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Mechanical properties of wheat grain in relation to internal cracks

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Abstract. Processes of heat and mass exchange that take place in the course of wheat grain wetting and drying, cause inner stress resulting in endosperm cracks. These cracks cause specific physical and biological effects. Spring wheat grain, cv. Henika, with an initial moisture content of 10% and varied endosperm structure (mealy and vitreous), was wetted for 1, 3, 6 and 9 h and then dried in room conditions to initial moisture content. Inner cracks to grain caused by the processes mentioned above, were detected by means of soft X-ray technique. The physical endosperm condition was described by the number of cracks. Barrel-shaped core samples, cut from some selected kernels, were then subjected to uniaxial compression tests to determine such parameters as: compressive strength (σ_{max}), modulus of elasticity (E), strain (ε_{max}) and specific work (w_{max}). A significant, high, negative correlation was found between grain mechanical properties and their earlier wetting time. Similarly high and significant correlation was noted between these properties and the number of inner cracks. Vitreous kernels were characterized by higher values of mechanical properties than the mealy ones.

Keywords: moisture treatment, damage index, stress, strain, modulus of elasticity, specific work

NOMENCLATURE

t	- wetting time, h
NC	- number of cracks
$m.c.$	- moisture content, % w.b.
a	- thickness of a kernel
b	- width of a kernel
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
$\underline{A}$	- average cross sectional area, mm^2
F	- compression force, N
l_o	- initial height of sample, mm
Δl	- change in height, mm
E	- modulus of elasticity, MPa
σ_{max}	- maximum compressive stress, MPa
ε	- strain, %
W	- work of deformation, mJ
w	- specific work, mJ mm^{-3}
V	- volume of the sample, mm^3

INTRODUCTION

Inner damage to grain is understood as disruption of the natural tissue continuity. Cereal grains are frequently damaged by the operation of working elements of agricultural machinery during harvest and transportation. They are also damaged during post harvest processing due to internal stresses induced by high moisture gradients occurring in the course of grain wetting and drying [3,4,13,14]. Cracked kernels are characterized by reduced mechanical strength and a ten dency to crumble during post harvest processing easier than grain with no such damage [1,2,10,12]. Therefore, storage of the damaged grain may lead to an increased hazard of starch dust explosion in the silos. The ultimate consequence of all of the above mentioned phenomena is a decrease in grain quality. So, it is very important to choose adequate parameters for the technological processes to minimaize the level of grain damage and hence a decrease in grain quality.

Investigation on the physical state of individual cereal kernels by the X-ray technique offers a chance to examine the effect of the properties of kernel structure (inner damage of the endosperm) on its mechanical properties [12]. The X-ray procedure enables to determine position, size and type of inner damage, and in consequence, allows to estimate the physical state of a grain which has been changed by various factors [6,7,11,13,14]. The physical state of grain endosperm influences the mechanical behaviour of a grain subjected to external forces during various stages of technological processes. Knowledge on the basic mechanical

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properties of grain is indispensable for the simulation of grain mechanical behaviour under various types of loads. A nondestructive X-ray technique enables to perform examinations on a series of kernels that can afterwards be subjected to strength tests.

The objectives of this research have been to:

- determine the state of inner damage to the kernels with various types of endosperm structure (i.e., mealy or vitreous) wetted for differentiated periods of time,
- determine fundamental mechanical properties of wheat kernels,
- determine the relation between mechanical properties of kernels and the state of their inner damage.

MATERIAL AND METHODS

Sample preparation

Kernels with a typical vitreous or mealy endosperm were selected from the sample of spring wheat cv. Henika. Grains with the initial moisture content of 10%, and without inner damage were wetted in water of 20°C for 1, 3, 6, 9 h, and then dried (in room conditions) to the initial moisture content. Figure 1 shows relations between grain moisture content and the length of wetting time.

A precision micro-miller for cutting kernels was used to preparate a flat and parallel surface on both ends of slices of wheat kernels. The micro-miller was designed by Niewczas and WoŸniak (Institute of Agrophysics, Polish Academy of Sciences, Lublin, Poland) and developed by Kowalczyk (Agriculture University, Lublin, Poland).

