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INTERNAL DAMAGE VS. MECHANICAL PROPERTIES OF MICROWAVE-DRIED WHEAT GRAIN*

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A b s t r a c t. Grain of Almari winter wheat variety, with two levels of initial moisture content (20 and 25%), was microwave dried for different time periods from 2.5 to 25 min. The resultant internal cracks were detected using soft X-ray technique. The physical condition of the endosperm was then quantified in terms of a damage index. Barrel-shaped core samples, cut from randomly selected kernels were then subjected to uniaxial compression tests to determine the stress at rupture point, strain, and the modulus of elasticity. A statistically significant correlation between drying conditions and mechanical properties was found. No effect of the initial moisture content on the physical conditions of the endosperm and on the mechanical properties under study was observed.

K e y w o r d s: drying, moisture content, damage index, stress, strain, modulus of elasticity

NOMENCLATURE

t - drying time, min
IS - overall index
X - moisture content, % w.b.
X_0 - initial moisture content, % w.b.
m - mass of grain sample, g
a - thickness of kernel, mm
b - width of kernel, mm
A_g - cross sectional area-germ side, mm^2
A_c - cross sectional area-central part of kernel, mm^2
A_f - cross sectional area-fuzz side, mm^2
$\overline{A}$ - average cross sectional area, mm^2
E - modulus of elasticity, MPa
δ_r - stress at rupture point, MPa
ε - strain, %
F - compression force, N
l_0 - initial height of sample, mm
Δl - change in height, mm

INTRODUCTION

Cereal grains are frequently damaged as a result of agricultural machinery during harvest and transportation. They are also damaged during post harvest processing by high moisture gradients occurring in the course of grain wetting as well as drying [11,12,18,21,24,25].

In recent years one can observe increasing interest in drying technologies which are energy saving and/or reduce drying time. One such method is microwave drying [1-3,5,10] however, damage arising from this process causes unfavourable physical and biological changes to grain [10]. Damaged kernels have faster respiration and a higher rate of moisture absorption from their environment [4]. Cracked grain has reduced mechanical strength and crumbles more easily during post-harvest processing [6,7].

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Storage of damaged grain may lead to starch dust explosions in silos. Hence it is extremely important to choose technological processes which minimise grain damage and therefore a reduce losses.

The following techniques are used to detect internal grain damage: magnetic nuclear resonance [16,20], scanning microscopy [6,22,23], laser and autoradiography methods [8], and X-ray techniques which have the added advantage of low cost and the possibility of conducting non-destructive tests [10,13,21,24,25]. X-ray detection permits the determination of the location and of the extent of damage within a kernel, and provides an insight into the physical condition of the grain endosperm [14]. The physical condition of the endosperm affects the behaviour of the kernel when subjected to external forces at various stages of its technological processing. Knowledge of the basic mechanical properties such as modulus of elasticity, maximum stress and deformation is necessary to for the simulate grain behaviour under the effect of various loads [17].

The elastic properties of a material are characterized by the modulus of elasticity. Hence most studies concerned with the mechanical properties of agricultural materials have been centred on the determination of that modulus [9,19]. The methods most frequently used for determining the modulus of elasticity include the following:

- compression of kernels between flat parallel plates; in such cases the modulus of elasticity is determined on the basis of Hertz's theory,
- penetration by a spherical probe of a diameter small in relation to the kernel size; in this case the modulus is calculated on the basis of Hertz's theory,
- penetration by a cylindrical probe of small diameter and flat base; in this method the value of the modulus is calculated on the basis of Boussinesque's theory for semi-infinite space,
- uniaxial compression of core samples cut from a kernel and placed between two flat parallel plates; in such cases the modulus of elasticity is determined on the basis of Hooke's law.

The results presented in this study, concerning changes in the structure of the endosperm and in the mechanical properties of grain subjected to microwave drying, can be useful in developing criteria for such technologies of grain drying which take into consideration the specific properties of cereal grain as a material.

OBJECTIVES

The objectives of this study are the following:

- to determine the status of endosperm damage in grain of varied initial moisture content dried by means of microwaves for different lengths of time,
- to determine the fundamental mechanical properties of microwave dried wheat grain,
- to identify any relationships between the mechanical properties of grain and the status of internal damage to the grain.

