SOME MECHANICAL CHARACTERISTICS OF WHEAT SEEDS OBTAINED BY UNIAXIAL COMPRESSION TESTS

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The paper presents the results of some experimental research on the mechanical behavior of three varieties of wheat crops from Southern Romania, namely: Flamura, Trivale and Glosa. Measurements were made in the laboratory on samples of 50 seeds, ramdomly selected from each wheat variety. Each of the 150 seeds was subjected to uniaxial compression test using Hounsfiled (H1 KS) mechanical testing machine, and force-deformation curves were recorded. From each curve, data were taken on force, deformation and energy consumption on bioyield point respectively rupture, and the modulus of elasticity was calculated. For each of these parameters, mean values were determined. Mean curve force-deformation was drawn for each of the three varieties of wheat seeds, obtained by mediation of compression force values while maintaining the same values of strains. By analyzing the obtained data it was found that the three varieties of wheat have similar behavior in uniaxial compression tests, but they have however, different average values of rupture forces (104.2 N for Flamura, 83.2 N for Trivale respectively 94.7 for Glosa variety), of energy consumed to the point of rupture and the modulus of elasticity (0.038 J, respectively 298 MPa for Flamura, 0.018 J, respectively 369 MPa for Trivale, 0.016 J, respectively 468 MPa for Glosa variety). It was found that both average curves of the three varieties of wheat and the force-deformation curves of the analyzed seeds have similar shapes.

Key words: wheat seed, compression test, force-deformation curve, rupture point, bioyield point, modulus of elasticity, energy absorbed

1. Introduction and review

Roller mills perform the grinding of cereal seeds by the combined action of compression, friction, cutting, shearing and impact forces developed by the two grinding rollers (fluted or smooth) in rotary motion, on the seeds.

The compression of wheat seeds is performed in three different stages: the first stage is elastical deformation, characterized by the proportionality between the compression force and the deformation; the second stage is plastic deformation, characterized by large increases of seed deformation at small

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increases of compression force; the last stage consists in cracking or rupture, being characterized by seed crushing when reaching a certain value of compression force, [1,2,3].

Compression test is an objective method for determining the mechanical properties of cereal seeds and also one of the best techniques for determining the modulus of elasticity by the study of their behavior at compression stress, using force-deformation curve, [4,5].

By means of uniaxial compression tests, various research were carried on the relationships between the specific energy consumption for grinding and the mechanical properties of seeds, and on the effect of moisture on the mechanical properties of wheat seeds (compression strenght), [6,7,8,9,10].

By performing uniaxial compression tests on wheat seeds, force-deformation curve is obtained, giving the possibility to determine the following characteristics: hardness, apparent modulus of elasticity, crushing resistance, force and deformation in the inflection point, bioyield point and rupture point; mechanical work in the inflection point, bioyield point and rupture point, energy consumption, maximum contact stress, [4,11].

In paper [7] were presented significant dependences (α=0.05) between the mechanical characteristics resulted from compression tests and the specific energy of wheat seeds grinding (positive correlations between the force in the bioyield point, the force in rupture point and specific grinding energy: r = 0.78, respectively r=0.95).

Cereal seeds have a different behavior under the action of compression forces, depending on their moisture content, [1]. Thus, generally, as the moisture content of cereal seeds increases, the applied compression force decreases, while the absolute deformation of the seeds until the rupture point increases. This fact is also mentioned in paper [8], where it was shown that the compression force decreases from 152.11 N to 63.99 N, respectively the energy required for crushing (rupture) increases from 19.32 to 28.35 mJ, with the increase of moisture content from 7.8% to 20%, for wheat seeds of Shiroody variety, from Iran.

In paper [7] it was found that with the increase of moisture content of wheat seeds (Turnia variety, from Poland, 2002) from 12% to 16% the deformation increases, and for a increase of moisture content from 12% to 14% the compression force in the bioyield point decreases.

Grezgorz and Laskowski, [9], analyzed the influence of moisture content of wheat seeds (Kobra variety) on the deformation, during uniaxial compression. It was found that for cereals having low moisture content (10-12 %) the deformation has a slow increase, while as the moisture content increases and the force applied at compression decreases, the deformation has a higher increase, especially after the 16% moisture content is exceeded.

