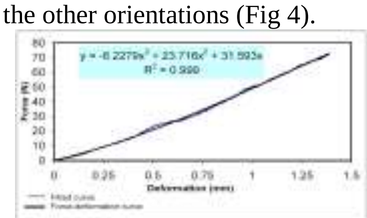


Fig. 3. Force-deformation curve and a typical polynomial fit

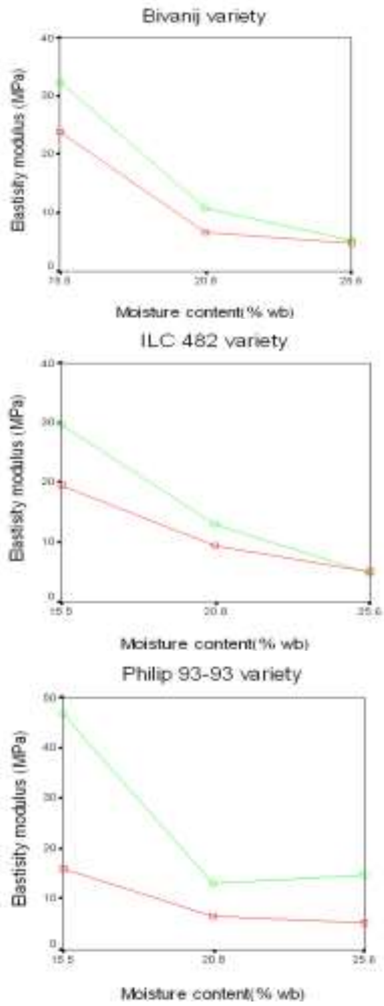


Fig. 4: Effect of chickpea moisture content, loading orientation and variety on the apparent modulus of elasticity: (□), Length; (○), Width.

The best regression model was found as the equation 11. Exponential regression model for estimation of elasticity modulus, based on moisture content and geometric mean diameter, are given in Table 3.

$$E = M_C{}^m \times D_G{}^n \qquad (11)$$

In which E is elasticity modulus in MPa, M_C is moisture content in % wb, and D_G is geometric mean diameter in mm.

Table 3: Coefficients of regression model for predicting models of elasticity modulus (Eq. 11)

Loading orientation	m	n	R^2
W	-2.88	5.34	0.96
L	-2.4	4.44	0.95

Maximum Contact Stress

Contact stress of chickpea kernels decreased with increasing moisture content and as it can be seen (Table 4 & Figure 5), there is an inverse relationship between moisture content and contact stress. Increasing in moisture content from 15.5 to25.6 wb cause to decrease contact stress from 11.69 to 2.96 MPa. Minimum and maximum contact stress values were 1.29 and 31.41 MPa, respectively. Also, in all varieties, the differences of stress between 15.5 and 20.8 % mc wb levels is more than that between 20.8 and 25.6 mc levels. Contact stress value of the kernels loaded in a length orientation(5 MPa) was found less than that for width orientation(7.47 MPa) at all range of moisture content. Bivanij and ILC 482 varieties had lower contact stress than that for Philip 93-93 variety.

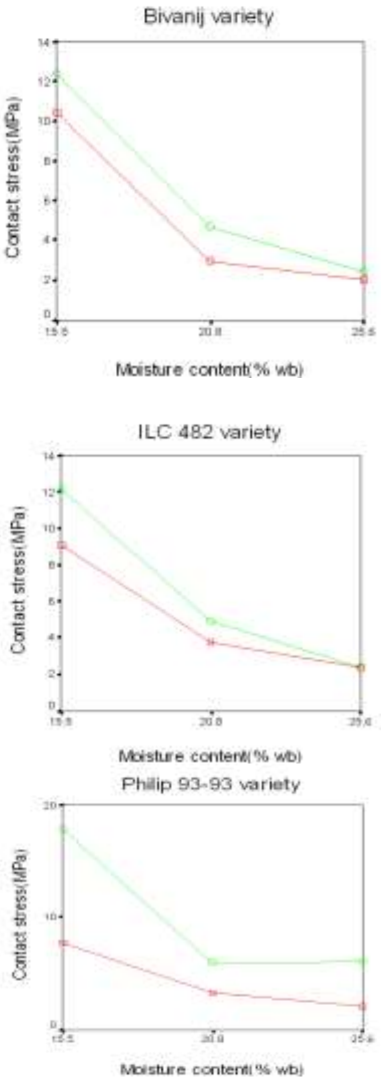


Fig. 5: Effect of chickpea moisture content, loading orientation and variety on contact stress; (□), Length; (○), Width.

As indicated in Table 1, the effects of moisture content, loading orientation and variety on contact stress are very significant at the 0.01 level. Effect of moisture content on contact stress is more pronounced than that of loading orientation and variety (Table 2). Minimum contact stress was obtained with the ILC variety at 25.6 % mc wb, loaded longitudinally.

Exponential regression models, obtained for contact stress as a function of moisture content and geometric mean diameter, are shown in Table 5 for each loading orientation. This model can be showed mathematically as model 12. Knowing moisture content and geometric mean diameter, these models can be utilized for estimation of contact stress.

$$\sigma = M_C^{\ m} \times D_G^{\ n} \qquad (12)$$

In which σ= contact stress in MPa, MC= moisture content in % wb, DG= Geometric mean diameter in mm.