MATERIAL AND METHODS

Sample preparation - drying

The study was conducted using combine harvested wheat grain of the Almari variety of 11% moisture content, originating from field experiments at the Institute of Agrophysics, Polish Academy of Sciences, Lublin. Grain selected for the experiments was uniform in size: 6.6±0.25 mm in length, 3.6±0.15 mm in width, and 3.2±0.15 mm in thickness.

Air dried grain (10% w.b.) was divided into two parts, one of which was wetted to a moisture content of 20% and the other to 25%. After wetting, each sample of grain was spread uniformly in a single layer over a perforated plate placed inside a microwave chamber. The grain was then exposed to microwave radiation at 2450 MHz and a constant power of 50 Watts. Simultaneously, hot air at 328 K was forced through the grain layer at a constant superficial velocity of 0.6 m/s. Such a low flow rate was chosen to avoid mixing and fluidisation. Successive grain samples were dried for 2.5, 5.0, 7.5, 10.0, 12.5, 15.0, 20.0, and 25.0 min. Following microwave drying, the grain samples were weighed and dried in a convective oven for three days at a temperature of 301 K. A control sample of grain was wetted to 20 and 25% and then dried in a convective oven for 5 days at a temperature of 301 K. Grain moisture content was determined on the basis of weight loss of the grain samples according to the following equation:

$$X = 100 - \frac{m_o}{m} - (100 - X_o) \text{ [\% w. b.]}. \quad (1)$$

The rate of water removal (per 100 g of initial sample weight) after time t of microwave drying was assessed according to the formula:

$$v = \frac{m_o - m}{m_o} \frac{100}{t} \text{ [g/min]} \quad (2)$$

where m_O - initial mass of a grain sample (g), m - final mass of a grain sample (g), X_O - initial moisture content of the grain (% w.b.), X - moisture content of the grain after drying (% w.b.), t - drying time (min).

X-ray procedure

Internal damage to the grain kernels were visualized by means of soft X-ray photography using a compact, short focal length camera (supply voltage 220V-50 Hz, power 70 Watts, acceleration voltage 20 kV, current 50 mA). The images were recorded on X-ray KODAK plates 13x18 cm over 1 min of exposure with x5 magnification. Because soft X-ray radiation is absorbed to a different extent by the damaged and undamaged structures of the kernels, the internal cracks can be seen on a magnified negative image of the kernel as characteristic dark, fairly sharp shadows of different length and width. Photo 1 presents the X-ray images of kernels prepared for strength tests; the groove yields a distinct dark line in both control and microwave dried kernels.

a b

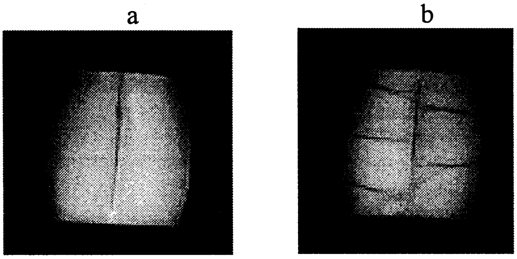

Photo 1. X-ray images of the central part of kernels: a-control (undamaged) kernel, b-with internal stress cracks as a result of high intensity drying.

The X-ray images of kernels were analyzed by means of the "GRAINS" software package developed by the Institute of Electronics, Technical University of Łodź in co-operation with the Institute of Agrophysics, Polish Academy of Sciences, Lublin, Poland. The extent of damage to the endosperm was then quantified by digital indices [14, 15].

Digitalization of stress cracks

For the digital description of the cracks, a rectangular grill was imposed on the X-ray image of each kernel. This grill sliced the kernel image into 6 horizontal fields of equal width which resulted in resolution of 0.67 mm. Then the image was examined for the presence of any crack in the particular field, and corresponding indices of either 1 or 0 were assigned to the fields with and without cracks, respectively (see Photo 2). The assessment of the degree of damage to the grain was equal to the sum of partial assessments indices, and was called the overall index of damage - *IS* [10,15]. With such a division of the image, the overall index of damage assumes values from 0 (no damage) to 6 (damage in each of the fields).

