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Behavior of Wheat Kernels under Quasi-static Loading and its Relation to Grain Hardness

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ABSRACT

There are two reasons for measuring the mechanical properties of cereal grains. First, the possibility of grain classification based on texture and, second, to obtain information for modification in the design of post-harvest machinery. In both cases, the objectives will be the reduction of qualitative and/or quantitative losses of grain. In this research, eight different parameters obtainable from the force-deformation curves of wheat kernels under compression were determined. The most important of these included: the apparent modulus of elasticity, maximum compressive contact stress and maximum load at rupture. Other grain characteristics such as the dimensions of single wheat kernels and the particle size index of bulk samples for five varieties of wheat were measured. By performing 200 uniaxial compression tests on intact wheat kernels (from soft to very hard varieties), the values of modulus of elasticity ranging from 486 to 1631 MPa were determined based on measurements according to the Hertz theory. Results indicated a simple linear relationship between grain hardness and mechanical properties, such as modulus of elasticity and deformation at the linear limit on the force-deformation curve, and physical attributes, such as grain mass and major diameter. Grain orientation had no significant effect on the dependent variables. Moisture content had a very significant effect on mechanical properties. From the statistical analysis of the data (ANOVA and DMRT), it was found that it is possible to distinguish between soft and hard wheat kernels based on different parameters obtainable from the force-deformation curve. Hence, any one of these parameters may be used as a suitable indicator for grain hardness determination.

Keywords: Mechanical properties, Quasi-static loading, Single kernel, Wheat hardness.

INTRODUCTION

Kernel hardness is an important characteristic, since it influences the way wheat behaves during processing, especially the milling behaviour of wheat. It is also an inherent quality factor (Simmonds, 1989) and, therefore, is very often used in wheat classification. Cereal scientists generally agree that protein level, protein quality, and grain hardness are three minimal parameters that could identify wheat for "best end use" (Mattern, 1990). Investigations on methods of measuring grain mechanical texture indices have been the subject of many studies. In such research efforts, it was important to develop an objective instrument for practical use (Kindlmann and Kindlmann, 1983; Lai *et al.,* 1985; Pomeranz *et al.,* 1988; and Martin *et al.,* 1993). However, despite numerous studies on the mechanical properties of wheat (Arnold and Robert, 1969; Arnold and Mohsenin, 1971; Bargale *et al.,* 1995; and Kang *et al.*, 1995), there appears to be little information about the relationship between wheat kernel hardness and its fundamental mechanical properties.

Compression testing of intact biological materials provides an objective method for determining mechanical properties significant in quality evaluation and control of the maximum allowable static load for minimiz-

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ing mechanical damage (ASAE, 1999a).

The objectives of this study were: (1) to determine the mechanical properties of five (soft to hard) varieties of wheat under quasi-static loading, (2) to determine the suitable mechanical parameters that distinguish wheat varieties and (3) to describe the relationship between the PSI (particle size index) hardness index and mechanical parameters.

MATERIALS AND METHODS

Sample Preparation

Five different samples of wheat grains, ranging from soft to very hard (*Tritcum aestivum*, varieties: "Mahdavi", "Roshan", "Alamoot", "Ghods" and "Bezostaya") which grow in different regions of the country were obtained from the Seed and Seedling Research Institute located in Karaj. All wheat samples were cleaned and sieved to remove broken, shrunken, and damaged kernels. A randomly selected sample of 100 g per variety was studied. In order to control grain minimum and intermediate size effect, all wheat samples were sieved using Tyler No.7 mesh (Ohm, *et al*., 1998) so that only large kernels were studied. To prepare the moist samples, a calculated quantity of water was added to each sample placed in an air-tight container. These isolated containers were kept at 4°C for the desired period of time to attain equilibrium. The moisture content of the samples was determined using a standard moisture content measurement method for unground grains and seeds (ASAE, 1999b). The two levels of grain moisture content considered in this study, were 7.5% w. b. (dry treatment) and 16.5% w. b. (moist treatment).