Afkari Sayyah and Minaei, [12], performed compression tests on 5 varieties of wheat from Iran (from soft wheat to very hard wheat) and showed that the varieties of soft wheat differ from those of hard wheat by the characteristics of force-deformation curve (deformation in the rupture point, deformation in the inflection point), obtained from compression test. Also, based on the compression tests it was proved that the position of wheat seeds during compression (lying – ”lying flat”, on one side – ”sideways”) has no significant influence on the mechanical characteristics of seeds. The authors say that it is reasonable to use the most stable position of seed, usually the” lying flat” duringcompression tests. Moreover, during grinding process with grinding rollers (fluted or smooth), seeds are oriented randomly, trying to occupy the most stable position (orientation).

Wheat seeds hardness is also related to compression tests performed by Babic et al., [13], from which it was established that the value of compression force for hard wheat in bioyield point (241.5 N for Dragna variety with moisture content 0.133 kg kg^{-1} and 244.4 N for Simonida variety with moisture content 0.136 kg kg^{-1}) is approximalely 2.2 times higher than the value of the force in the bioyield point for soft wheat variety (106.8 N for NS 40S variety with moisture content 0.141 kg kg^{-1}).

For the compression of wheat seeds between two flat parallel plates, Shelef and Mohsenin [14], Afkari Sayyah and Minaei, [12] and Khodabakhshian and Emadi, [5] found that the determination of seeds modulus of elasticity can be made by using a calculus relation which contains the geometrical parameters of the seed, before and after deformation, the applied compression force, Poisson ratio, relation that is also presented in the standard method (ASAE 2008), [4].

The results obtained in paper [5] have shown that the method of uniaxial compression of wheat seeds between two flat parallel plates is the most appropriate (correct), due to adequate correlations between theoretical and experimental data of force-deformation curve.

This paper aims to present some results on the mechanical behavior of wheat seeds for three different varieties, grown in Southern Romania, namely: Flamura, Glosa and Trivale.

2. Theoretical considerations

For the grinding of wheat seeds in industrial mills, roller mills are used.

Main stress to which seeds are subjected, during passing through the grinding rollers, is given by the type of rollers surface, respectively if that is smooth or fluted. Regardless of the type of this surface, one of the main stress on the seeds during grinding is compression (or crushing), especially if the grinding rollers are smooth. To estimate the behavior of wheat seeds passing through the grinding rollers, experimental research are required on the compression stress of different varieties of wheat seeds, knowing that not all varieties posses the same mechanical characteristics. However, even seeds of the same variety have different bahavior, due to the uneven development both within the ear, as well as from one ear to another.

Compression test is an objective method to determine the mechanical properties of cereal seeds and one of the best techniques to determine the modulus of elasticity by the study of seeds behavior at compression stress, based on the force-deformation curve obtained after performing the test, [4,5].

Worldwide research [5,14], shown that, for wheat seeds, the most appropriate (adequate) method of uniaxial compression is the one using two flat parallel plates.

Mechanical behavior of wheat seed from uniaxial compression tests is divided into three areas: *elastic*, where the behavior is linear, characterized by the proportionality between compression force and deformation; *plastic deformation*, by flow, characterized by large increases of seed deformation at small increases of compression force; *seed crushing*, when the compression force has reached a certain value, [1,2,3].

In fig.1 is presented a typical force-deformation curve for compressed Flamura wheat seed.

The review of literature indicates that many studies have determined the compressive properties of wheat seeds produced from force-deformation curves obtained from uniaxial compression test [5,8,9,12,13,14,15]: bioyield and rupture force, deformation to bioyield and rupture point, energy absorbed in bioyield and rupture point, apparent modulus of elasticity, hardness.

