Effect of seed coat thickness on seed hardness

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Frączek, J., Hebda, T., Ślipek, Z. and Kurpaska, S. 2005. **Effect of seed coat thickness on seed hardness**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **47**: 4.1 - 4.5. This study was carried out to determine the effect of seed coat thickness on the hardness of selected seeds at different levels of moisture content. The research was conducted on twelve seed types with and without coats at five levels of moisture content (0.11, 0.15, 0.19, 0.23, and 0.33 kg/kg dry mass (dm)). The study showed that the hardness of studied seeds decreased rapidly at levels of moisture content ranging from 0.11 to 0.19 kg/kg (dm). Moisture content was significantly correlated with the hardness of the seeds studied. Differences in hardness between seeds with and without coats decreased gradually with increased moisture content. The seeds were grouped into seven groups and an empirical equation was developed to describe the hardness of all these groups, using different regression coefficients. **Keywords**: seeds, seed coat thickness, hardness, moisture content.

Cette étude avait pour objectif la détermination de l'effet de l'épaisseur du tégument sur la dureté de graines sélectionnées et ce, pour différentes teneurs en eau. L'étude a été réalisée sur douze types de graines, avec ou sans tégument, à cinq teneurs en eau (0,11, 0,15, 0,19, 0,23 et 0,33 kg/kg matière sèche (ms)). Cette étude a montré que la dureté des graines étudiées décroissait rapidement à des niveaux de teneur en eau compris entre 0,11 à 0.19 kg/kg (ms). La teneur en eau a eu un effet significatif sur la dureté des graines étudiées. Les différences de dureté entre les graines avec ou sans tégument décroissaient graduellement avec une augmentation de la teneur en eau. Les graines ont été regroupées en sept groupes et une équation empirique a été développée pour décrire la dureté de chacun de ces groupes en utilisant différents coefficients de régression. **Mots clés**: graines, épaisseur du tégument, dureté, teneur en eau.

INTRODUCTION

Knowledge of the physical properties of seeds is needed for proper design of machinery for the food industry and also for the development and cultivation of new varieties. Hardness is one of the most important and most commonly considered mechanical properties of seeds. According to Morris and Massa (2003), hardness is one of the important factors in quality of seeds. As evidence are the Single Kernel Characterization System (SKCS) (Perten Instruments AB, Huddinge, Sweden) and research conducted at Kansas State University (Pasikatan et al. 2001, 2002; Wang at al. 2002) and Washington State University (Morris at al. 1999, 2001a) employing near-infrared reflectance (NIR) methods.

Moisture in plant seed materials is the factor that affects its hardness the most. This has been confirmed by numerous studies, including studies on the effect of moisture on the hardness of rye endosperm (Gasiorowski and Kolodziejczyk 1990; Tranquilli at al. 2002; Morris 2002), studies on compressive strength of seeds (Foutz at al. 1993; Liu at al. 1990), studies on seed hardness and elasticity (Fraczek and Hebda 2001b; Haman at al. 1994; Zayas at al.1996), a study on the effect of moisture on the resistance and the work of slicing seeds (Figiel 1999), and a studies on the effect of moisture content on technological hardness (Wozniak 2001, 2002; Morris at al. 2001b). The effect of seed moisture on crushing energy was studied by Romanski and Niemiec (2001), Flizikowski (2002), Paulsen at al. (1981), Bormuth (1994), Dobrzanski (1997), and Lamb and Hurburgh (1991). These studies showed that anatomical structure as well as moisture content determine the mechanical properties of seeds, including hardness.

Many studies have examined the influence of morphology on seed hardness, but most of them have been very general. Detailed study of this aspect is important for breeders and machine designers, particularly in regard to the seed coat, which protects the endosperm nutrients from being washed away. The seed coat is also responsible for the overall health and strength of the seeds.

In spite of widespread interest in the physical properties of plant seed material, there is a lack of information on the role of the seed coat in the development of seed hardness. The purpose of this study was to determine the effect of seed coat thickness on the hardness of a range of selected seeds under a variety of moisture conditions.

MATERIALS and METHODS

The study was conducted on the following seeds: lupine (*Mirela*), pea (*Piast* and *Nike*), bean (*Wiejska, Atena, Jubilatka* and *Augustynka*), vetch (*Szelejewska*), field pea (*Perkoz*), wheat (*Roma* and *Korweta*) and rye (*Dankowskie Zlote*).