Mechanical properties

To evaluate the mechanical properties of grain the kernels with their tips cut-off were uniaxially compressed between two parallel plates [9,20]. Cut tips secured good contact of the kernel surfaces with the loading plates while well-defined surface area resulted in a better accuracy of measurements and further simplified the calculation procedure. The shape of the kernel cross-sectional area had no effect on the result of measurements, so their interpretation based on Hook's law posed no objection. The only question was the necessity of removing both tips from the kernel, which weakened its structure and may have lowered the strength of the core sample. Since the central part of the kernel, which contains the nutrient substance, was left over, it was assumed that the removal of the germ and the fuzz would not cause a significant reduction of the material strength. However, taking into account the anisotropy of

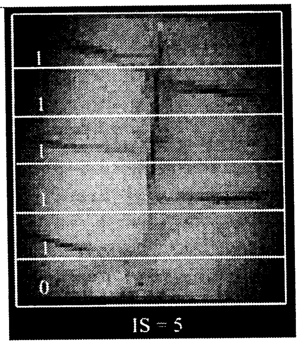

Photo 2. X-ray image of the central part of kernels with rectangular grill.

the kernel, it must be emphasized that the method applied allowed the modulus of elasticity to be determined along the groove of the kernel. Other methods examine this modulus in a direction perpendicular to the groove. In spite of this reservation, it seemed that determination of the mechanical properties of grain on the basis of Hooke's law was the most reliable due to the fact that it eliminated the effect of both the geometry of the kernel and the contact of the rough surfaces of the involucre with the loading plates. The authors assumed that there was no friction on contact areas between wheat sample and loading plates.

A core sample 4 mm high was cut from every kernel, and the surface areas of both ends and the cross-sectional area of the central part were determined. Then, the circle was adopted as an approximation of the shape of all three areas of the kernel, and the apparent surface area was calculated according to the formula:

$$A = \frac{\pi}{16}(a+b)^2, \tag{3}$$

where a and b are the thickness and the width of the kernel cross section, respectively (see Fig. 1).

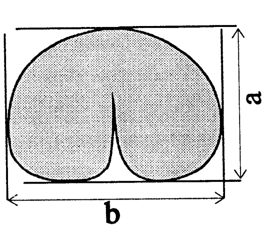

Fig. 1. Cross section of wheat kernel; a - thickness, b - width.

The mechanical tests were performed using a strength tester, model Instron 6022 with a 0-1 kN measuring head and a deformation rate of 0.1 mm/min. A tipples kernel was placed between two parallel plates and subjected to uniaxial compression. The applied force was recorded in the function of displacement. The force was determined with an accuracy of 1 N, and the deformation with an accuracy of 0.01 mm. Figure 2 presents a typical plot of force vs. deformation obtained in an uniaxial compression test.

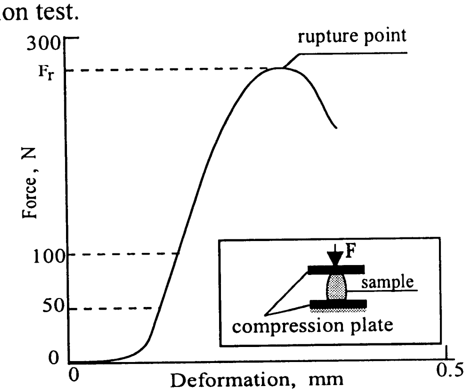

Fig. 2. Force-deformation curve for uniaxial compression of core specimens between two parallel flat plates.

The stress at rupture point of sample was determined from the following equation:

$$\sigma_r = \frac{F_r}{\overline{A}}, \tag{4}$$

where F_r - force at rupture point, $\overline{A}$ - mean surface area of kernel cross section.

Considering the kernel with the tips removed as two truncated cones of non-revolution joined by their larger bases, the mean cross-sectional area can be determined as:

$$\overline{A} = \frac{A_g + 2A_c + A_f}{4}, \tag{5}$$

where A_g, A_f are the surface areas of the cone bases, and A_c is the surface area of the largest cross-section of the kernel.

The modulus of elasticity was calculated from Hooke's law:

$$E = \frac{\sigma}{\varepsilon} = \frac{F\, l_o}{\overline{A}\,\Delta l}. \tag{6}$$

The modulus of elasticity was determined within the range of elastic deformation which, for all the objects under study, fell within the range of from 50 to 100 N. Tests were performed for 30 kernels selected randomly for any variant of the experiment: drying without microwave radiation (control sample), and eight drying times with the use of microwave radiation for both initial moisture content levels of the grain. Altogether, a total of 540 kernels were tested.

