Physical properties of cereal grain and rape stem

S. Grundas, G. Skubisz

Bohdan Dobrzanski Institute of Agrophysics of Polish Academy of Sciences, Lublin, Poland

Abstract: The paper presents the results of a study on the mechanical properties of cereal grain and of rape stems, conducted within the framework of the continuing long-term cooperation between the Bohdan Dobrzański Institute of Agrophysics, The Polish Academy of Sciences (IA PAS) in Lublin, and the Czech University of Life Sciences (CULS) in Prague, Czech Republic. Within the scope of the mechanical properties of cereal grain, the study showed a significant relation between the physical conditions of kernels of common wheat as determined through X-ray detection, and their mechanical properties determined by means of standard tests used in the mechanics of structural materials and of the tests used in the technology of cereal grain processing. The study on the mechanical properties of rape stems demonstrated inter-variety differences between plants with varied resistance to lodging. The estimation of the variability of the mechanical properties along the length of rape stems showed the existence of a characteristic point located close to the first bifurcation. Significant effects were noted of the density of the canopy expressed in the number of plants per square meter, and of nitrogen fertilisation on the strength characteristics of rape stems obtained on the basis of tests of mechanical properties. At the same time, a relation was proved between the mechanical properties of the stems and absorption of X-rays

Keywords: wheat grain; rape stem; physical properties; utility value

Taking into consideration the jubilee character of our article, dedicated to Prof. Radoš Řezníček, and the fact that the presented research works were to a large extent inspired by Jubilee and sometimes by his wards, the authors decided to show also the results of the current research, which bear witness to a close co-operation. This long-term co-operation between the Department of Physics of Technical Faculty of CULS in Prague (formerly the Faculty of Mechanisation CUA in Prague) and the Department of Physical and Technological Properties of Agromaterials of IA PAS in Lublin has lasted continuously since the beginning of '70ties of XX century and in each year extends the research interests of both sides. The authors present the results of research in two main areas of interest: physical properties mainly of wheat grain but also of rape stems.

Modern technology of harvesting and threshing requires the knowledge of the mechanical properties of cereals, if the objective is to optimise these processes and to reduce the quantitative and qualitative losses of grain. Preliminary research in the domain of cereal grain properties covered the question of the origin of quantitative losses of grain in combine harvesting.

One of the factors causing these losses is the spontaneous shedding of grain in the field by hitting the elements of the harvesting system, another one is the unthreshed grain left in ears. In the first case, the grains are bound to the ear torus with too small forces, while the leaving of unthreshed grain occurs with the varieties strongly binding grain within the ear, at improper regulation of working parameters of the combine harvester (Řezníček 1970; Řezníček *et al.* 1978a,b; Szot & Řezníček 1984). As a continuation of the above mentioned investigations, Grundas and Pecen (2004) described some characteristics of physical properties of single kernel in wheat heads.

Two main destructive factors of grain were taken into consideration in our co-operation. Internal cracks originate already in the pre-harvest period and lead to a crop reduction as the result of the weakening of the structure of endosperm. Grain becomes softer and less resistant to dynamic loads inflicted by the active elements of harvesting and static or quasi-static loads during transport or storage. Fragmented grain is more susceptible to the attacks by infesters and infectors in storage bins. The second factor is storage pest activity in storage