The experiment began with measurements carried out on air-dried material at a moisture content of 0.11 kg/kg (dm). The seeds were then moistened to greater levels of moisture content by the addition of water. During moistening, the seeds were locked in hermetic containers for 24 hours and periodically shaken. Moisture content was measured with a WPE-300S scale-dryer (Radwag, Radom, Poland) at 0.1% accuracy of reading. When the desired seed moisture content (0.11, 0.15, 0.19, 0.23, 0.33 kg/kg (dm)) was achieved, measurements were carried out separately for whole seeds and for seeds without coat, which was removed by abrasion using abrasive paper P600 grade (SIA 1913 siawat plain, Swiss Industrial Abrasives Ltd., Frauenfeld, Switzerland) or with a scalpel (dicotyledonous seeds).

A portion of the seeds from the studied sample was prepared for seed coat thickness measurements, which were done according to an original method described in detail by Fraczek and Hebda (2004). In accordance with this method, the seeds were flooded with Technovit 7100 (Carl Zeis Jena, Jena, Germany), then after six hours the seeds were flooded with a

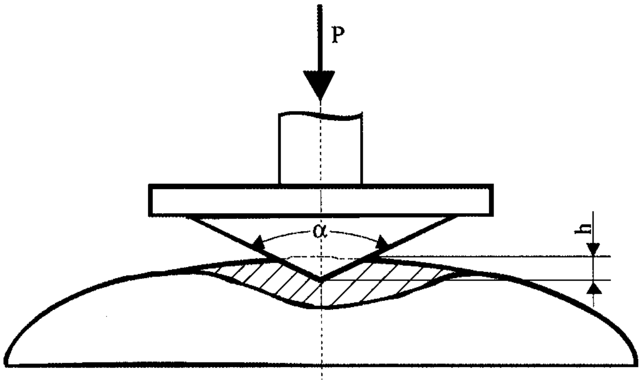

Fig. 1. Measuring scheme.

hardener (Carl Zeis Jena, Jena, Germany) to cause hardening of the samples. The samples thus prepared were placed in the grip of an ERGOSTAR HM 200 sliding microtome (Microm, Walldorf, Germany) and sliced at the point of the sample's greatest diameter. The revealed surface was then photographed. The resulting image was transferred to a computer using the Show Time Plus (Computer Scanning Systems II, Warszawa, Poland) analogue-digital converter. Seed coat thickness was measured from the image using the Multi Scan 6.08 (Computer Scanning Systems II, Warszawa, Poland) program and support applications.

The seed hardness was determined by measurement of the penetration depth *h* of a conical penetrator. The penetration depth was measured by an indicator (Mitutoyo ID-F150, Mitutoyo Co., Takatsu-ku, Kawasaki, Japan) mounted on a measuring device made in the Department of Mechanical Engineering and Agrophysics of the Agricultural Academy, Krakow, Poland. The apex angle of the conical penetrator was 120° (Fig. 1). The duration of measurement was 15 min (Fraczek and Hebda 2002, 2003). Measurement accuracy was 0.001 mm at the force *P* equal to 2 N. The sample size was 10.

The hardness value of the studied material was calculated according to Eq. 1 (Fraczek and Hebda 2001a):

$$HV = P \frac{\sin\left(\frac{\alpha}{2}\right)}{\pi h^2 \tan^2\left(\frac{\alpha}{2}\right)} \quad (1)$$

where:

HV = hardness (MPa),
P = force loading the penetrator (N),
h = penetration depth (mm), and
α = apex angle of the penetrator (degrees).

RESULTS

Hardness of whole seeds HV_{ws}

At moisture content of 0.11 kg/kg (dm), the greatest hardness of seeds with seed coat was noted in Nike pea (HV_{ws} = 94.25 MPa) and Dankowskie Zlote rye (HV_{ws} = 82.15 MPa). The least hardness was observed in Atena bean (HV_{ws} = 12.79 MPa) (Table 1).

The greatest decrease of HV_{ws} was obtained in the moisture content range from 0.11 to 0.19 kg/kg (dm). This was most noticeable in Nike pea, where the hardness value decreased by 99%. A 95 and 91% decrease in the hardness value was observed for Jubilatka and Augustynka beans, respectively. The least reductions, 81 and 82%, respectively, were observed in Roma and Korweta wheats. For the other seeds studied, the decrease was about 90%.

For moisture content above 0.19 kg/kg (dm), HV_{ws} reached a constant value for all seeds. The least hardness was observed for Piast and Nike peas (HV_{ws} = 0.09 MPa at moisture content of 0.33 kg/kg (dm)).

Hardness without seed coats HV_{wsc}

The change in hardness of seeds without seed coat was similar to that of seeds with the seed coat (Table 1). The greatest decrease in hardness occurred up to a moisture content of 0.19 kg/kg (dm), and above this level the hardness value reached a constant value.