A random sample of twenty wheat kernels at each moisture level and from each variety (10 replications for each treatment) was used in the tests. Immediately before conducting the tests, three dimensions of each grain were measured using a 0.02 mm micrometer. Each kernel was weighed using a precision digital balance and the 200 wheat kernels were then subjected to compression tests.

Compression Tests

Due to the irregular shape of wheat grain and its convex surface, it is not possible to use the direct equations of contact stress for calculating fundamental mechanical properties. However, by performing axial compression tests on intact grains (Arnold and Robert, 1969; Arnold and Mohsenin, 1971), variables such as the apparent modulus of elasticity (hence–forth referred to as the modulus of elasticity for simplicity) and the maximum compressive contact stress could be determined.

Based on a standard method (ASAE, 1999a), single wheat grains were placed between two parallel plates of the lower and upper heads of a compression-testing machine (Instron, Model 1186). At a constant loading rate of 2 mm per minute, twenty series of tests (five varieties, two levels of moisture content and two directions of grain orientation) were conducted with 10 replications. This number of replications was chosen according to the normal distribution of the data, especially the maximum load (Eckhoff, *et al.,* 1988), and also based on many similar studies which have used 10 replications, or less, in their investigations (Bargale, *et al.,* 1995; Henry, *et al*., 2000).

Equations (1) and (2), were used to calculate the modulus of elasticity and maximum compressive contact stress, respectively (ASAE, 1999a) as follows.

$$E = \frac{0.338 K^{\frac{3}{2}} F (1-\mu^2)}{D^{\frac{3}{2}}} \left[\frac{1}{R_{\min}} + \frac{1}{R_{\max}} \right]^{\frac{1}{2}} \quad (1)$$

$$\sigma_{\max} = \frac{1.5 F}{\pi ab} \quad (2)$$

In the above equations, E, is the modulus of elasticity for grain, MPa; K, is a dimensionless factor which depends on geometric properties of wheat grain; F, is compressive force, N; D, is the deformation of grain at about middle of D_T (total deformation), m; μ, is Poisson's ratio which is dimensionless and its value is taken to be 0.3 for wheat grain (Shpolyanskaya, 1952, quoted by Bargale, *et al.,* 1995); R_{min} and R_{max}, are the minor and major radii of curvature for grain at the point of contact, m; σ_{max}, is maximum stress occurring at the centre of contact area due to compression, MPa; and *a* and *b* are semi-major and semi-minor axes of the elliptical contact area, m.

The values of F and D in equation (1), were obtained from the point *Pc* (point of calculation), which is determined visually

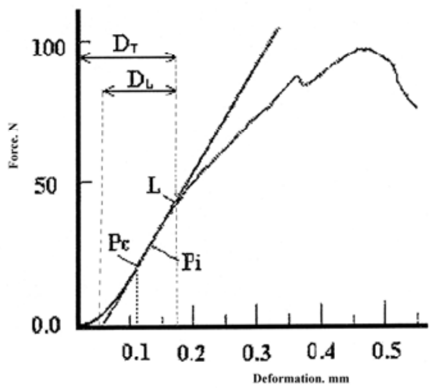

Figure 1. A typical force-deformation curve of wheat grain (*Mahdavi Var.*), in which *Pc, L*, and *Pi* are shown.

(see Figure 1), based on the standard method (ASAE, 1999a). The same procedure is used for determination of point L (linear limit). As Figure 1 shows, the force component of point *Pc*, is taken as D_T /2 which was considered on the basis of the suggestion of Arnold and Mohsenin (1971) and is normally lower than the point of inflection (Pi).

By applying quasi-static loading, at a constant rate of 2 mm/min to individual grain kernels, the characteristics of force-deformation for 200 kernels were determined. Independent variables included two levels of moisture content and two different orientations, for five varieties with ten replications.