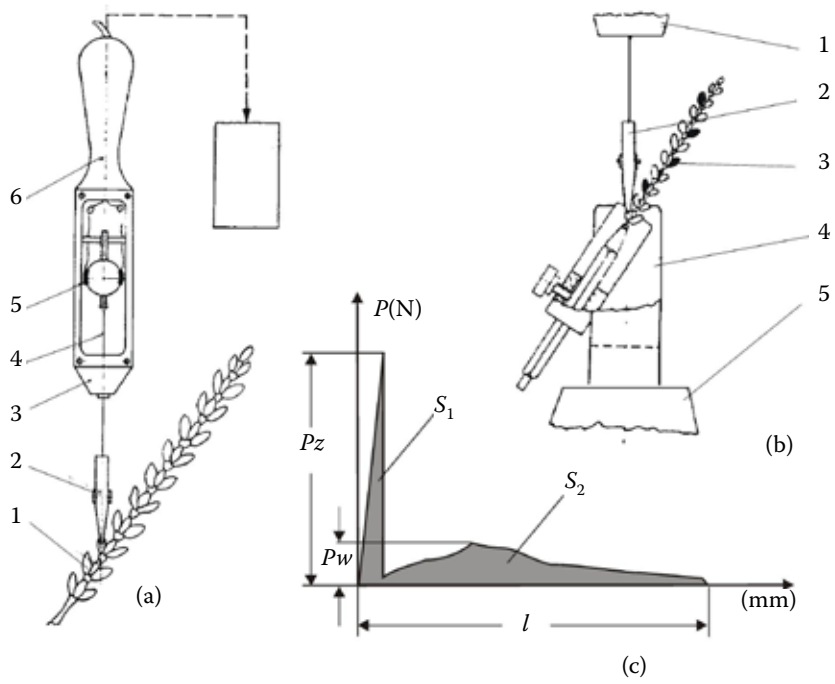

Figure 1. Scheme of measurement sets: (a) diagram of the tensometric micro-picker (CLUS-Prague): 1 – ear, 2 – pliers, 3 – body of the micro-picker, 4 – flexible connector, 5 – tensometric ring, 6 – holder of the micro-picker, 7 – recorder; (b) diagram of the measuring system of the Instron 1253 machine (IA PAS Lublin): 1 – loading head, 2 – pliers, 3 – ear, 4 – universal holder, 5 – base of the holder; (c) diagram from the recorder of the Instron apparatus, presenting the course of separating grain from ear: P_z – maximum force of grain-to-ear torus binding, P_w – maximum force keeping grains in glumes after breaking off from torus, l – total way a grain must cover for its complete separation from ear to occur, S_1 – energy necessary to break grain off from ear torus, S_2 - energy necessary to remove grain from among glumes (dechaffing)

bins. Granary weevil (*Sitophilus granarius* L.) is the most significant infester of storage grain in Europe. The activity of insects leads to an increase of the moisture content and temperature of stored grain which is the cause of the occurrence of conditions favourable for the infection by fungi and subsequent reduction of quality by mycotoxins. Infested grain is hazardous for humans due to the contamination by metabolites, body fragments, and dead bodies, strongly allergenic to human.

The second field of investigation looked for the reason of proneness of rape stem to lodging. Rape plants are prone to lodging, which reduces the level of rape seed yield obtained. As it is known, the resistance of plants to lodging is closely related to the mechanical properties of their stems. This fact has been reflected in many years of research on the mechanical properties of plant stems (Řezníček *et al.* 1978a, 1980; Blahovec *et al.* 1983, 1984, 1985; Skubisz *et al.* 1989; Blahovec & Skubisz 1990; Skubisz 1982, 1991, 1998, 2001a,b; Skubisz & Müller 1991; Skubisz & Blahovec 1997).

In the studies, the static test was used to determine the stem rigidity and maximum bending stress, and the dynamic test to determine the shearing energy and shearing energy per unit of rape stem cross section area (Skubisz *et al.* 1989; Blahovec & Skubisz 1990; Skubisz 2001a,b). Also, analyses were made of the mechanical properties of rape varieties in the course of the plant growth and development. At the same time, the estimation was conducted of the mechanical properties of stems of plants grown under varied conditions in terms of plant density per square meter and of nitrogen fertilisation applied (Skubisz 1995, 2001a,b). In the final stage of the study, the authors searched the relations between the mechanical properties and X-ray absorption by rape stems (Skubisz & Velikanov 1994, 2000).

MATERIALS AND METHODS

Wheat grain investigations

In co-operation with Physical Dept. of CULS in Prague, a direct method based on the measurements of the force binding particular grains with the ear has been worked out. Using the tensometric micro-picker elaborated in Prague, the investigations were carried out in the prior period of cooperation in 1973–1975. The research material consists of wheat varieties cultivated in both countries on a wide scale and staying in the range of experiments at least over the period of the mentioned three years. In effect, the investigations comprised the winter wheat varieties Kavkaz and Mironovskaya, and the spring wheat variety Zlatka, cultivated in the Czech Republic, and the winter wheat varieties Kavkaz, Grana, and Helenka as well as the rye Dankovskie Zlote cultivated in Poland. The methodology of this investigation (Figure 1) is clearly described in a paper by Řezníček *et al.* (1978b). In the paper by Grundas and Pecen (2004), the experimental material consists of common winter wheat of the cultivar Kris. The heads from the main and lateral stalks of this cultivar were gathered prior to full maturity of grain at the Station of Varieties Estimation in Czeslawice