A core sample 3.5 mm high was cut from each 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 kernel areas, and the apparent surface area was calculated according to the formula:

$$A = \frac{\pi}{16}\left(a+b\right)^2 \tag{1}$$

where: a and b are thickness and width of the kernel cross section, respectively (see Fig. 2).

X-ray procedure

For the detection of inner damage to the grain, the authors used a compact, short focal length X-ray camera. The images were recorded on X-ray KODAK plates, 13x18 cm in size, with x5 magnification. The operating parameters of the camera were as follows: supply voltage 220V (50 Hz), power 70 Watts, acceleration voltage 20 kV, current 50 mA, exposure time 1 min. Soft X-ray radiation is absorbed to a varying extent by the damaged and undamaged structures of the kernels. When the X-ray beam passes through a kernel, a magnified image of the kernel is formed on the plate. In the negative image can be observed the groove (which yields a distinct dark image) and internal damage, visible as characteristic dark, fairly sharply defined shadows. Photo 1 presents X-ray images of kernels prepared for strength tests.

The X-ray images of the kernels were analyzed by means of the "GRAINS" software package [9]. The extent of a damage to the endosperm was then quantified by the number of cracks - *NC*.

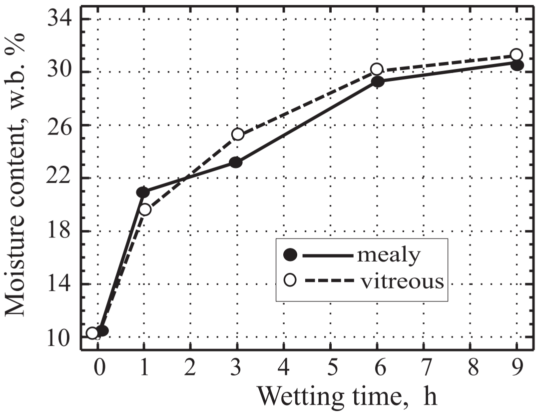

Fig. 1. Relation between grain moisture content and wetting period.

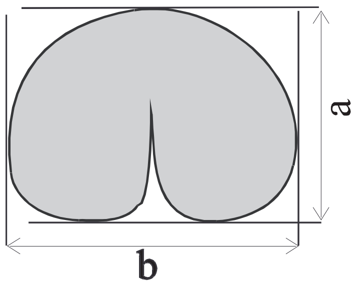

Fig. 2. Cross section of a wheat kernel; a - thickness, b - width.

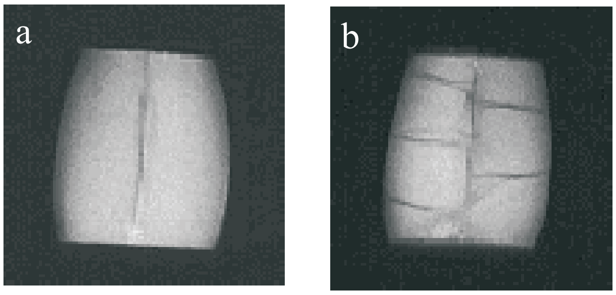

Photo 1. X-ray images of the central part of kernels: a - undamaged, b - with internal stress cracks as a result of moisture treatment and drying.

Test of mechanical properties

Mechanical tests were performed by a strength tester, model Instron 6022 with 0-1 kN a measuring head and a deformation rate of 0.1 mm min^{-1}. A truncated kernel was placed between two parallel plates and subjected to uniaxial compression. The applied force was recorded as a function of displacement. The force was determined with an accuracy of 1 N, and the deformation with an accuracy of 0.01 mm. Figure 3 presents a typical plot of force vs. deformation obtained in an uniaxial compression test.

Compressive strength σ_{max} (maximum compressive stress which the material is capable of sustaining) was calculated from the maximum load (F_{max}) during the compression test and the average cross-sectional area ($\overline{A}$) of the specimen [5,8]:

$$\sigma_{max} = \frac{F_{max}}{\overline{A}} . \tag{2}$$

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

$$\overline{A} = \frac{A_g + 2A_c + A_f}{4} \tag{3}$$

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

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

$$E = \frac{\sigma}{\varepsilon} = \frac{F \cdot l_o}{\overline{A} \cdot \Delta l} \tag{4}$$

where: E - modulus of elasticity, σ - compressive stress, ε - strain, F - compression force, l_o - initial height of sample, Δl - change in height, $\overline{A}$ - average cross-sectional area.