Measurement of Particle Size Index

Based on the standard method (AACC, 1996), a 22 g sample of wheat grain from each variety was ground by a laboratory hammer mill at its finest setting. Then 10 g of meal was weighed, separated and transferred to a Tyler No. 200 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). Particle size index was then calculated using equation 3.

$$PSI\ \% = (W/\text{Sample weight})*100 \qquad (3)$$

Typical data indicative of relative hardness are shown in Table 1.

RESULTS

Means of Mechanical Properties

Table 2 shows the particle size index data for wheat of various varieties. A wide range of hardness values is observed for the varieties selected. Based on results of these measurements, the minimum value of the modulus of elasticity, 468 MPa, is associated with the softest variety (Mahdavi). For moist samples, and the maximum modulus of elasticity, equal to 1631 MPa, is related to

Table 1. Relative Hardness Scale, PSI % (AACC, 1996)**.**

Category	PI
Extra hard	Up to 7
Very hard	8 – 12
Hard	13 – 16
Medium hard	17 – 20
Medium soft	21 – 25
Soft	26 – 30
Very soft	31 – 35
Extra soft	Over 35

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Table 2. Percent of particle size index, mean (n=10), standard error (S. E.) for modulus of elasticity and maximum contact stress.

			Wheat Varieties				
			M[a]	A[a]	R[a]	B[a]	G[a]
	PSI (%)		29.2	23	18.1	12.2	11.9
σ_{max} (MPa)	Dry	S. E.	12	9.2	15	27	19
		Mean	149	148	148	190	191
	Moist	S. E.	13	11	11	19	17
		Mean	54	44	60	61	55
E (MPa)	Dry	S. E.	114	60	85	284	131
		Mean	1151	1154	1308	1631	1421
	Moist	S. E.	115	106	91	124	108
		Mean	468	469	564	595	643

[a] M=Mahdavi; A=Alamut; R=Roshan; G=Ghods and B=Bezostaya (Variety) # Dry (7.5%) and Moist (16.5%) w.b.

a very hard variety (Bezostaya) for dry samples. These values were obtained for large kernels (kernels with an intermediate diameter larger than 2.84 mm), to control the "size effect" as mentioned earlier. This may have somewhat decreased the modulus of elasticity values obtained here. However, as a whole, the results show good agreement with those obtained by other researchers. So that, in applying the parallel plate method (used in this research) to whole kernels, the measured values of modulus of elasticity are practically the same as the results obtained by other researchers. In this regard, a range of 230 to 4100 MPa has been reported for the modulus of elasticity with a mean standard error of 172 MPa (Mohsenin, 1978; Arnold and Robert, 1969; Bargale, *et al.,* 1995). In the current research, the mean standard error was about 135 MPa which is somewhat smaller than 172 MPa and so indicates a normal level of accuracy in measurement and sampling. However, as it is shown in Table 2, the values of the coefficient of variation exhibit considerable scatter of data. Data spread is natural, because we are not dealing with engineered materials such as steel, but with a biological material which exhibits wide natural variations. Especially, in the case of mechanical properties of wheat grain and its hardness, the large variation may be due to the interactions of protein and starch granules (Greenwell and Schofield, 1986). Also, a major source of this natural variation is due to the various shapes and sizes and existence of cracks or flaws in the kernels. Indeed, the variation of data is the most important problem in measuring hardness of wheat single kernels (Hoseney *et al,* 1992). In other words, the high data scatter is basically due to the nature of the grain not the testing procedure. The results of this study confirm previous investigations into this phenomenon especially in relation to the fundamental properties of the modulus of elasticity and contact stress. To overcome this difficulty (data scatter), some researchers tried to develop an automatic hardness tester for possibility of testing large quantities of grain (more than 200 kernels) in a sample (Lai *et al.,* 1985; Eckhoff *et al.,* 1988; Martin *et al.*, 1993). For example, Eckhoff (1988) stated that by applying 1000 replications, the coefficient of variation was more than 20%. The results of the current study (Table 4) show that it is possible to use the characteristics of the linear portion of a force-deformation curve up

Table 3. Mean values (n=10) and standard error (Std. Er.) for kernel size and the parameters of grain under static loading.