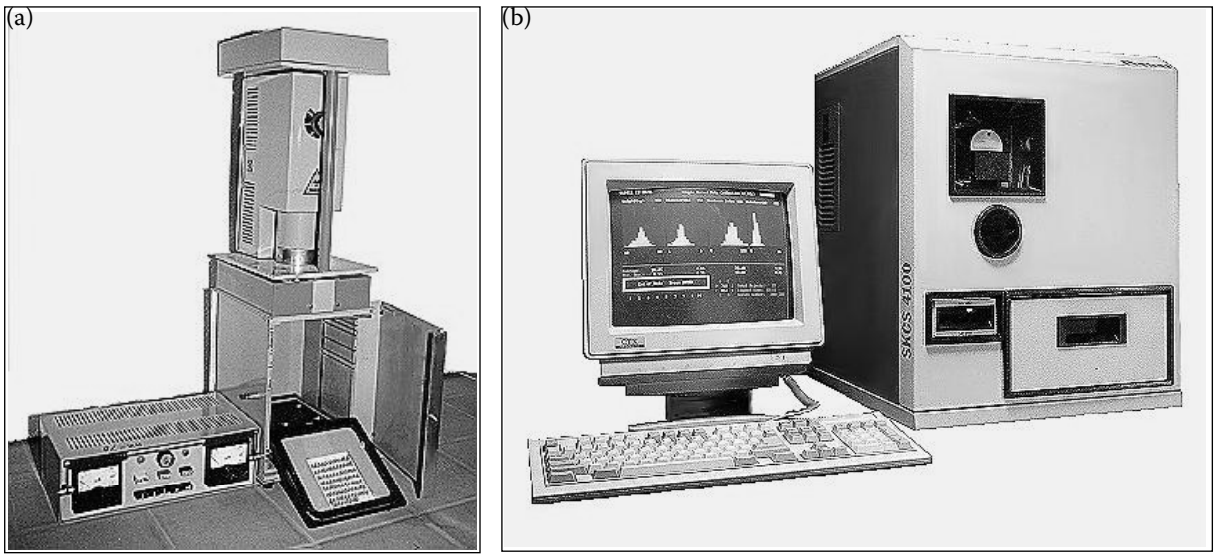

Figure 2. View of the X-ray apparatus (a), and the SKCS (b)

(Poland). In these investigations, two apparatuses: Single Kernel Characterization System (SKCS) and X-ray apparatus were used (Figure 2).

The physical properties of wheat grain are described to a great extent by the properties of endosperm which takes 80–86% of its volume. Endosperm is a composite material consisting of thin-walled cells which are filled mostly with starch granules embedded in a strong- protein matrix. Pores constitute the remainder of the cell volume. Methodical aspects are described in detail in a paper by Hnilica and Grundas (1985). Endosperm density and the density distribution (Figure 3) were measured in specimens in the shape of rectangular prisms cut out of grains of three winter wheat varieties (Hnilica *et al.* 1989).

Some problems of the measurement of the rheological properties of grain endosperm by the pulse ultrasound method (Figure 4a) were also studied (Hnilica & Grundas 1983). The samples were rectangular in shape and were prepared from the wheat varieties Jana and Grana, and from the barley variety Rapid.

In cooperation with Hnilica (Grundas & Hnilica 1985), an introductory study of the internal porosity changes in the endosperm of the wheat variety Jana was also carried out by Grundas and Hnilica (1985). Mercury porosimetry and samples in the form of rectangular prisms were used in this study. The samples were subjected to elastic and plastic deformation prior to the experiments.

In the paper by Grodek *et al.* (2006) some results of the application of ImageJ to X-ray image analysis of wheat kernels are presented. ImageJ based on X-ray technique enabled to construct rapid and

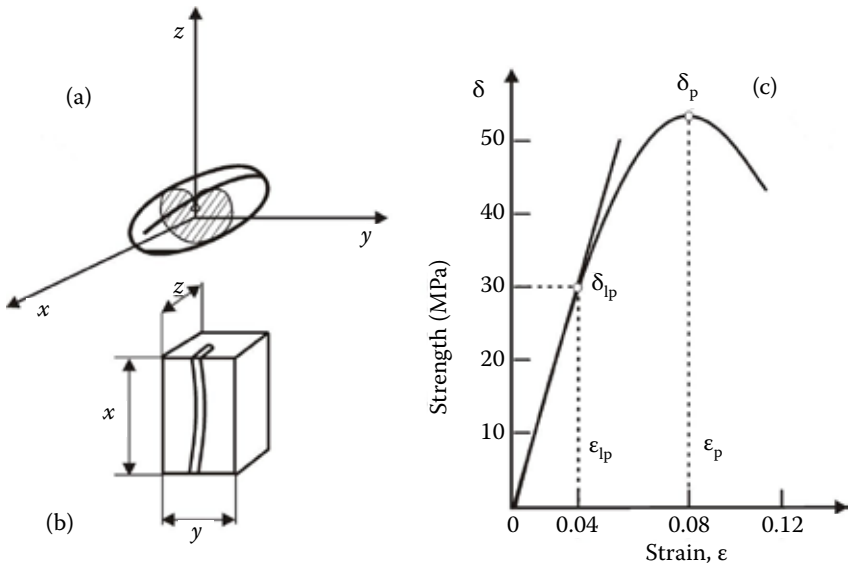

Figure 3. Wheat grain spatial orientation (a), endosperm section shape (b), and characteristic curve with parameters recorded by Instron machine (c)