RESULTS AND DISCUSSION

Drying

The time-related variation of grain moisture content calculated according to Eq. (1) (drying curve) is shown in Fig. 3, while Fig. 4 presents the variation of a drying rate calculated according to Eq. (2) with drying time. The curves for microwave-assisted drying follow in general the respective curves for convective drying of cereal grains, i.e., drying takes place in the falling rate period with practically no initial and constant rate periods. For both levels of initial moisture content, the highest drying rates are at the beginning of microwave drying, which in these experiments extends up to about 10 min. Higher drying rates are clearly related to enhanced internal heat generation during this stage of drying as the intensity of microwave heating is proportional to the volume (mass) of water in the grains sample. For the same reason, higher drying rates were noted for grains with higher initial moisture content. In contrast to convective drying where the drying rate decreases gradually with time, in microwave-assisted drying, the drying rate stabilises after a certain drying time and then slightly increases. Because of characteristic spline of drying curves (Fig. 3), the empirical results were approximated by a third degree polynomial:

$$X(t) = a_0t^3 + a_1t^2 + a_2t + X_o$$

where X_o is the initial moisture content of the grain and a_0, a_1, a_2, are indices of the polynomial.

Table 1 presents the values of indices for both the polynomials, their standard errors and determination coefficients R^2.

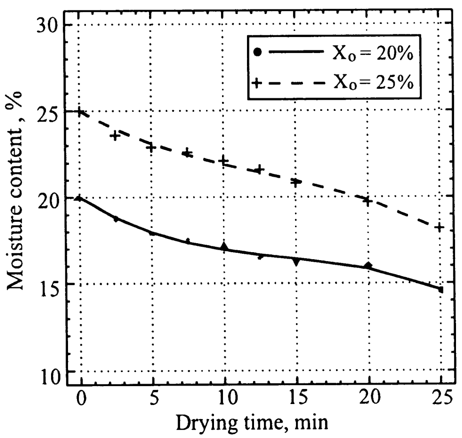

Fig. 3. Drying curves for microwave drying of wheat grain.

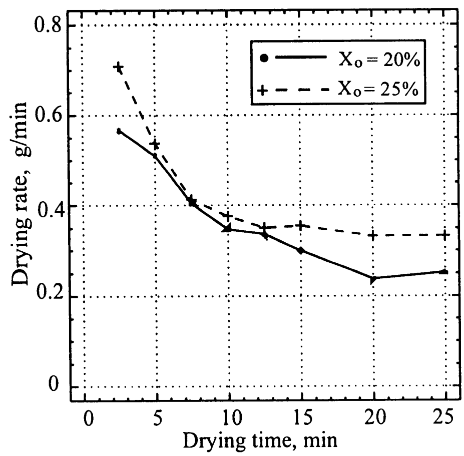

Fig. 4. Drying rate as the function of time (per 100 g of initial mass of).

A limited number of experiments on microwave-assisted drying does not allow a conclusive explanation of such a nontypical run of drying curves. The most likely reason for the increased drying rate at the end of drying appears to be the increasing number of cracks which develop progressively in the course of drying. Cracks in a wheat kernel shorten the path for moisture diffusion and thus reduce the internal resistance to mass flow which controls the drying rate. Also, internal cracks which extend to the grain surface enlarge the heat and mass transfer areas. This alters the overall drying rate

Table 1. Indices of the polynomial approximating the function $X(t)$, standard errors and determination coefficients R^2

X_o [%]	a_0 Estimated value	a_0 Standard error	a_1 Estimated value	a_1 Standard error	a_2 Estimated value	a_2 Standard error	R^2
20	-0.00072	0.00011	0.03124	0.00375	-0.54425	0.03004	0.994
25	-0.00057	0.00017	0.02244	0.00609	-0.47687	0.04936	0.991

if it is related to the mass of grains instead of the grain surface. The hypothesis that cracks play a crucial role in drying rate is well supported by the significant and high correlation of the index of damage (IS) with drying time. As seen in Fig. 5, the index of damage, which is a measure of stress cracks in wheat grain, is proportional to drying time. It means that, at a certain time of drying, the positive effect of cracks on moisture diffusion may balance or even overcome the negative effect of increasing diffusion path due to receding evaporation front.