	Wheat Variety			
	Hard (B)		Soft (M)	
	F	E	F	E
Min.Dia. (mm)	3.19	3.02	3.11	3.10
Std. Er. (mm)	0.083	0.058	0.064	0.058
Int. Dia. (mm)	3.31	3.30	3.67	3.67
Std. Er. (mm)	0.053	0.039	0.046	0.122
Maj.Dia. (mm)	6.85	6.83	7.38	7.30
Std. Er. (mm)	0.159	0.139	0.168	0.179
Rupture Energy (J)	0.02	0.04	0.02	0.06
Std. Er. (J)	0.0023	0.0057	0.0034	0.011
Yield Energy (J)	0.014	0.021	0.011	0.042
Std. Er. (J)	0.0023	0.0041	0.0017	0.010
Load at Linear Limit (N)	135.8	99.5	98.4	100.8
Std. Er. (N)	14.62	13.37	9.48	10.47
Deformation at Linear Limit (mm)	0.09	0.08	0.09	0.12
Std. Er. (mm)	0.017	0.010	0.009	0.022
Deformation at Maximum Load (mm)	0.14	0.21	0.15	0.40
Std. Er. (mm)	0.020	0.024	0.020	0.079
Maximum Load (N)	172.1	146.7	119.3	156.3
Std. Er. (N)	9.20	11.12	8.60	12.39

F=*Lying Flat* , E=*Sideways* (Grain Orientation)
B=Bezostaya , M=Mahdavi (Variety)

to the rupture point (modulus of elasticity) as an index of grain hardness and it is not possible to use the initial portion of this curve (contact stress), which may possibly be affected by properties of wheat bran, for this purpose.

Mean values of other mechanical parameters, in addition to kernel size, for two varieties of soft and very hard wheat kernels (based on Table 1) are summarized in Table 3. Also, typical force-deformation curves for soft and very hard wheat at two levels of moisture content are presented in Figure 2. As this figure indicates for both dry and moist samples, there are obvious differences between varieties, especially in the tangent modulus at *Pi*, deformation at linear limit, and deformation at maximum load. Furthermore, it seems that dry grains introduce more uniform curves than moist grains, which could be useful in their classification.

Comparison of Mechanical Parameters

An analysis of variance for comparison of mechanical properties of different varieties indicates that it is possible to classify the varieties using these properties. Results show that there are more significant differences among varieties when loaded “sideways”, though performing the tests in this position is more difficult than “lying flat”.

Analysis of the data included Duncan’s multiple range test (DMRT) for comparison of the means. Results of the DMRT are as follows:

1- In dry samples; hard wheat was separated from soft wheat based on maximum load in the “lying flat” position (α=0.01).

2- In moist samples, based on deformation at maximum load, the medium soft wheat could be distinguished from soft and medium hard wheat, in the “*sideways*” position (α=0.01).

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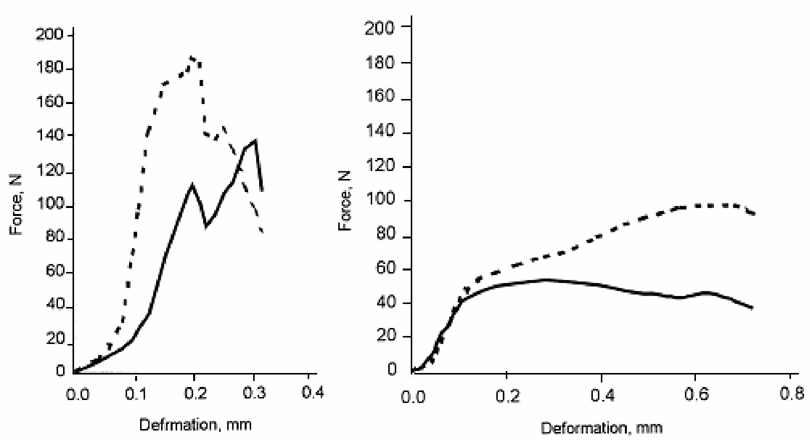

Figure 2. Force-deformation curves for moist (right) and dry (left) samples of soft (solid line) and hard (dotted line) wheat grain.