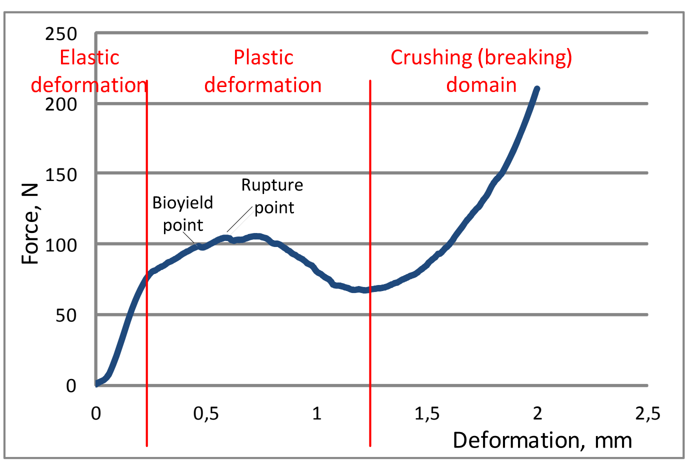

Fig.1. A typical force –deformation curve of wheat grain (Flamura)

Bioyield point is the point where an increase in deformation results from a decrease or no change in force, [4].

Force in rupture point (rupture force) is the minimum necessary force for wheat seed cracking (rupture), [16,17]. Deformation at bioyield and rupture point is the deformation at loading direction, [16,17]. Values of force and deformation to bioyield and rupture point are directly read from force-deformation curve and recorded by the machine used for compression test, [4]. The energy absorbed until the rupture point is the energy required to break (rupture) the seed. Energy absorbed in bioyield and rupture point could be determined from the area under the force-deformation curve between the initial point and the bioyield and rupture point, respectively, using equation [16,17]:

$$W = \frac{F \cdot D}{2} \quad [mJ] \tag{1}$$

where: W is the absorbed energy (mJ), F is the force in bioyield or rupture point (N), D is deformation in bioyield or rupture point (mm), (see fig.1).

Based on a standard method (ASAE 2008), for a seed placed between two parallel plates, the modulus of elasticity could be calculated with following equation, [4]:

$$E = \frac{0.338 \cdot k_g^{3/2} \cdot F\left(1-\upsilon^2\right)}{D^{3/2}} \cdot \left[\frac{1}{R'} + \frac{1}{R_1'}\right]^{\frac{1}{2}} \quad [MPa] \tag{2}$$

where: E – modulus of elasticity for cereal seeds, (MPa); k_g – coefficient which depends on the geometrical characteristics of wheat seeds ($k_g = 1.303$ - adapted from Table 1 0f (ASAE 2008) - calculus tables of Kozma and Cunningham, 1962); F – compression force, (N); D – seed deformation (m); ν - Poisson ratio, (ν = 0.3 for wheat seeds [18]); R' and R'_1 – small and large radius of the curvature of convex surface seed in contact with the flat surface, (m), (see fig. 2).

According to the standard method (ASAE 2008), also presented by Mohsenin in [14,17], the curvature radius of convex surface, R' and R'_1 (fig. 2) can be calculated using relations (3) and (4):

$$R' \cong \frac{H}{2} \tag{3}$$

$$R' \cong \frac{H^2 + \frac{L^2}{4}}{2H} \tag{4}$$

where: H is seed thickness, (m), and L is seed lenght, (m), in undistorted state.

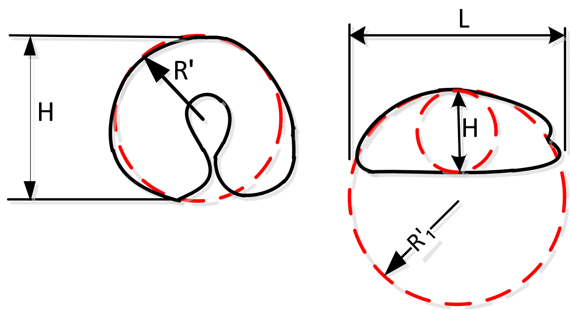

Fig.2. Estimation of curvature radius, [14,17]

According to the method (ASAE 2008), values of force *F* and deformation *D*, from equation (2) are calculated for the proportionality area of force-deformation curve in the point of calculation P_c (fig.3). The position of this point is estimated visually, as the point is located halfway between curve origin and proportionality limit P_L (fig.3). It was found that the point of calculation P_c is located lower than the point of inflection, also established visually, [4].

This method was used by many researchers in order to determine the modulus of elasticity for different agricultural products, [12,15,19,20].