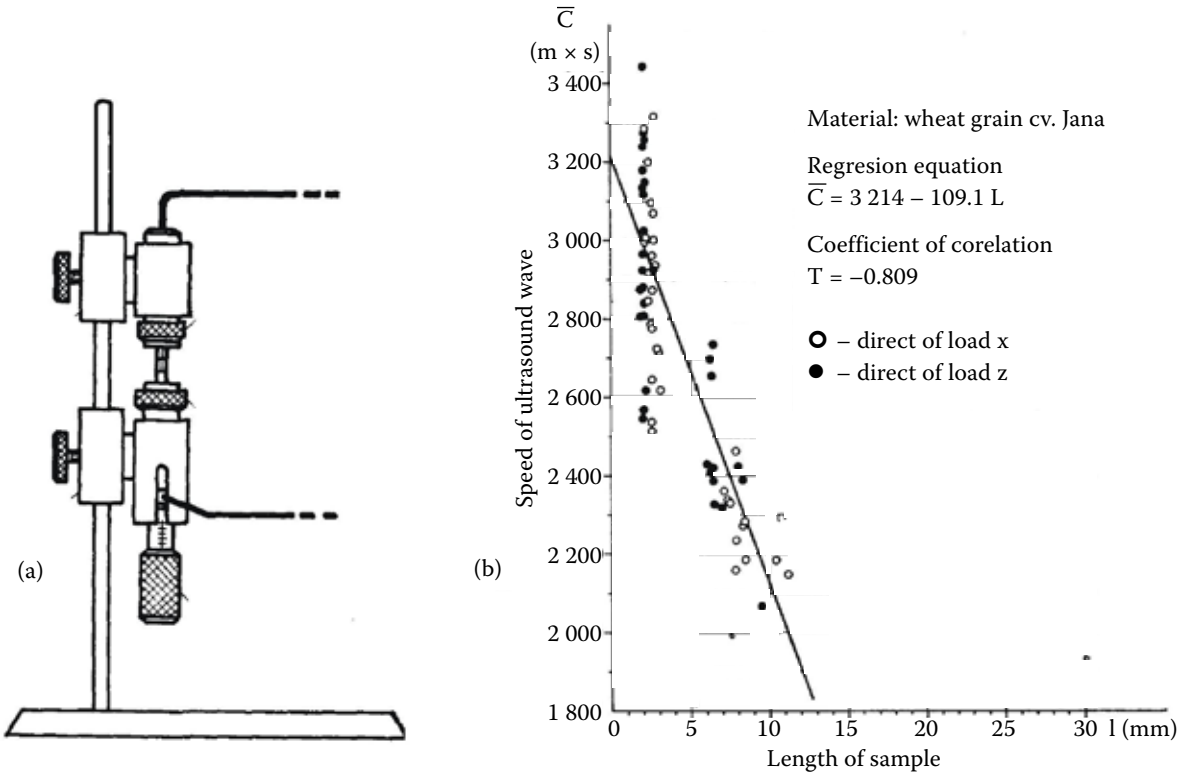

Figure 4. Diagram of the mechanical part of the equipment used to measure the speed of ultrasound waves in grain endosperm (a), and the values of the speed of ultrasound wave front in the endosperm of wheat and the course of its regression dependence on the height of sample column (b)

accurate procedures for the estimation of grains internal structure and its quality. Digital Image Analysis (DIA) has been used in many branches of science. Among them, the attention should be paid to ImageJ (NIH Images). ImageJ (http://rsb.info.nih.gov/ij/) was written in JAVA and run on every computer platform (Linux, Mac OS 9, Mac OS X, Windows, and the Sharp Zaurus PDA). Further, the impact of the scanning resolution on the accuracy of automatic detection of internal damage in X-ryayed wheat kernels was evaluated by Grodek (2007).

Rape stem investigations

The study on the mechanical properties of stems comprised varieties of winter rape and included varied cultivation conditions for the plants (sowing density, row spacing, and nitrogen fertilisation). The measurements were carried out during flowering, at the stage of full pods, and during the technical and full ripeness of rape seeds. A representative sample comprised 30 stems.

The mechanical properties of rape stems were expressed on the basis of their mechanical parameters determined in static and dynamic tests. In the static test, an Instron strength tester was employed to determine, in the process of bending, the stem rigidity (EI) and maximum bending stress (σ_{max}) and, in the process of shearing – shearing energy (E_s). The results were recorded by means of a computer system, using a program specially developed for the purpose. Maximum bending stress was expressed as a function of natural cross section area of the stem σ_{max} (Skubisz *et al.* 1989; Skubisz 1993). Shearing energy E_s was obtained by integrating the area beneath the curve recording the force of shearing. In the dynamic test, dynamic shearing energy (E_d) was measured by means of a Dynstat type apparatus operating on the principle of a pendulum hammer, in which the knife moved at a velocity of v = 2.1 m/s. The values of E_s and E_d – through division by the area of the stem cross section (S) – were used to calculate the equivalent value of the work performed to shear a unit of the stem cross section area (w_S and w_d). The values of the stem cross section area S and S' (natural and after the removal of the parenchyma) were determined by means of a ΔT area meter. To determine the variability of the mechanical properties along the stem length, the measurements were taken at several heights of the stems (from the root to the tip). The estimation of the plant lodging was made using a 10-step scale where 10 means the absence

of lodging and 1 corresponds to the most advanced lodging (stem close to the ground).

In the final stage of the study on the mechanical properties of rape stems the X-ray method was employed (Skubisz & Velikanov 1994, 2000), where the densitometric method was used to determine the value of ΔOD which defines the degree of the film lighting after the passage of X-rays through the stem, which is equivalent to the amount of radiation energy absorbed by the stem.