3- Soft wheat kernels were identified from hard and medium hard kernels, based on the area under the curve up to the yield and rupture points (α=0.05).

Using a t-test for comparison of the mean values of mechanical parameters indicated that grain moisture content had a very significant effect on all these parameters (α = 0.01). The increase in moisture content causes a decrease in strength properties of the grain (namely, force at rupture, force at linear limit, modulus of elasticity and contact stress). This result is exactly the same as the results of previous studies (Bargale *et al.,* 1995; Kang, *et al.,* 1995; Misra and Young, 1981). Based on this test, kernel orientation both (sideways and lying flat) had no significant effect on the mechanical properties under study.

Table 4. Simple linear regression coefficients of determination (R^2), between single kernel mechanical properties and particle size index.

	Moist Grains		Dry Grains	
	F	E	F	E
Min. Dia. (mm)	ns	ns	ns	ns
Int. Dia. (mm)	ns	0.82*	ns	ns
Maj. Dia. (mm)	0.75*	ns	0.85*	0.89*
Weight (g)	0.86*	ns	ns	ns
Max. Load (N)	ns	ns	ns	ns
Deformation at Maximum Load (mm)	0.79*	ns	ns	0.75*
Deformation at Linear Limit (mm)	0.81	ns	ns	0.80*
Energy to rupture (J)	ns	ns	ns	ns
Modulus of Elasticity (MPa)	0.87**	-	0.77*	-
Max. Contact Stress (MPa)	ns	-	ns	-
Elliptic Volume	083*	ns	ns	091**

*,** = coefficient of determination significant at P<0.05 and P<0.01, respectivily ; ns = not significant.
F=*Lying Flat* , E=*Sideways* (Grain Orientation)

Relationship Between Mechanical Properties and Wheat Hardness

Values of the simple coefficient of determination (r^2), for the relationship between the mean of mechanical properties of wheat grain and particle size index (as an indicator of wheat hardness) are summarized in Table 4. A linear relationship was found between wheat hardness and some mechanical parameters, such as deformation at maximum load, deformation at linear limit and modulus of elasticity, which exhibited a significant correlation. The fact that no significant correlation between minor and intermediate diameters and wheat hardness was found is possibly due to using large kernels in the study. Also, the results indicate no significant relationship between maximum contact stress and wheat hardness.

Figure 3, shows the decrease in the modulus of elasticity with increasing wheat hardness, in both levels of moisture content. Although this decrease is linear, it is not recommended to define a model for the relationship due to the significant variation in each variety. It can be also seen from the chart (Figure 3), that two varieties fall in one class of hardness. Nevertheless, there is an obvious difference between them in the two levels of moisture content.

CONCLUSIONS

Based on the results of this study on five different varieties of wheat kernels at two levels of moisture content, quasi-static loading tests and subsequent statistical analyses, the following conclusions are drawn.

(1) Based on Hertz's theory and by conducting a series of compression tests on intact wheat kernels, a range of apparent modulus of elasticity measured between 0.47 GPa (in a soft variety and moist treatment) and 1.63 GPa (in a very hard variety and dry treatment), was obtained which agrees well with those obtained by other researchers.

(2) It is possible to distinguish soft and hard wheat varieties based on some parameters obtainable from the force-deformation curve through quasi-static loading. These parameters included deformation at the rupture point and deformation at the linear limit. The results also show the considerable effect of grain geometry, shape and weight on kernel hardness.