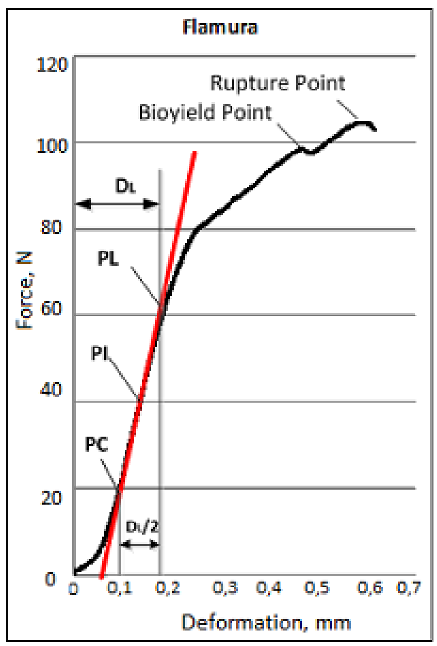

Fig. 3. Force-deformation curve of Flamura wheat seed, [adapted from [17]]
PL – proportional limit; PI – point of inflection; P_c – point of calculation

3. Materials and methods

For this paper, determinations were made on samples of 50 seeds from three varieties of Romanian wheat: Flamura, Trivale and Glosa. Moisture content of the three varieties of wheat was determined using MAC 110 thermobalance and the values ranged between 12.00 - 12.14 % for Flamura wheat seed, 12.09 - 12.27 % for Trivale, respectively 10.43 - 10.57 % Glosa.

Main dimensions of seeds were measured (lenght, width, thickness), using a digital gauge with precision of 0.01 mm, and then the individual mass of seeds was determined using a Kern electronic balance with precision of 10^{-1} g.

To determine the resistance characteristics of seeds, uniaxial compression tests were performed for each of the 50 seeds from each variety of wheat, with the Hounsfield mechanical testing machine, using a force cell of 1000 N, (fig.4).

Speed of the crushing device was kept constant at 5 mm·min^{-1}.

From the uniaxial compression tests, force-deformation curves were obtained for each seed, and from each curve data was taken about the force and deformation in the bioyield point, respectively force and deformation in the rupture point.

Using standard method (ASAE 2008) and equations (2), (3) and (4) the values of modulus of elasticity for each of the 150 seeds from the three varieties of wheat, were determined. Their mean values are presented in table 1. Mean values of the mentioned characteristics were determined (F_b, F_r, W_b, W_r, D_b, D_r), as well as the mean modulus of elasticity E for seeds of each variety, as arithmetic average of the 50 values obtained for each seed type.