The modulus of elasticity was determined within the range of elastic deformation which, for all the objects under study, fell within the range from 50 to 100 N.

Deformation work W was graphically presented as the surface area between the graphs of the compression function and the X-axis (Fig. 3). However, deformation work depends on the sample size. In order to characterize the material itself, the notion of specific work w which is equal to the deformation work W calculated for the unit of sample volume is determined as:

$$w = \frac{W}{V} \tag{5}$$

where: $V = \frac{1}{3} l_o \left(A_g + A_f + 2A_c + \sqrt{A_g A_c} + \sqrt{A_f A_c} \right)$, is the volume of a truncated kernel (two non-rotational cones joined with their larger bases were assumed as an approximation - Fig. 4); A_g - cross sectional area-germ side, mm^2; A_f - cross sectional area-fuzz side, mm^2; A_c - cross sectional area-central part of kernel, mm^2.

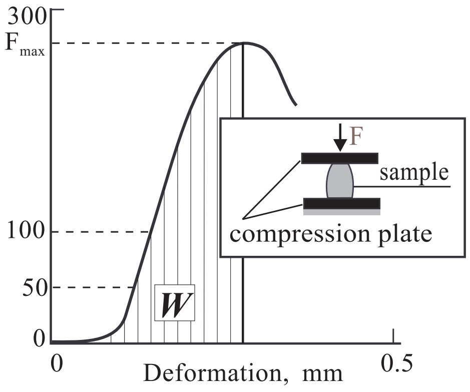

Fig. 3. Force-deformation curve for uniaxial compression of core specimens between two parallel flat plates.

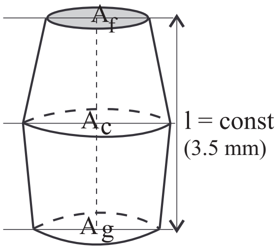

Fig. 4. A truncated kernel presented as two non-rotational cones.

Tests were performed for 50 kernels selected randomly for any variant of the experiment: control sample, and four wetting times for vitreous and mealy endosperm. Total number of specimens was 500. The multifactor analysis of variance and regression analyses were used in the statistical data processing.

RESULTS AND DISCUSSION

Table 1 presents mean values of the following parameters: number of inner cracks - NC, the maximum stress (σ_{max}), deformation (ε), modulus of elasticity (E) and specific work (w) for the kernel sections with mealy or vitreous endosperm type, wetted for 1, 3, 6 , 9 h and then dried to 10% moisture. For the control kernels, the wetting time was determined as 0.

The analysis of variance was performed to examine the effect of wetting time and type of endosperm on the considered parameters. The analysis showed that the prescribed wetting times resulted in wide differentiation of the mean values. The number of cracks increased with an increase in the wetting time of up to 6 h, and decreased with further increase in time. There was no significant influence of endosperm type on the value of the index of damage. The analysis of variance for the maximum stress σ_{max}, modulus of elasticity E and specific energy w in the configuration

T a b l e 1. Mean values of number of cracks (NC), maximum compressive stress (σ), strain (ε), modulus of elasticity (E) and specific energy (w) for two types of endosperm and wetting times of wheat grain

Type of endosperm	Variable	Wetting time (h)					Mean for wetting time
		0	1	3	6	9	
Mealy	NC	0	0.54	1.46	4.52	3.52	2.01
	σ	44.50	43.15	37.47	30.48	24.73	36.07
	ε	6.07	6.69	6.35	6.82	6.56	6.50
	E	1023	1007	865	668	622	837
	w	1.33	1.40	1.16	1.00	0.78	1.13
Vitreous	NC	0	0.90	1.12	3.94	2.94	1.78
	σ	63.16	59.90	52.74	40.71	33.63	50.03
	ε	7.07	7.64	6.52	6.89	7.02	7.03
	E	1327	1181	1121	881	809	1064
	w	2.30	2.26	1.72	1.25	1.10	1.73
Mean for type of endosperm	NC	0	0.72	1.29	4.23	3.23	1.89
	σ	53.83	51.53	45.11	35.60	29.18	43.05
	ε	6.57	7.16	6.43	6.86	6.79	6.76
	E	1175	1095	993	775	716	951
	w	1.81	1.83	1.44	1.13	0.94	1.43