(3) In investigating the relationship be-

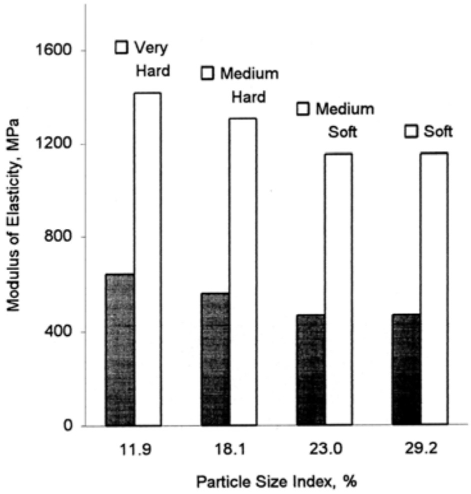

Figure 3. Relationship between modulus of elasticity of wheat grain and PSI hardness index In dry (white columns) and moist (grey columns) treatments.

tween grain mechanical parameters and wheat hardness, the moist samples yield better results (significant correlation) when tested “lying flat”, while dry samples are better tested “sideways”. A linear relationship was found between grain hardness and mechanical parameters (moduli of elasticity and deformation at the rupture point). In other words, it is possible to use the characteristics of the linear portion of a force-deformation curve up to the rupture point for estimating the kernel hardness, but it is not possible to use the initial portion of the curve (contact stress) for this purpose.

(4) Statistical analysis of the data shows that moisture content has a significant effect on mechanical factors, whereas grain orientation has no pronounced effect on mechanical parameters. Therefore, it is reasonable to use the most stable position of wheat kernel which is “lying flat” in such tests.

REFERENCES

1. American Association of Cereal Chemists 1996. *Approved Methods of the AACC. Method 55-30*. The Association: St. Paul, MN.
2. ASAE Standards 1999a. *Compression Test of Food Materials of Convex Shape*. American Society of Agricultural Engineers, S368.3.
3. ASAE Standards 1999b. Moisture Measurement for Unground Grains and Seeds. American Society of Agricultural Engineers, S352.2.
4. Arnold, P. C. and Robert, A. W. 1969. Fundamental Aspects of Load-deformation Behaviour of Wheat Grains. *TRANS. ASAE*, **12**: 104 -108.
5. Arnold, P. C. and Mohsenin, N. N. 1971. Proposed Techniques for Axial Compression Tests on Intact Agricultural Products of Convex Shape. *TRANS. ASAE*, **14**: 78-84.
6. Bargale, P. C., Irudayaraj, J. and Marquist, B. 1995. Studies on Rheological Behaviour of Canola and Wheat. *J. Agric. Eng. Res*. **61:** 267 - 274.
7. Eckhoff, S. R., Supak, W. A. and Davis, A. B. 1988. A Rapid Single-kernel Wheat Hardness Tester. *Cereal Chem*., **65**: 503-508.
8. Greenwell, P. and Schofield, J. D. 1986. A starch granule protein associated with endosperm softness in wheat. *Cereal Chem*., **63**: 379 - 380.
9. Henry, Z. H., Su, B. and Zhang, H. 2000. Resistance of Soya Beans to Compression. *J. Agric. Eng. Res*. **76:** 175 - 181.
10. Hoseney, R. C. and Faubion, J. M. 1992. Physical Properties of Cereal Grains. In: *Storage of Cereal Grains and Their Products*. 4th edn. American Association of Cereal Chemists, Inc. St. Paul, M. N. pp. 1-28.
11. Kang, Y. S., Spillman, C. K., Steele, J. L. and Chung, D. S. 1995. Mechanical Properties of Wheat. *TRANS. ASAE*, **38**: 573-478.
12. Kindlmann, J. and Kindlmann, P. 1983. Determination of the Technological Quality of Cereal Grain by Measuring its Crushing Strength. In: "*Progress in Cereal Chemistry and Technology*". (Ed.): Kratochvil, J. Vol. II, Elsevier Publications, Prague**.**
13. Lai, F. S., Rousser, R., Brabec, D. and Pomeranz, Y. 1985. Determination of Hardness in Wheat Mixture. II. Aparatus for Automated Measurement of Hardness of Single Kernels. *Cereal Chem*., **62**: 178 - 184.
14. Martin, C. R., Rousser, R. and Brabec, D. L. 1993. Development of a Single Kernel Wheat Characterization System. *TRANS. ASAE*, **36**: 1399-1404.
15. Mattern, P. J. 1990. Wheat. In: “*Handbook of Cereal Science and Technology*”, (Eds.): Lorenz, K. J. and Kulp, K. Marcel Dekker, New York. pp. 1 – 53.
16. Misra, R. N. and Young, J. H. 1981. A Model for Predicting the Effect of Moisture Content on the Modulus of Elasticity of Soybean. *TRANS. ASAE*, **24**: 1338-1341.
17. Mohsenin, N. N. 1978. *Physical Properties of Plant and Animal Materials*. 1st. edn. Gordon and Breach Publishing Co., New York, NY.
18. Ohm, J. B., Chung, O. K. and Deyoe, C. W. 1998. Single-kernel Characteristics of Hard Winter Wheat in Relation to Milling and Baking Quality. *Cereal Chem*. **75**: 156 - 161.
19. Pomeranz, Y., Martin, C. R., Rousser, R., Brabec, D. and Lai, F. S. 1988. Wheat Hardness Determined by a Single-kernel Compression Instrument with Semi Automated Feeder. *Cereal Chem*., **65**: 86-94.
20. Simmonds, D. H. 1989. *Wheat and Wheat Quality in Australia*. 2nd edn. Williams Books. Queensland, Sidney.