RESULTS AND DISCUSSION

Results of wheat grain investigations

In respect to the examination of the mechanical properties of cereal grains, a significant relation was confirmed between the binding force of kernel to ear of common wheat and rye. The variability of this parameter indicates the differentiation in the range of the examined cultivars of wheat and rye. The results obtained in the frame of the investigations of grain binding to ear by the tensometric micro-picker were compared with the measurement data received from the apparatus Instron. These results indicate unequivocally that grains are bound the most strongly in the middle part of the ear, the most weakly in the upper part, while medium values occur in the lower part of the ear. Significant differences between the particular years were also noted which undoubtedly results from the different atmospheric conditions during the development of grain and its maturity. It was stated that the varieties cultivated in the Czech Republic were characterised by the decidedly higher value of the grain-to-ear binding force in comparison to the Polish varieties. It was established that the methods of direct measurements of the grain-to-ear binding force applied in the Czech Republic and in Poland were sufficiently accurate and allow for an exact determination of this important property of the cereals investigated. These first investigations carried out jointly within the frame of international co-operation with the application of direct methods (Figure 1c) constitute an important step forward in the works on unifying the methods of investigating the physical properties of cereal plants.

The research of mechanical properties of wheat grain endosperm proved a strict relation between density and the type of endosperm structure and its mechanical characteristics. Using X-ray method and mechanical properties of wheat grain endosperm, a strict relation between density and the type of endosperm structure and its mechanical properties was proved (Grundas & Hnilica 1983, 1987; Hnilica & Grundas 1985, 1992; Bochynski *et al.* 1991).

For example, in Figure 4a the values of the speed of the ultrasound wave front in the endosperm of the wheat variety Jana and the course of its regression dependence on the height of the sample column are presented. The results of the study carried out by Grundas and Hnilica (1985) may serve for solving the problems of technological processing of grain and for machine designing.

The results obtained from the porosimetric study showed in increased internal porosity from initial 0.085 to 0.225 in the samples deformed beyond the pressure strength limit. It was ascertained that the plasticity of the tested material is caused by the formation of micro-cracks the radii of which are in the range of the starch grain dimensions. The microcrack formation is connected with the tearing of the protein matrix from the starch grain.

Further research proved that the intensive changes of grain moisture during the moistening of dry grain or drying of wet grain in laboratory led to an increase of the internal damage of grain which took place in

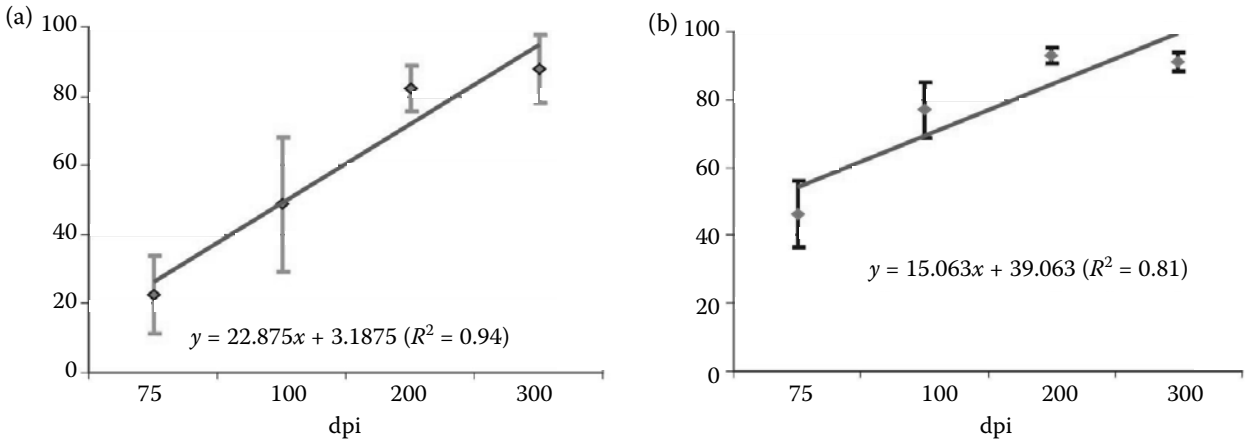

Figure 5. Accuracy of automatic procedure of image analysis (%) for each scanning resolution of roentgenograms of cracked (a), and infested (b) kernels

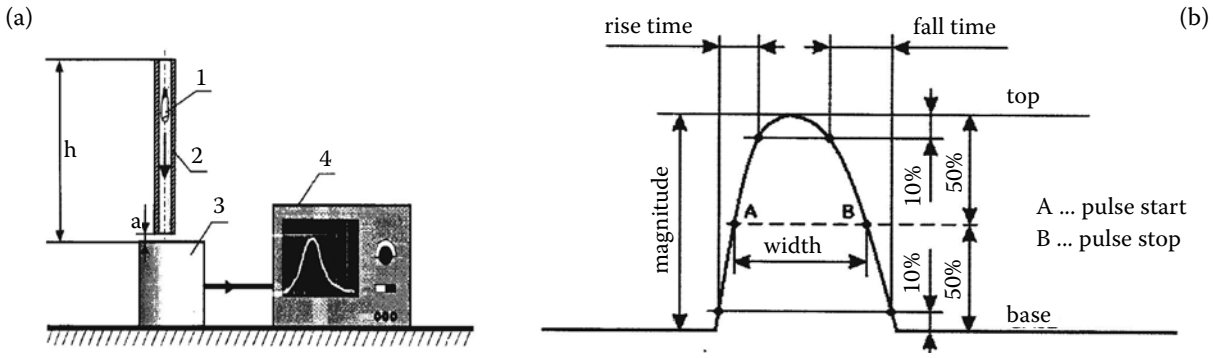

Figure 6. Scheme of the used apparatus (a): 1 – barley kernel, 2 – glass tube, 3 – force transducer, 4 – digital oscilloscope (DSO): and graphic presentation of the pulse parameters and their geometric sense (b)