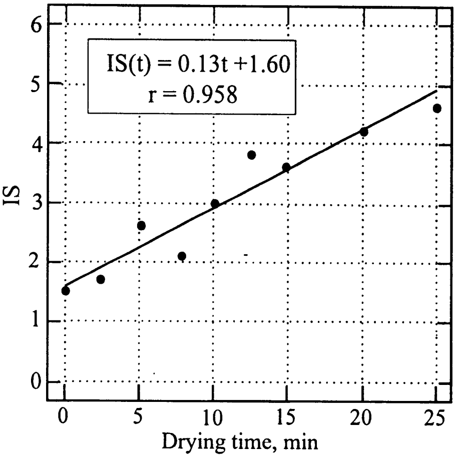

Fig. 5. The index of damage vs. the microwave drying time.

Digital indices

The absolute values of the indices of damage result from the following components: - damage to the grain caused by factors beyond the control of the researchers, both before the harvest (weather conditions) and during the harvest (mechanical effect of the combine assemblies),

- damage due to grain wetting and conditioning before drying,
- damage resulting from high intensity microwave drying,
- damage resulting from low intensity finish drying after microwave drying (otherwise necessary to bring the moisture content of all samples to the same level.

For drying tests, grain samples were selected at random, and therefore the effect of the primary, uncontrolled factors on the values of damage indices could be considered as the result of random factors. The finish (low intensity) drying could not significantly increase the values of the indices of damage because of tempered processing [24].

As follows from the analysis of variance in the system of "initial moisture content of the grain x time of microwave drying", the assumed levels of initial moisture content did not cause any significant differentiation in mean values of IS, in contrast to considerable differentiation in mean values of IS between selected drying times.

Generally, the values of damage indices increase with the increased time of wheat grain microwave drying (Table 2). For grain with an initial moisture content of 20%, the value of IS increased from 1.1 (for samples at t = 0 min, i.e., not microwave dried) to 4.9 (for samples microwave dried for 25 min). Significant differences in the index with relation to the control sample occurred for t > 10 min. Correspondingly, with an initial grain moisture content of 25% the value of IS increased from 1.9 to 4.2, with the most significant differences with relation to the control occurring for a drying time of t > 20 min. Therefore, the absolute increase in the value of the index of damage was greater for the lower initial grain moisture content, i.e., 20%.

A significant and high correlation was found between the indexes of damage and the

T a b l e 2. Mean values of the index of damage, stress at rupture point, strain, and modulus of elasticity, and Tukey half-intervals of confidence for the assessment of the effect of microwave drying time of grain and its varied initial moisture content:

A. Mean values of the index of damage (IS), stress at rupture point (σ_r), strain (ε), and modulus of elasticity (E) for the two levels of initial moisture content and for the drying times, and for a combination of these factors

X_o [%]	Variable	Microwave drying time [min]								
		0	2.5	5.0	7.5	10.0	12.5	15.0	20.0	25.0
	IS	1.1	1.6	3.3	2.7	3.2	4.1	3.9	3.8	4.9
20	σ_r	28.7	28.3	27.2	25.2	25.8	25.7	23.3	25.8	22.3
	ε	5.6	5.5	5.8	5.5	5.5	6.0	6.3	6.1	6.3
	E	779.5	774.3	652.8	647.2	640.4	581.7	571.4	561.1	497.6
	IS	1.9	1.8	2.0	1.5	2.9	3.5	3.3	4.6	4.2
25	σ_r	27.6	27.1	25.3	27.2	24.9	23.4	27.0	23.6	20.3
	ε	5.1	5.3	5.3	5.4	5.5	6.0	6.2	6.0	6.5
	E	778.5	735.0	732.5	690.4	645.8	581.8	565.1	512.4	420.1
Mean	IS	1.5	1.7	2.6	2.1	3.0	3.8	3.6	4.2	4.6
for	σ_r	28.8	27.7	26.2	26.1	25.4	24.6	25.2	24.7	21.3
X_o	ε	5.3	5.4	5.5	5.5	5.5	6.0	6.2	6.0	6.4
	E	779.0	754.7	692.7	668.8	643.1	581.8	568.2	536.8	458.9

B. 95% Tukey half-intervals of confidence

Variable	X_o	t	X_o x t
IS	0.4	1.0	1.7
σ_r	0.9	3.2	5.2
ε	0.1	0.5	0.8
E	20.5	69.9	112.0

adopted times of microwave drying. Figure 5 shows an estimated linear graph. The points correspond to the mean values from 60 source observations of IS (for both initial moisture content together), and the line is the graphic presentation of a regression equation.