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بررسی رفتار دانه گندم طی بارگذاری شبه استاتیک و ارتباط آن با سختی دانه

ا. ح. افکاري سياح و س. ميناييـ

چكيده

اندازه‌گيري خواص مكانيكي دانه‌هاي غلات از دو جهت حائز اهميت است، يكي امكان شناسايي دقيقتر بافت دانه كه در راستاي طبقه‌بندي آن صورت مي‌گيرد و ديگري بدست آوردن اطلاعاتي كه به بهينه‌سازي ماشين‌هاي برداشت، جابجايي و ذخيره‌سازي دانه مي‌انجامد. درهر دو مورد هدف نهايي كاهش ضايعات كمي و كيفي دانه از مرحله برداشت تا توليد محصول نهايي خواهد بود. دراين تحقيق هشت پارامتر مختلف بر اساس آزمون فشاري بر روي تك دانه گندم و منحني نيرو تغيير شكل حاصله استخراج گرديدند. از مهمترين فاكتورهاي بدست آمده مي‌توان از ضريب كشساني ظاهري، بيشينه تنش تماسي و نيروي بيشينه در نقطه گسيختگي نام برد. ديگر خصوصيات دانه شامل ابعاد دانه گندم و شاخص توزيع اندازه ذرات در نمونه‌هاي توده براي پنج رقم مورد بررسي اندازه‌گيري شد. با انجام ۲۰۰ تست فشاري محوري بر روي دانه كامل گندم، (بر روي ارقام نرم تا خيلي سخت)، مقادير ضريب كشساني ظاهري محاسبه شده بر اساس تئوري Hertz از MPa ٤٦٨ براي نمونه مرطوب رقم مهدوي تا MP ١٦٣١ براي نمونه خشك رقم بزوستايا متفاوت بود. نتايج نشان دهنده وجود ارتباط خطي بين اين شاخص و پارامترهايي همچون ضريب كشساني، تغيير شكل در حد خطي و خصوصيات فيزيكي دانه همچون وزن و قطر بزرگ دانه بود. در اين حال، جهت قرارگيري دانه تأثير معني‌داري بر متغيرهاي وابسته نداشت. درحاليكه رطوبت تاثير بسيار معني‌داري بر خواص مكانيكي داشت. بر اساس نتايج حاصل از تجزيه آماري داده‌ها (ANOVA و DMRT)، مشخص شد كه مي‌توان دانه‌هاي نرم و سخت گندم را بر اساس پارامترهاي مختلفي كه از منحني نيرو تغيير شكل حاصل مي‌گردند از يكديگر تشخيص داد. از اينرو، مي‌توان از هر يك از فاكتورهاي ذكر شده به عنوان شاخصي مناسب در سختي تك دانه استفاده نمود.

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