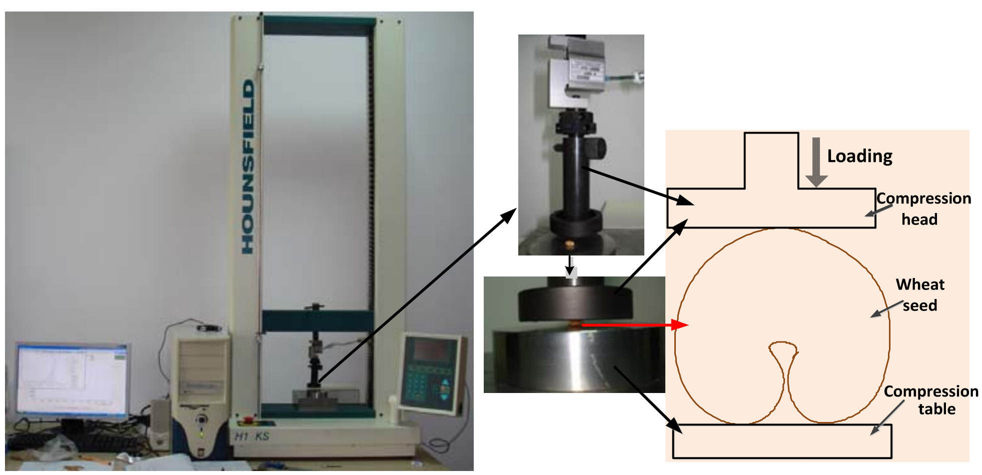

Fig. 4. Hounsfield - Mechanical testing machine used in compression test

Force-deformation curves, for each of the 50 determinations (of a variety) were processed so that each has the same origin (same starting point), and the same intervals of reading. Values for the parameter on the ordinate (forces in the mentioned points) were averaged (arithmetic average for the 50 determinations was calculated using Excel) for the same value of deformation (parameter on the abscissa), and these values were used to retrace the force-deformation curve, which represents the curve of mean values of compression force (fig.5). Using the approximately normal distribution, the limits within the mean force-deformation curve is found were statistically estimated, for a confidence interval of 95%. For normal distribution, the confidence interval corresponding to 95% confidence level ranges between +/- 1.96, considered standard deviations. Thus, the confidence interval of mean curve was calculated using the following equation:

$$\mu = m \pm 1.96 \cdot \frac{\sigma}{\sqrt{n}} \tag{5}$$

where: μ is the confidence interval, and m is the mean value of the analyzed parameter (in this case, the compression force).

$$\frac{\sigma}{\sqrt{n}} = S_m \tag{6}$$

where: S_m is the standard error of the mean, σ – standard deviation, and n –number of seeds from each variety of wheat (in this paper, n = 50).

On the curve of mean values (fig.5), were visually determined directly the values of mechanical characteristics mentioned before (forces and deformations in the characteristic points) and it was calculated the value of modulus of elasticity using the standard method (ASAE 2008), for mean curve (for the three varieties of wheat).

Knowing the forces and deformations in the points of bioyield and rupture, from the area under the force-deformation curve between the initial point and the bioyield and rupture point, respectively, using equation (1), energy absorbed in bioyield and rupture point was determined.

Measurement errors were determined for those parameters, according to the two determination methods presented:

$$\varepsilon_x = \frac{\bar{x} - x_o}{x} \cdot 100 \quad (\%) \tag{7}$$

where: ε_x is relative error, $\bar{x}$ is the mean of parameters (forces in bioyield, respectively rupture points and the modulus of elasticity), x_o is the value of determined parameter of mean (curve of mean values for the 50 determinations).

4. Results and discussions

Direct measurements on the geometric dimensions of the three varieties of wheat seeds showed that:

- for Flamura variety, seeds lenght was l = 5.59 – 7.29 mm, width b = 3.78 – 2.97 mm, thickness c = 2.59 – 3.57 mm and mass m = 0.034 – 0.068 g;
- for Trivale variety, seeds lenght was l = 5.09 – 7.22 mm, width b = 2.19 – 3.52 mm, thickness c = 1.96 – 3.28 mm and mass m = 0.021 – 0.066 g;
- for Glosa variety, seeds lenght was l = 6.11 – 7.22 mm, width b = 2.68 – 3.75 mm, thickness c = 2.57 – 3.36 mm and mass m = 0.036 – 0.066 g.

Analysis of data presented in table 1 showed that the values of bioyield force, respectively values of the force in the point of rupture of wheat seeds, determined from the mean curve are very close to the values of these forces obtained from the force-deformation curves for each particular seed.

Calculating the error of determination (table 2) with relation (7) shows deviations of 2.4 % for bioyield force for Trivale variety and 5.5 % for the same force for Flamura variety.

Table 1

Values of measured and determined parameters in uniaxial compression test

Measured parameters of wheat seeds		Mean of parameters values for the 50 seeds			Values of parameters read from the mean curve of the 50 measurements		
		Flamura	Trivale	Glosa	Flamura	Trivale	Glosa
Bioyield force F_b, (N)		93.2	83.1	98.0	98.4	81.1	94.0
Bioyield energy W_b, (J)		-	-	-	0.028	0.018	0.016
Rupture force F_r, (N)		107.8	90.5	103.6	104.2	83.2	94.7
Rupture energy W_r, (J)		-	-	-	0.038	0.018	0.016
Bioyield deformation	Relative deformation, δ_b	0.138	0.092	0.077	-	-	-
	Absolute deformation, D_b (mm)	0.304	0.267	0.260	0.464	0.348	0.292
Rupture deformation	Relative deformation, δ_r	0.099	0.109	0.086	-	-	-
	Absolute deformation, D_r (mm)	0.419	0.320	0.290	0.576	0.400	0.360
Modulus of elasticity, (MPa)		313	364	486	298	369	468

Calculus error for the forces in the point of rupture has values of 3.3 % for Flamura and 8.6 % for Glosa. Regarding the values of modulus of elasticity, determined with the two methods presented in this paper, it was found that they are also relatively close for each variety of analyzed wheat, calculus errors ranging between 1.5 % for Trivale and 4.9 % for Glosa.