95% Tukey half-intervals of confidence

Variable	Wetting time	Type of endosperm	Wetting time x type of endosperm
NC	0.57	0.26	0.93
σ	2.15	0.97	3.53
ε	0.31	0.14	0.51
E	44.74	20.31	73.45
w	0.13	0.06	0.22

„type of endosperm structure x wetting time” showed that both of these factors differentiated the mean values in a significant way.

A significant decrease of kernel strength in relation to the control ($t = 0$ min), took place after 3 h of wetting, when the kernels reached moisture levels above 20%. Further increase of the wetting time resulted in a monotonic decrease of kernel strength. After 9 h of wetting, strength of the mealy kernels decreased by 44% (from 44.50 to 24.73 MPa), and of the vitreous kernels by 47% (from 63.16 to 33.63 MPa).

Modulus of elasticity decreased by 40% after 9 h of wetting in relation to control: for the mealy kernels from 1023 to 622 MPa, and for the vitreous kernels from 1175 to 716 MPa. A significant decrease of the modulus of elasticity level was observed after 3 h of wetting of mealy kernels and already after 1 h of wetting of vitreous kernels.

One-hour period of wetting after which the kernels reached moisture level of about 20%, did not cause any significant change in the specific work during deformation. After 3 h of wetting, there was a monotonic decrease of specific work value. The mean value of specific work was by 41% lower than for the control in the case of mealy kernels (1.33 and 0.78 mJ mm^{-3}, respectively), and by as much as 52% lower for the vitreous kernels (2.30 - 0.94 mJ mm^{-3}).

Wetting did not exert any significant influence on the deformation size of truncated kernels.

A significant and high correlation was found between the investigated mechanical parameters of grain and the applied wetting times ($-0.970 < r < -0.998$). Estimated courses are shown in Figs 5 to 7 where the points represent mean values of compressive strength, the modulus of elasticity and specific work.

Also the correlation between these parameters and the number of cracks NC ($-0.869 < r < -0.931$) was significant and high. With the increase in the number of endosperm inner cracks, the values of kernel mechanical parameters decrease, which can be clearly seen in the regression curves presented in Figs 8-10.

It should be stressed that the applied method of determining grain mechanical parameters allowed the presents author to obtain results similar to the results quoted in literature [2,4].

Summarizing it may be stated that wetting of grain with low initial moisture content resulted in damage to their endosperm. An increase in the number of inner damages resulted in a decrease of grain strength, its modulus of elasticity and specific work. It is worth to emphasise, that while type of endosperm did not influence the indices of inner damage, the values of mechanical parameters were clearly different for mealy grain than for vitreous grain. Therefore, a decrease in the grain strength, modulus of elasticity and specific work cannot be associated directly

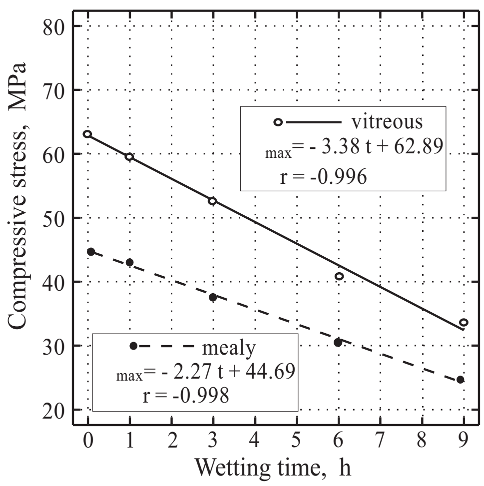

Fig. 5. Compressive strength vs. wetting time of wheat grain.