At a moisture content of 0.11 kg/kg (dm), the greatest hardness among the studied seeds was noted for Nike pea (HV_{wsc} = 87.80 MPa), the endosperm of the cereal Korweta wheat (HV_{wsc} = 57.59 MPa), and Dankowskie Zlote rye (HV_{wsc} = 62.42 MPa). The least hardness at that moisture content was in Mirela lupine (HV_{wsc} = 6.48 MPa).

At a moisture content of 0.33 kg/kg (dm), the greatest hardness was observed for the endosperm of cereal seeds (HV_{wsc} = 0.36 - 0.74 MPa) and the least, as was the case for seeds with the seed coat, for Nike pea (HV_{wsc} = 0.07 MPa).

These observations were statistically verified using the three-factor analysis of variance with within-subject (10 repeated measurements) (ANOVA) employing Statistica v.6.1 (StatSoft Inc., Tulsa, OK). It was proved that all tested factors, variety, moisture content, and the seed form (whole seeds or seeds without the coat) had statistically significant effect on hardness HV. Significance of dependence was confirmed also between variety and moisture content as well as between moisture content and the seed form.

The Duncan test results for the main factors delineated two homogenous groups for variety factor alone, Jubilatka and Augustynka beans, and for Atena and Augustynka bean, Mirela lupine and Piast pea. No homogenous groups were differentiated for the factor of moisture content, which means that every change in the seed moisture content significantly affected its hardness. The statistical analysis, therefore, did not support the earlier observations that hardness reached a constant value with an increase in moisture content. No homogenous groups were observed for the factors of whole seeds and seeds without the seed coat. It can be settled that the seed coat significantly affects the hardness of the entire seed.

The Duncan test was also performed for the interaction between moisture content and the seed form (whole seeds or seeds without the coat). It ascertained that, starting at moisture content of 0.19 kg/kg (dm), the hardness of whole seeds HV_{ws} and the hardness of the seeds without seed coat HV_{wsc} did not differ significantly. Thus, it can be suggested that the mechanical properties of the seed coat change more than those of the endosperm or germ. At small moisture content, the seed coat is relatively hard and brittle, whereas at greater moisture contents it acts like an elastic membrane.

Differences between varieties based on Duncan tests may be erroneous; however, a study by Fraczek and Hebda (2004) showed that two groups of seeds may be isolated, which exhibit

Table 1. Hardness of various seeds at various moisture contents.

Various seeds	Moisture content (kg/kg dm)	HV_{WS} (MPa)	HV_{WSC} (MPa)	Various seeds	Moisture content (kg/kg dm)	HV_{WS} (MPa)	HV_{WSC} (MPa)
Wiejska bean	0.11	21.022	7.585	Piast pea	0.11	15.300	10.036
	0.15	3.069	1.433		0.15	3.539	2.560
	0.19	0.926	0.617		0.19	1.306	0.959
	0.23	0.440	0.359		0.23	0.236	0.193
	0.33	0.116	0.106		0.33	0.092	0.091
Jubilatka bean	0.11	26.206	12.467	Szelejewska vetch	0.11	30.301	15.861
	0.15	5.316	3.484		0.15	13.045	5.599
	0.19	1.220	0.673		0.19	2.992	1.972
	0.23	0.754	0.335		0.23	0.670	0.528
	0.33	0.125	0.102		0.33	0.264	0.223
Atena bean	0.11	26.589	12.874	Perkoz field pea	0.11	52.346	12,237
	0.15	3.310	1.769		0.15	18.774	4.029
	0.19	1.423	0.864		0.19	4.938	1.281
	0.23	0.668	0.473		0.23	0.510	0.264
	0.33	0.110	0.103		0.33	0.220	0.139
Augustynka bean	0.11	12.788	7.801	Korweta wheat	0.11	62.356	57.862
	0.15	4.931	4.112		0.15	24.185	13.166
	0.19	1.193	0.793		0.19	11.371	6.837
	0.23	0.490	0.312		0.23	6.092	4.010
	0.33	0.308	0.220		0.33	0.501	0.362
Mirela lupine	0.11	20.018	6.475	Roma wheat	0.11	46.003	39.670
	0.15	5.309	1.645		0.15	21.347	17.290
	0.19	1.908	0.662		0.19	8.849	5.180
	0.23	0.755	0.341		0.23	3.559	1.916
	0.33	0.272	0.230		0.33	0.593	0.737
Dankowskie Zlote rye	0.11	81.150	62.419	Nike pea	0.11	94.252	87.797
	0.15	30.922	22.892		0.15	12.698	7.273
	0.19	8.764	6.558		0.19	0.998	0.694
	0.23	3.591	1.975		0.23	0.326	0.264
	0.33	0.570	0.473		0.33	0.086	0.072

opposite tendencies of a change in a seed coat thickness under the influence of the change in moisture content.