Table 2

Error of determination

Measured parameters of wheat seeds	Error (%)		
	Flamura	Trivale	Glosa
Bioyield force F_b, (N)	5.5	2.4	4.1
Rupture force F_r, (N)	3.3	8.1	8.6
Modulus of elasticity, (MPa)	4.9	1.5	3.7

Analysis of curves presented in figure 5 shows that they have similar shapes for the three varieties of wheat, and also within each of them and the force-deformation curves for each individual seed analyzed from each variety of wheat.

As absolute values of the force in the bioyield point, respectively in the rupture point, they are found in between 83.1 N for Trivale variety and 98.0 N for Glosa variety regarding the bioyield force, respectively 90.5 N for Trivale and 107.8 N for Flamura (values calculated with arithmetic average of the 50 determinations). These values are very close to the values presented in literature [21], where it is stated that crushing force (rupture) of wheat seeds is of approximately 10 daN.

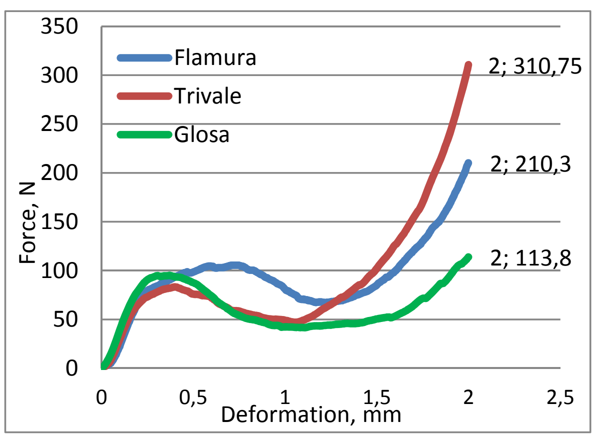

Fig.5. Mean curves force-deformation for three wheat varieties

On the relative deformation of seeds, during the compression tests, for the force in the bioyield point (bioyield force), respectively rupture, data in table 1 also show relatively close values for the wheat seeds of the three varieties.

Relative deformation values are found within the limits of 0.077 for Glosa and 0.138 for Flamura (absolute values 0.260 mm for Glosa, respectively 0.304 mm for Flamura). For deformation at rupture, values of relative deformation and absolute values are found between 0.086 for Glosa and 0.109 for Trivale, respectively 0.290 mm for Glosa and 0.419 mm for Flamura.

The energy absorbed for seeds deformation, both for bioyield point and for rupture point was determined by planimetry of the area under the curve on the graphics shown in figure 5, namely on the curves of force-deformation mean values. These values range between 0.016 J for Glosa and 0.028 J for Flamura variety, regarding the energy in the bioyield point. For the rupture point, energy values are 0.016 J for Glosa and 0.038 J for Flamura variety. For Trivale variety, the energy absorbed for seeds deformation in both bioyield and rupture points, is also found within the limits presented for the other two varieties.

On the modulus of elasticity, its values are approximately 313 MPa, for Flamura and 486 MPa, for Glosa variety (calculated as arithmetic average of the values obtained for the three samples, each having 50 seeds).

Fig. 6 shows the force-deformation curves for mean force values at the same deformation stages, and the confidence interval of the curve, corresponding to 95% confidence level.