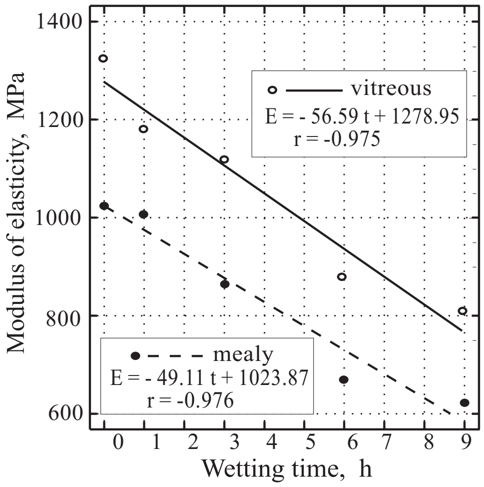

Fig.6. Modulus of elasticity vs. wetting time of wheat grain.

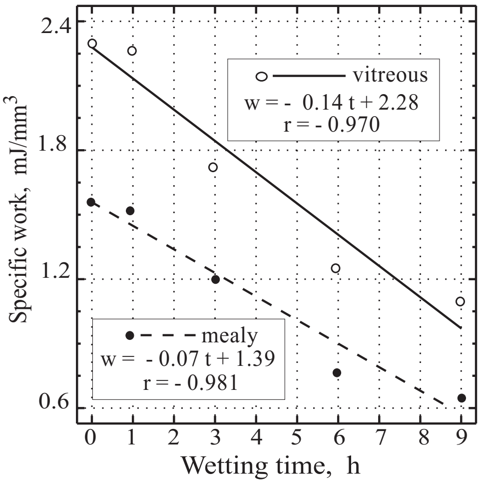

Fig. 7. Specific work vs. wetting time of wheat grain.

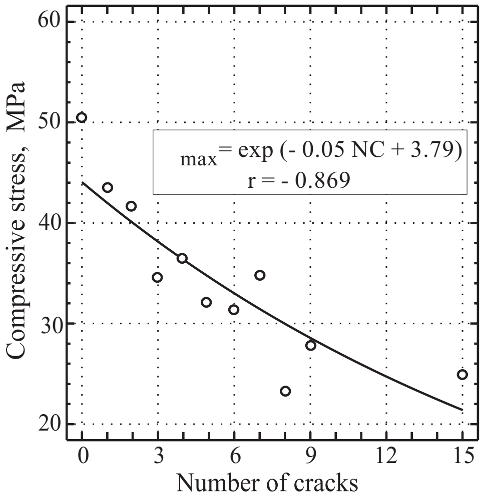

Fig. 8. Compressive strength vs. number of cracks of wheat grain.

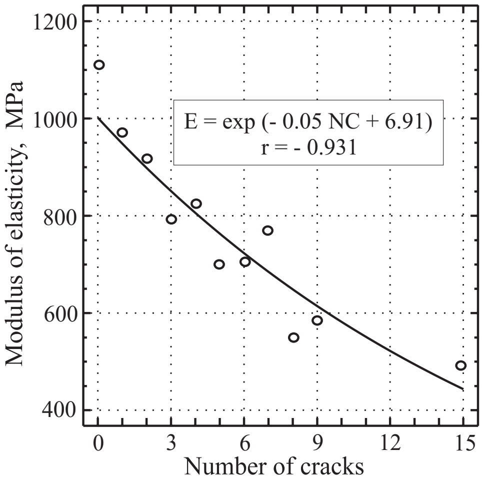

Fig. 9. Modulus of elasticity vs. number of cracks of wheat grain.

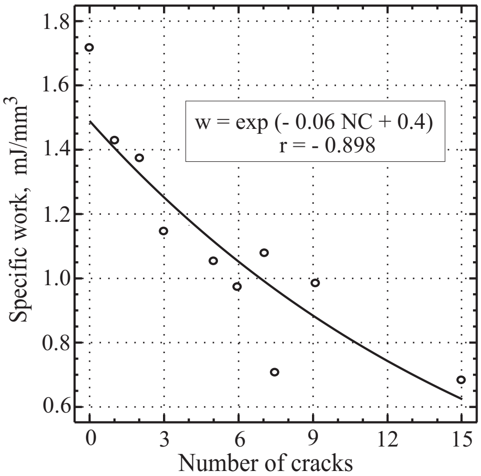

Fig. 10. Specific work. vs. number of cracks of wheat grain.

with the increase in the index of inner damage, but may be associated with different endosperm structure of mealy and vitreous grain. However, a decrease in the mechanical parameters of grain damaged by changes in moisture content, is a real phenomenon. As such, it should be accounted for, when choosing parameters for post-harvest processes, since damaged grain is more sensitive to crushing, breaking or cracking while transported or stored.