pre-harvest field conditions as well. Different susceptibility of grain to this kind of damage may cause obvious losses in the yield during harvesting and a decrease of quality in storage and processing (Pecen *et al.* 1992, 2001, 2002; Grundas *et al.* 2002, 2005; Grundas & Pecen 2004).

Figure 5 presents the accuracy of the automatic procedure of image analysis for scanning resolution of roentgenograms of cracked and infested kernels, and 95% confidence intervals according to Grodek (2007).

In this case the application of the digital image analysis of wheat grain in different stages of infestation is supported by a modern technique of shock (impact) load registration by a digital oscilloscope equipped with a super sensitive impulse detector (Figure 6) which put our research in line with the most advanced measuring techniques (Pecen *et al.* 2003, 2006, 2007; Pecen 2007; Grodek *et al.* 2007).

This research is currently taken in the frame of a new scientific network gathering specialists from scientific centers in Poland, the Czech Republic (CULS, Prague – Josef Pecen), and Russia (Agrophysical Research Institute of RAAS in St. Petersburg – Michail Arkhipov and Leonid Velikanov).

Results of rape stem investigations

In the study on the mechanical properties of rape stems, variability of the parameters analysed was observed both along the length of the stems and in the growth stages of the plants (Skubisz 1991, 2001a,b). The character of the changes is described by a quadratic polynomial.

The study showed that the shearing energy values E_s and E_d provide comparable estimations of the inter-variety differences. High values of the correlation coefficients were obtained for those parameters at the level of $r_{0.05}$ = 0.80–0.90.

The analysis of the results concerning the variability of w_d along the length of rape stems showed the existence of a characteristic point located close to the first bifurcation of the plant stem (Figure 7) (Skubisz *et al.* 1989; Skubisz 2001a,b).

A strong correlation was found between the variability of the mechanical properties of rape stems, stem cross section area, and the absorption of X-ray radiation by the stems (Skubisz & Velikanov 1994, 2000).

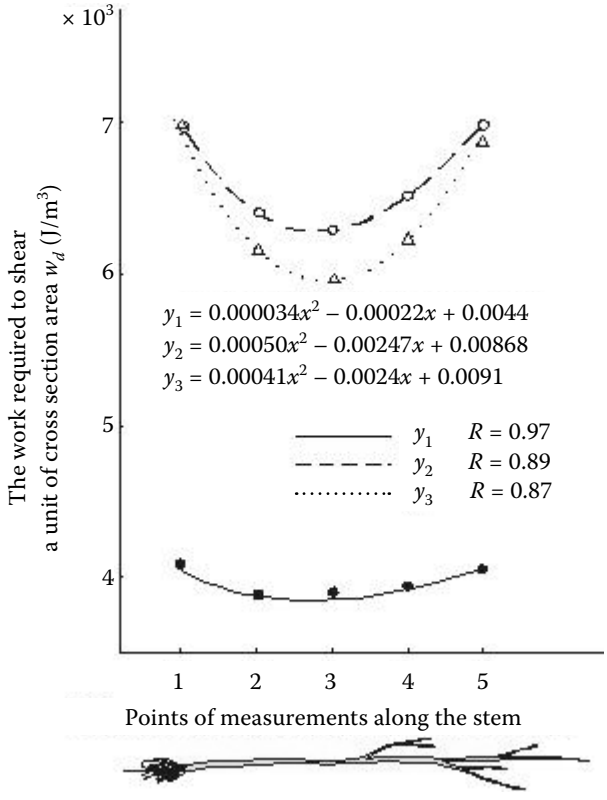

Figure 7. Distribution of the values of the shearing energy per stem cross-section area unit in dynamic test along the stem of Jupiter rape in successive phenophases (y_1,y_2,y_3 – regression curve, y_1 – complete silique filling, y_2 – technical ripeness, y_3 – full ripeness)

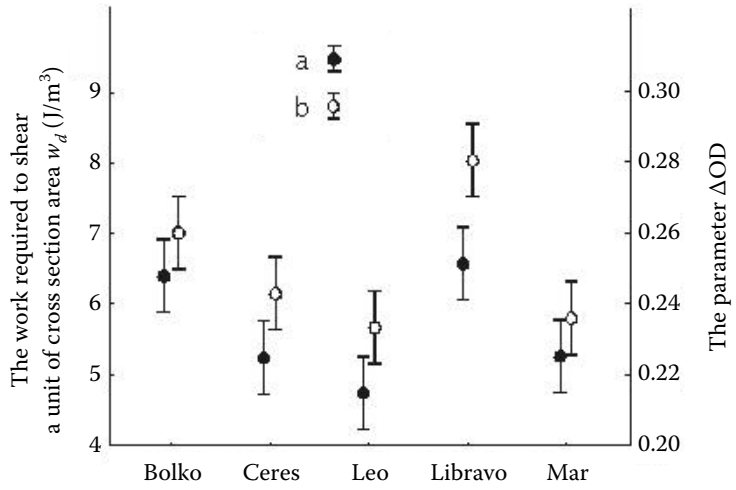

Figure 8. Mean values and the 95% Tukey HSD intervals of w_d (a), and ΔOD (b) stems for the varieties of the winter rape