In studies on the change in seed coat thickness resulting from changes in the moisture content of the seed, we differentiated two seed groups:

1. a group in which seed coat thickness increases with increased moisture content. This group includes Roma wheat, Korweta wheat, Dankowskie Zlote rye, Szelejewska vetch, Nike pea and Perkoz field pea;
2. a group in which seed coat thickness decreases with increased moisture content. This group includes Atena, Augustynka, Jubilatka and Wiejska beans, as well as Mirela lupine.

The explanation for such varied seed coat behavior versus seed moisture may be sought in their morphology. The seed coat is made up of several layers of cells that absorb water slower than the endosperm or the germ do.

There are three groups of seed coats. Based on their structure, they are divided into permeable, semipermeable, and impermeable. The water permeating through the seed coat is absorbed by the germ or by the endosperm. The rate of this transmission depends on diffusion and osmotic forces, and particularly on hydrating (inhibiting) pressure, the values of which may even reach a few hundred atmospheres in the first stages of moistening.

The seed coat of bean and lupine can be classed in the water-permeable group. Their germ also comprises a higher percentage of the entire seed mass than in the other studied seeds. This means that the germ increases in volume during moistening more than the seed coat does. The larger the seed, the more noticeable this process becomes. At the greatest moisture content level, the seeds of Wiejska bean increased in volume more than 20%. This increased the pressure within the seed coat; the consequent normal stresses caused linear strains in the seed coat, decreasing its thickness. The rapid occurrence of this process may split the seed coat.

In the case of seeds with decreasing seed coat thickness versus increasing moisture content, homogenous groups were distinguished in the moisture content interval of 0.15 to 0.33 kg/kg (dm). This means that the decrease in seed coat thickness due to moistening led to a rapid decrease in their hardness.

Table 2. Estimation results of coefficients in Eq. 2.

Group of seeds	Coefficients of the model			R^2 (%)
	a	*b*	*c*	
Korweta and Roma wheats	0.001	-2.049	-2.514	94.02
Dankowskie Zlote rye	0.955	-3.750	1.286	97.93
Augustynka, Jubilatka, and Wiejska beans	0.001	-6.104	-0.917	96.79
Aatena bean	0.164	-2.801	5.685	97.86
Mirela lupine	6.619	-3.707	3.458	96.39
Perkoz field pea	0.013	-3.818	0.040	95.63
Szelejewska vetch, Nike and Piast peas	2078.17	-9.565	8.931	96.28

Finally, the relation between seed coat thickness and moisture content was described for seed groups created according to the following criteria: single-germ or two-germ seeds; seeds with seed coat thickness increasing or decreasing with the increase in moisture content; Duncan test results; series test results; and seed coat structural characteristics. These criteria allowed us to create the following groups: Korweta and Roma wheats; Dankowskie Zlote rye; Szelejewska vetch, Nike and Piast peas; Perkoz field pea; Mirela lupine; Augustynka, Jubilatka and Wiejska beans; and Atena bean.

In the case of whole seed hardness HV_{ws}, the best fit of the theoretical curves to actual HV_{ws} (assessed through coefficient of determination R^2 in Table 2) was obtained for an exponential function of the form:

$$HV_{ws} = a(mc)^b l^c \qquad (2)$$

where:

HV_{ws} = hardness of whole seeds (Mpa),
mc = moisture content (kg/kg (dm)),
l = thickness of coat (mm), and
a,b,c = coefficients of the model.

The analysis showed that in spite of the ascertained significant effect of seed coat thickness on seed hardness, its inclusion as the sole factor determining the hardness of the whole seed is insufficient. Far greater predictiveness is obtained with both seed coat thickness and moisture content incorporated. This is shown by the interaction of moisture content with HV_{ws} and with HV_{wsc}. The measured hardness relates to the entire seed and not just to its seed coat. It can be assumed that the hardness is a sum of two components, namely the hardness of the seed coat, and the hardness of the seed interior. In the proposed model, Eq. 2, the seed coat thickness factor is the equivalent of the first component and the moisture content of the second component.

CONCLUSIONS

1. The study showed that the hardness of the studied seeds decreased rapidly in the moisture content range of 0.11 - 0.19 kg/kg (dm).
2. Statistically significant differences in hardness were found between whole seeds and seeds without seed coat (at p = 0.05). These differences gradually decreased with the increase in moisture content.
3. Seed hardness is the effect of two components: hardness of the seed coat and hardness of the seed interior.
4. Thickness of coat and moisture content should be taken into account for accurate prediction of seed hardness. The dependence of coat thickness and moisture content on hardness can be described by a power function, with goodness of fit of more than 94%.

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