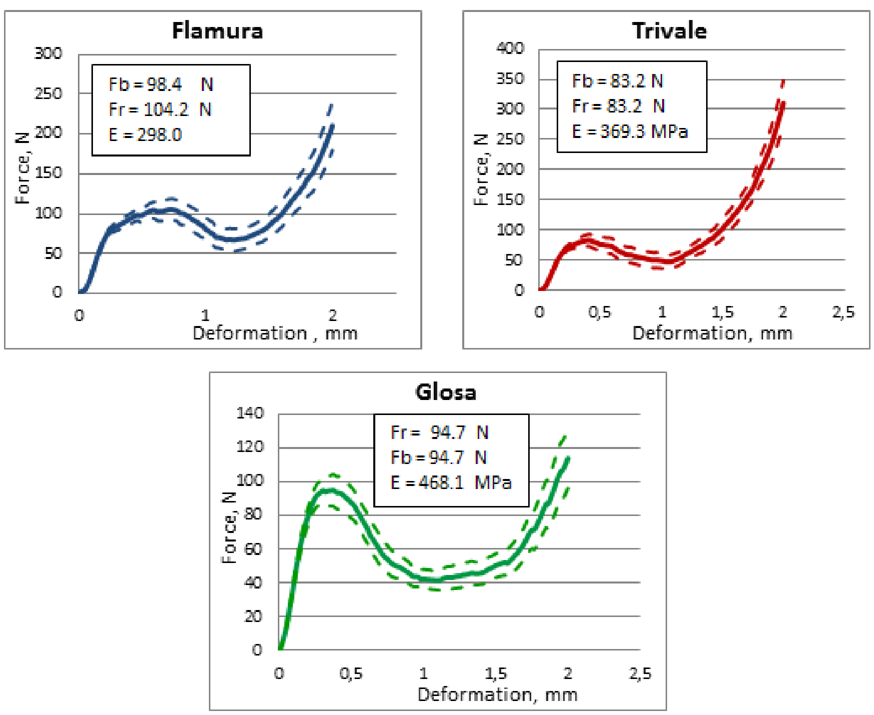

Fig.6. Mean curves and 95 % confidence interval (curves with dashed lines)

It can be observed that force variation depending on seed deformation has the same shape for the curves of confidence interval, with relatively close values for the three varieties of wheat. For all varieties, on the proportionality area, the curves are practically overlapping, proving the accuracy of the values for modulus of elasticity. For Flamura variety, mean value of force in rupture point, on the curve is 104.2 ± 9.18 N, and mean value of bioyield force is 98 ± 7.11 N, for a confidence interval of 95 %. For the same confidence interval, in case of Trivale and Glosa varieties, the value of force in the rupture point is equal to 83.2 ± 9.86 N, respectively 94.7 ± 9.09 N, and the value of force in the bioyield point is 81.1 ± 8.40 N, respectively 94.0 ± 8.70 N. Compared to the mean values, the variation interval of force values is similar for all varieties, ± 7 – 9 N.

5. Conclusions

It is important to know the mechanical characteristics of wheat seeds to estimate their mechanical behavior at grinding, and also to estimate the necessary power to drive the machines and the energy absorbed for seed deformation and crushing.

The three analyzed varieties of wheat have similar behavior at uniaxial compression tests, and yet they have different mean values for rupture forces and for the energy absorbed until crushing moment or for seeds modulus of elasticity.

The data presented in this paper shows that the lowest values of rupture force is found for seeds of Trivale variety (about 90 N), and the highest values of rupture force appear for Flamura variety (107 N).

On the energy absorbed until seeds rupture (crushing), the smallest values are found for Glosa variety (about 0.016 J), while the highest values are found for Flamura variety (0.038 J).

As for the modulus of elasticity, the smallest values are found for Flamura variety (313 MPa), while the highest values appear for seeds of Glosa variety (487 MPa). Trivale seeds have the modulus of elasticity between the values of Glosa and Flamura varieties.

It should be mentioned, however, that seeds from Glosa variety had a moisture content lower with 2% compared to the seeds from the other two varieties, which probably led to higher values of the modulus of elasticity, and to lower values of rupture energy, being known that wet seeds have higher plasticity than dry seeds, and the energy absorbed is also higher.

Data presented in this paper can be of real benefit for both designers and manufacturers of grinding machines, and also for those who use these machines.

Acknowledgement

The work has been funded by the Sectoral Operational Programme Human Resources Development 2007-2013 of the Romanian Ministry of Labour, Family and Social Protection through the Financial Agreement POSDRU/88/1.5/S/61178.

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