The analysis of variance demonstrated a significant inter-variety variability, both on the basis of the mechanical properties (w_d) and on the basis of X-ray radiation absorption by the stems (ΔOD) (Figure 8). This fact indicates also the applicability of the X-ray method for the study of the strength properties of the rape varieties.

The results of the study showed the effect of varied plant density per square meter on the variability of the mechanical properties of rape stems. At the same time, it was found that the density of plants/m^2 differentiates the plants in terms of their resistance to lodging. It was found that the mean values of the mechanical parameters decreased with increasing density of plants/m^2, and the degree of their lodging intensified (Skubisz 1995, 2001a,b).

One effect of the studies on the mechanical properties of rape stems is the application of a wide range of measurement methods and indication of the most suitable mechanical parameters that can be used for the strength testing of rape stems, with simultaneous consideration of varied conditions of cultivation of the plants and their various growth and development phases.

The application of the static test permitted to obtain the mechanical parameters of stems subjected to the process of bending and shearing with the help of a high-precision strength-testing apparatus that allowed monitoring the whole process of stem bending or shearing and an accurate recording of the range of elastic deformations and of the moment of the occurrence of permanent deformation. In the dynamic test, performed with the help of an apparatus operating on the principle of a pendulum hammer, the loss of kinetic energy was recorded, equivalent to the energy of shearing a rape stem. In both tests, thanks to the possibility of taking precise measurements of the irregular cross section area of rape stems using the optical method, the amount of work required to shear a unit of the stem cross section area was determined. That value undoubtedly indicates the density of the mechanical tissue at particular heights of the stem. This parameter proved to be especially useful in testing the mechanical properties of rape stems, as it demonstrated the existence of an extreme on the stems of winter rape, located close to the first bifurcation. The study showed an extensive variability of the mechanical parameters analysed, both along the length of the stem and in the phenological phases. Significant inter-variety differences were also observed.

As a result of the methods applied it was possible to determine maximum bending stress values through measurable stem cross section areas, and to demonstrate the applicability of that parameter for testing the mechanical properties of stems of winter rape varieties. Significant inter-variety differences were also found.

The comparison of rape stem strength characteristics obtained in the static and dynamic shear tests, by means of parameters E_s and E_d, revealed that both energy values characterise the mechanical properties of the stems of winter rape varieties in an identical manner. Therefore, it is possible to use the static and dynamic tests alternatively, while in the subsequent testing the dynamic test only was employed.

The work required shearing a unit of stem cross section area w_S, and the w_d parameter in particular, demonstrated the existence of a characteristic point on the length of the plant stem, located close to the first bifurcation, where a notable minimum was observed. This result justified the limitation of further studies to the test in one characteristic point

on the stem height, documented by the geometric structure of the stem.

The results of the study concerning the variability of w_d on the length of rape stem present the course of variability similar to the value of S'/S which attains a minimum of its value close to the first bifurcation (S' – cross section area after the removal of the parenchyma), performed by Skubisz *et al*. 1989. This conclusion indicates a relation between the shear energy per unit of the stem cross section area and the stem geometry.

The analysis of the mechanical properties of rape stems in the course of the plant development showed a maximum of the value of the dynamic shear energy per unit of the stem cross section area (w_d) in the phase of technical ripeness of seeds. This suggests the harvest time in the phase of technical ripeness as more favourable than that in the phase of full ripeness. In the phase of technical ripeness, rape stems are characterised by the greatest resistance to shear, the unit density of the mechanical tissue in the cross section being the highest.

Based on the analysed mechanical parameters of winter rape varieties, significant differences were noted in the course of the development of plants, indicating the possibility of employing the developed methodology in breeding cultivars. The mechanical parameters determined in the process of bending and shearing are applicable for the testing of cultivars. The study demonstrated the validity of the mechanical parameters determined for breeders of new cultivars of rape while the range of stem shearing energy provides useful information for harvest technology engineers.

Variations were found in the mechanical properties of rape stems, caused by the conditions of plant cultivation, and also a significant effect of the density of plants per m^2 on both the lodging of plants and the variability of the strength characteristics of rape stems. The study showed that, at their low density in the canopy, the plants stems have the most favourable mechanical parameters in terms of their resistance to lodging, and are characterised by three-fold greater rigidity (EI) and by high values of dynamic shear energy (E_d). The results suggest that the density of 40 plants/m^2 is the most favourable, the plants being strong in terms of the strength characteristics of their stems, and resistant to lodging.