Mechanical properties

The variance analysis for the mechanical parameters under study done in the system of "initial moisture content of grain x time of microwave drying" did not show any significant effect of the initial moisture content on those parameters. On the other hand, the time periods of microwave drying caused considerable differentiation among the mean values of the stress at rupture point, strain and modulus of elasticity.

Table 2 presents the mean values of the stress at rupture point, strain and modulus of elasticity of grain of different initial moisture contents, and microwave dried for different periods of time. A significant decrease in the rupture stress with relation to the control sample (t=0 min) occurred after 25 min of drying for both levels of initial moisture content. A significant increase in strain was noted only for the grain with an initial moisture content of 25%, after 12.5 min of drying. The mean modulus of elasticity decreased nearly by half - from 779 MPa for the control sample to 498 MPa for the sample after 25 min of microwave drying with an initial grain moisture content of 20%. A significant decrease in the value of the modulus with relation to the control sample is noted for t>5 min. For the initial grain moisture content of 25% the modulus decreases from 778 MPa to 420 MPa, correspondingly, and a significant decrease with relation to the control sample was observed for t>10 min.

A high and significant correlation was found between the mechanical properties of grain under study and the time periods of grain microwave drying. A similar high and significant correlation is noted between these properties and the overall index of damage. These high correlations justified the adoption of the linear model for the description of the relationships. Figures 6 to 11 present the estimated straight lines, the points corresponding to mean values

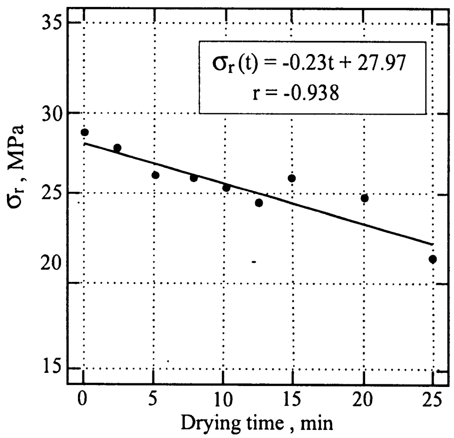

Fig. 6. Stress at rupture point vs. microwave drying time.

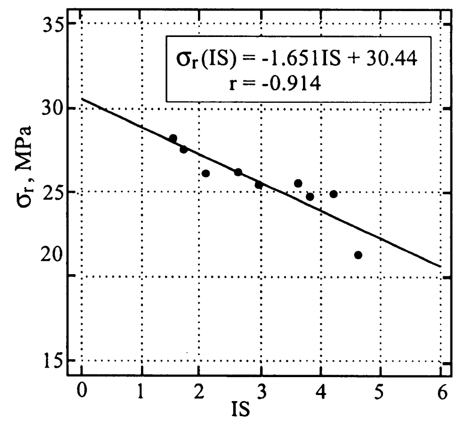

Fig. 7. Stress at rupture point vs. index of damage.

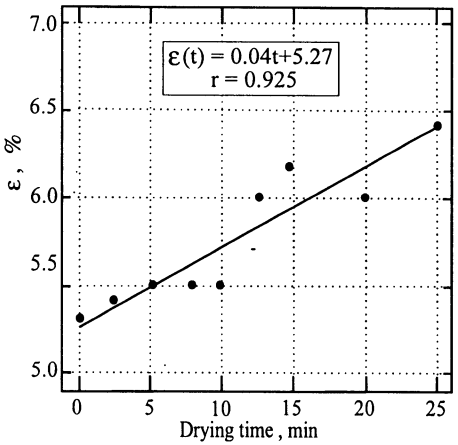

Fig. 8. Strain vs. microwave drying time.