CONCLUSIONS

The following conclusions were drawn on the basis of on statistical analysis of results of mechanical testing and X-ray examination:

- The number of cracks *NC* recorded for dry kernels (truncated) increased monotonically with the increase of the wetting time-up to 6 h and then decreased after 9-h period of wetting. The type of endosperm structure (mealy, vitreous) did not significantly influence the physical state of the endosperm described as the number of cracks. It was due to the fact that the inner parts of a kernel showed a similar level of inner damage regardless of the their structure type.
- Type of endosperm structure (mealy or vitreous) exerted a significant effect on the values of mechanical parameters. Vitreous kernels showed higher strength, modulus of elasticity and specific work than the mealy ones.
- Wetting of dry kernels up to the moisture level of about 30% followed by drying to the initial state, resulted in a decrease in grain strength, modulus of elasticity and specific work by 50% compared to the control. Very high negative correlation was found for the determined mechanical parameters and time of kernel wetting (correlation coefficient in the range from -0.970 to -0.998).
- Mechanical parameters showed high correlation with the number of inner cracks formed during the period of wetting. The correlation coefficient for the strength against *NC* was equal to -0.869, for the modulus of elasticity to -0.931, while in the case of specific work it was equal to -0.898.

REFERENCES

1. **Fortes M. and Okos M. R., 1980.** Changes in physical properties of corn during drying. Trans. ASAE, 23(4), 1004-1008.
2. **Glenn G.M., Younce F.L., and Pitts M.J., 1991.** Fundamental physical properties characterizing the hardness of wheat endosperm. J. Cereal Sci., 13, 179-194.
3. **Gunasekaran S. and Paulsen M.R., 1985.** Breakage resistance of corn as a function of drying rates. Trans. ASAE, 28(6), 2071-2076.
4. **Kang Y.S., Spillman C.K., Steele J.L., and Chung D.S., 1995.** Mechanical properties of wheat. Trans. ASAE, 38(2), 573-578.
5. **Mohsenin N.N., 1970.** Physical Properties of Plant and Animal Materials. New York: Gordon and Breach Science Publishers.
6. **Niewczas J., 1991.** The method of determination of the index of mechanical damage of a single kernel by means of X-ray detection. Zesz. Probl. Post. Nauk Roln., 389, 89-95.
7. **Niewczas J. and Woźniak W., 1991.** Application of the discretization of an X-ray picture of with grain for the evaluation of endosperm cracks. Zesz. Probl. Post. Nauk Roln., 397, 45-51.
8. **Shelef L. and Mohsenin N.N., 1967.** Evaluation of the modulus of elasticity of wheat grain. Cereal Chemistry, 44/4, 392-402.
9. **Strumiłło P., Niewczas J., Szczypiński P., Makowski P., and Woźniak W., 1999.** Computer system for analysis of X-ray images of wheat grains. Int. Agrophysics, 13, 133-140.
10. **Weller C.L., Paulsen M.R. and Steinberg M.P., 1990.** Stress cracking and breakage susceptibility as affected by moisture content at harvest for four yellow dent corn hybrids. Trans. ASAE, 33(3), 863-869.
11. **Woźniak W., 1995.** The effect of two types moisture treatment of wheat grain on endosperm damage. Int. Agrophysics, 9, 165-170.
12. **Woźniak W., Niewczas J., and Kudra T., 1999.** Internal damage vs. mechanical properties of microwave-dried wheat grain. Int. Agrophysics, 13, 259-268.
13. **Woźniak W. and Styk W., 1996.** Internal damage to wheat grain as results of wetting and drying. Drying Technology, 14(2), 349-367.
14. **Woźniak W., Styk W., and Geodecki M., 1994.** High relative humidity as a cause of inner damage of wheat grain. Int. Agrophysics, 8, 377-381.