As follows from literature concerned with the characterisation of winter rape varieties in terms of the quality and quantity of the yields obtained, plant density of 40 plants/m^2 constitutes the lower limit of plants/m^2 that can be left till spring in terms of profitability of the expected crop yield (Skubisz 2001a,b).

The X-ray method, included in the final stage of this study, permitted the determination of the strength properties of stems of rape varieties. Simultaneous application of the dynamic test and the X-ray method demonstrated that the value denoting the absorption of X-rays by the stem (ΔOD) correlates significantly with the energy of dynamic shearing (E_d), and especially strongly with the amount of work required to shear a unit of stem cross section area (w_d) which defines the density of the mechanical tissue (Skubisz 1996; Skubisz & Velikanov 2000).

Beyond any doubt, these results were achieved thanks to the wonderful personality, competence, and coordination of the guest of honour, Prof. Radoš Řezníček, and also to the great co-authors – Jiří Blahovec of the CULS in Prague, Leonid Velikanov of the Agrophysical Research Institute of the RAAS in St. Petersburg, Zolltan Müller, PhD of the University of Agriculture in Gödöllo, Hungary, and to the Project Manager, Prof. Bogusław Szot of the Institute of Agrophysics of the PAS in Lublin.

CONCLUSIONS

To the wheat grain investigations

- The results obtained in the studies of grain-to ear binding and single kernel characteristics on the length of wheat heads present a unique collection of data, which can be utilised in monitoring the process of wheat breeding.
- The results received in the porosimetric study lead to the presumption that microckracs can be initiated on the natural discontinuities which are the size of starch grains and develop further by tearing off the protein matrix from the starch grains.
- The results obtained with ultrasound may serve for solving the problems of the technological processing of grain and for machine designing.
- Using X-ray measured set, the possibility exists to evaluate inner damage of kernels connected with endosperm cracking which can not be detected by the commonly used method.
- Considering the measurement sets, it should be stated that the combination of both sets (SKCS method, X-ray method, and the newly proposed method of the impact of kernel by using the force transducer with the amplifier and the DSO) gives the possibility of the evaluation of many physical properties of single kernels in on-line systems.

– Proposition to build this kind of combine measurement systems found its reflection in the establishment of the Working Group on Single Kernel Technology by the American Association for Cereal Science and Technology (AACC) and can help in further progress in this field by cereal scientists in the world.

To the rape stem investigations

– There is a notable variability in the mechanical parameters of winter rape stems along the length of the stem and in the development phases of the plants. The study also showed inter-variety differentiation of the mechanical properties.
– The shear energy determined in the static (E_s) and the dynamic (E_d) tests provides acomparable estimation of the inter-variety differences. A high positive correlation was found between these energy values. This conclusion suggests the possibility of choice between the two types of test for rape stem shearing.
– The work required to shear a unit of the stem cross section area (w_d) indicated the existence of a characteristic point on the length of the stem, close to the first bifurcation.
– A significant correlation exists between the absorption of X-ray radiation and the parameters defining the mechanical properties of rape stems.
– The application of the X-ray method notably expanded the possibilities of the determination of rape stems susceptibility to shearing.
– A significant correlation was found between the mechanical properties of rape stems and the resistance of the plants to lodging.

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Abstrakt

Grundas S., Skubisz G. (2008): **Fyzikální vlastnosti obilného zrna a řepkové lodyhy.** Res. Agr. Eng., **54**: 80–90.

Práce uvádí výsledky studia mechanických vlastností obilného zrna a řepkových lodyh, které byly provedeny v rámci pokračující dlouhodobé spolupráce mezi Ústavem agrofyziky Bohdana Dobrzanského Polské akademie věd v Lublinu (IA PAS), Polsko a České zemědělské univerzity v Praze (CULS), Česká Republika. V rámci mechanických vlastností

obilného zrna, studie ukázala signifikantní vztah mezi společnými fyzikálními podmínkami zrn pšenice určenými rentgenovou detekcí a mechanickými vlastnostmi určenými ve standardních testech používanými v mechanice strukturních materiálů a testy používanými ve zpracovatelských technologiích. Studium mechanických vlastností lodyhy řepky demonstrovalo meziodrůdové rozdíly v poléhavosti. Odhad variability mechanických vlastností podél řepkové lodyhy ukázal charakteristický bod v blízkosti prvého rozvětvení. Významný vliv na pevnostní charakteristiky lodyhy vykazovaly hustota porostu (vyjádřená počtem rostlin na metr čtvereční) a hladina hnojení dusíkem. Zároveň byly nalezeny závislosti mezi mechanickými vlastnostmi lodyhy a absorpcí rentgenových paprsků.

Klíčová slova: pšeničné zrno, řepková lodyha, fyzikální vlastnosti, užitková hodnota

Corresponding author:

Prof. Stanislaw Grundas, Bohdan Dobrzanski Institute of Agrophysics of Polish Academy of Sciences, Doswiadczalna Str.4, 20-290 Lublin, Poland
tel.: + 4881 744 50 61; fax: + 4881 744 50 67; e-mail: grundas@ipan.lublin.pl