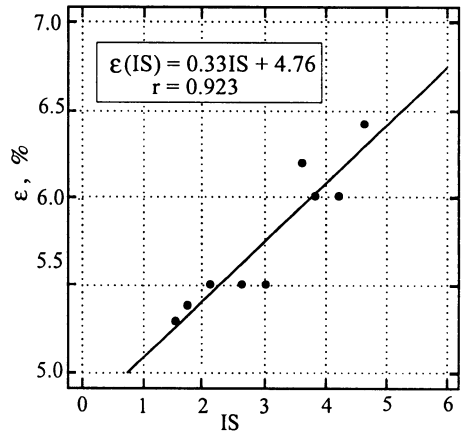

Fig. 9. Strain vs. index of damage.

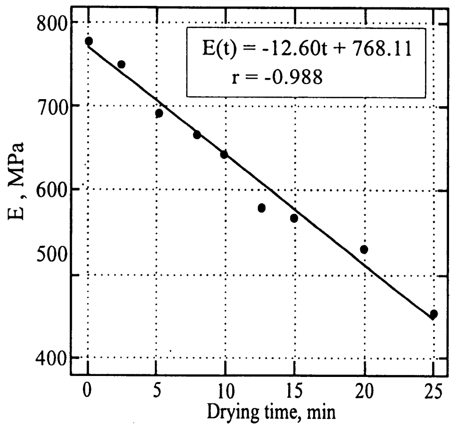

Fig. 10. Modulus of elasticity vs. microwave drying time.

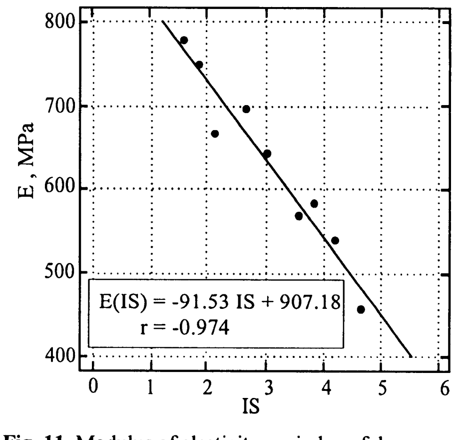

Fig. 11. Modulus of elasticity vs. index of damage.

from 60 source observations of rupture stress, strain and modulus of elasticity.

Summing up the results obtained it can be stated that damage of the endosperm increases with increasing time of microwave drying. The relative increase in the indexes of damage with relation to the control was approximately 200%. Such a high increase in the level of internal damage resulted, in turn, in a decrease in grain rupture stress by 26% and in the modulus of elasticity by 46%. The strain of grain with the highest index of internal damage was 20% higher than the strain of the control sample. Therefore, cracked grain will be more susceptible to crushing, breaking or cracking in further, after drying, stages of the post-harvest processing - in transport and during storage. Hence the extreme importance of selecting drying parameters that ensure proper final moisture content, and least possible degree of damage to the endosperm.

CONCLUSIONS

X-ray proved to be an efficient tool for the detection of internal damage to wheat grain caused by microwave drying, and the applied digital indexes IS permitted a quantitative description of the damage.

The initial moisture content of the grain had no significant effect on the value of the indexes of damage, nor on the mechanical parameters of the grain under study.

As the time of microwave drying increased, the value of the indexes of damage increased. After 5 min of drying there occurred a significant increase in the IS with relation to the control sample. The maximum adopted time of drying caused a 200% increase in the value of the mean index of damage.

The stress at rupture decreased in a linear manner with the drying time, and therefore also with increasing level of internal damage. A significant decrease in the rupture stress of the grain occurred after 12.5 min of drying. The rupture stress of grain microwave-dried for 25 min decreased by 26% compared to the control.

Grain strain increased with drying time and increasing level of internal damage. Strain of grain with the highest index of internal damage was 20% higher than strain of control grain. A significant increase in strain with relation to the control occurred after 12.5 min of drying.

The modulus of elasticity decreased linearly with increasing time of microwave drying. A significant decrease in the value of the modulus with relation to the control occurred after 5 min of drying. The increase in the level of damage resulting from the application of the maximum drying time caused a decrease in the value of the modulus of elasticity by 46% .

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