Table 4: Coefficients of regression model for predicting contact stress (Eq. 12)

Loading orientation	m	n	R^2
W	-2.67	4.62	0.94
L	-2.46	4.14	0.91

Maximum Deformation

The mean values of deformation of chickpea kernel at the rupture point were between 0.42 to 3.25 mm. As indicated in Table 1, maximum deformation was affected significantly by moisture content and loading orientation. Maximum deformation value increased with increasing moisture content. In a way that, increasing moisture content from 15.5 to 25.6 % wb cause to increasing deformation from 1.52 to 1.88 mm. Deformation value of cowpea kernels at 15 %mc wb expressed by Allen & Watts 1997, are lowly more than that of chickpea kernels. The deformation value of chickpea kernels loaded in the longitudinal orientation were higher than those loaded in width orientation for 15.5 and 20.8 range of moisture content. This result is in agreement with the result of Gupta and Das, (2000) for sunflower and Vursavaş & Özgüvenö (2004) for apricot pit. But in 25.6 % mc wb this result varied and reversed (Fig. 7). Variety did not have significant effect on deformation at the rupture kernel point.

Results of regression analysis showed that there is a non linear relationship between deformation and moisture content. Polynomial models developed for deformation (D_e) as a function of moisture content (M_C) are presented in equation (13) (Fig.6). In this relation, Table 5 gives the coefficients of polynomial model.

$$D_e = m + nM_C + pM_C^{\ 2} \qquad (13)$$

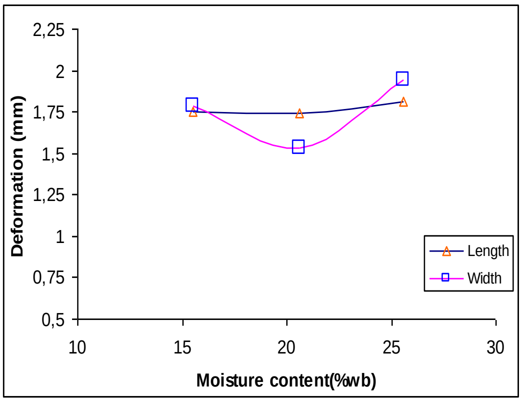


Fig. 6. Deformation of chickpea kernel versus moisture content and loading orientation

In which M_C= moisture content in % wb, D_e= deformation in mm.

Table 5. Coefficients of regression model for predicting deformation and strain (Eq. 13)

m	n	p	Loading orientation	R^2
6.784	-0.526	0.013	width	1
2.285	-0.059	0.002	Length	1

Rupture Energy

Kernel rupture energy was calculated by integrating the area under the F-X curve up to the rupture point. Minimum and maximum values of rupture energy were obtained to be 24.7 mJ at 25.6% mc wb, and 156.3 mJ at 15.5% mcwb, respectively, both in the longitudinal loading direction. Allen & Watts (1997) reported the rupture energy of cowpea to be 43.3-99.7 mJ at 15.5/7% mcwb, which is somewhat less than that of chickpea. Results of analysis indicated that increasing moisture content resulted in a significant decrease of rupture energy (Fig. 7). This reverse relationship is not observed in all agricultural materials. Allen & Watts (1997), Gupta & Das (2000), and khazaei, (2003) revealed that energy required to cause fracture of kernels increased as the moisture content increased.

There were some reasons for this result; definition of the failure criteria, range of moisture content, sample preparing conditions, materials moisture potential, and etc. in this research, rupture force decreased and deformation increased as moisture content of chickpea kernels increased, but deformation at cotyledon separation point increased lower in comparison to decreasing rupture force. At higher moisture content splitting chickpea kernels under compressive loading (cotyledons separation) occurred softly. But at lower moisture content cotyledon separation take happen sharply and crisply. Affect of loading orientation on rupture energy was not significant. However chickpea kernels did not absorb more energy for rupturing when loaded in the length orientation (70.71 *mJ*) in compare with the width orientation (66.38 mJ) due to primary failure.

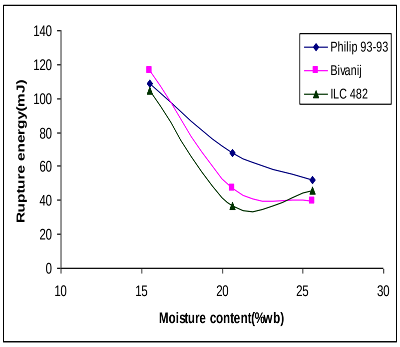


Fig. 7: rupture energy of chickpea kernel versus moisture content and variety

Conclusions

In this research splitting phenomena of chickpea kernels were evaluated. The results showed that the effect of moisture content on all chickpea strength properties was significant at the 0.01 level. Increasing moisture content results in significant decrease of rupture force, apparent modulus of elasticity, rupture energy and maximum contact stress on the one hand, and increase of strain and deformation on the other hand. Loading orientation had a significant effect at the 0.01 level on rupture force, apparent modulus of elasticity and contact stress, and also had a significant effect at the 0.05 level on strain and non-significant effect on rupture energy. Values of Chickpea strength properties were lowest when loaded in the length loading orientation. Thus, longitudinal loading orientations resulted in most damage to the kernels. The effect of chickpea variety was significant on rupture energy, rupture force and maximum contact stress. However, among the three varieties of chickpea, ILC 482 was most sensitive to damage and splitting and Bivanij was the second. Kernel splitting occurred under length and width loading orientations of chickpea. Splitting damage was most probable in the ILC variety under longitudinal compression at 25.6 % mc wb. Several regression equations were obtained, having R^2 values over 0.90, for estimation of chickpea strength parameters.

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