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FRICTIONAL PROPERTIES OF SELECTED SEEDS

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Abstract

The thickness, width, length and weight of five seed species (buckwheat, vetch, pea, lupine and faba bean) and their external friction angle were determined on two types of surfaces – steel and rubber. The experiment was performed with the use of a an inclined plane with an adjustable angle of inclination that measures the angle of external friction and the time taken by seeds to travel a given distance, which supports the determination of the coefficient of kinetic friction. The measured parameters were used to calculate arithmetic and geometric mean diameter, aspect ratio and sphericity index. The dimensions, weight and the calculated indicators of the examined seeds did not significantly affect their coefficients of static and kinetic friction or their coefficients of rolling resistance and rolling friction. The studied parameters were largely influenced by the type of friction surface, and significantly lower average values were reported for steel than rubber. In the studied seed species, the static friction coefficient was determined in the range of 0.187 to 0.582, kinetic friction coefficient – 0.134 to 0.479, rolling resistance coefficient – 0.148 to 0.529 and rolling friction coefficient – 0.29 to 1.80 mm.

Symbols:

D_a – arithmetic mean diameter, mm,
D_g – geometric mean diameter, mm,
m – seed weight, mg
f_1, f_2 – coefficient of rolling friction of seeds on steel and rubber, respectively, mm,
r – radius of a rolling seed, mm,
R – aspect ratio, %,
S – travel distance of the particle, m,
t – time required by the particle to travel distance, s,
T, W, L – seeds thickness, width and length, mm,
x, SD – average value and standard deviation of trait,
$x_{\min}$, $x_{\max}$ – minimum and maximum value of trait,
α – angle of external friction of seeds, °,
α_{s1}, α_{s2} – angle of static friction of seeds on steel and rubber, respectively, °,
α_{t1}, α_{t2} – angle of rolling friction of seeds on steel and rubber, respectively, °,
μ – coefficient of external friction of seeds,

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μ_{k1}, μ_{k2} – coefficient of kinetic friction of seeds on steel and rubber, respectively,
μ_{s1}, μ_{s2} – coefficient of static friction of seeds on steel and rubber, respectively,
μ_{t1}, μ_{t2} – coefficient of rolling resistance of seeds on steel and rubber, respectively.
Φ – sphericity index, %.

Introduction

A thorough understanding of frictional forces is required for analyzing and modeling various processes. The knowledge of frictional properties is essential for the selection of sowing, harvesting, transport, cleaning, sorting, storage and processing parameters of plant materials (HORABIK 2001, ALTUNTAS, DEMIRTOLA 2007, KABAS et al. 2007, KRAM 2008, RIYAHI et al. 2011, JOUKI, KHAZAEI 2012, SOLOGUBIK et al. 2013). Biological materials are characterized by morphological variation, and their frictional properties can differ significantly. An analysis of published sources (MOHSENIN 1986, HORABIK 2001, YALÇIN, ÖZARSLAN 2004, KRAM 2006, 2008, AFZALINIA, ROBERGE 2007, ALTUNTAS, DEMIRTOLA 2007, SHAROBEEM 2007, DAVIES, EL-OKENE 2009, IZLI et al. 2009, ŁUKASZUK et al. 2009, GHARIBZAHEDI et al. 2011, KALKAN, KARA 2011, TARIGHI et al. 2011) indicates that frictional parameters of plant materials are determined by species (variety), ripeness, moisture content, friction surface material, material porosity, velocity relative to the friction surface, orientation relative to the direction of motion, normal pressure exerted on particles, variations in particle shape and time of material storage.

Seeds can be cleaned and sorted with the use of a string sieve. The structure and geometric parameters of a string sieve have been discussed by the author in previous publications (KALINIEWICZ 2011, 2013a). Since separated seeds move along strings, and the width of openings between strings changes along the screen, possible correlations between the coefficient of external friction, dimensions and weight of seeds have to be investigated before the separation process is analyzed. In a study of principal cereal species (wheat, rye, barley, oats and triticale) (KALINIEWICZ 2013b), significant correlations were not observed between the above attributes. Conclusive information about the presence of such correlations in other species of seed-producing plants is not available in literature.

The objective of this study was to determine the variability in external friction coefficients of selected seed species and to identify the correlations between those parameters and the main physical attributes of seeds. The resulting data can be used to model industrial processes, in particular seed separation on a string sieve.

Materials and methods

The experimental material comprised buckwheat, vetch, pea, lupine and faba bean seeds obtained from three sources (Table 1): Potato and Seed Breeding Center in Olsztyn, a seed farm in Wodzierady and Department of Plant Breeding and Seed Production of the University of Warmia and Mazury in Olsztyn. Subject to species, the relative moisture content of seeds was decreased to 10.9–12.5% to enable long-term storage (KALETA, GÓRNICKI 2008, RUDZIŃSKI 2011).

Table 1

Experimental material

Seed species	Seed variety	Producer	Moisture content [%]
Buckwheat	Panda	Department of Plant Breeding and Seed Production of the University of Warmia and Mazury in Olsztyn	12.5
Vetch	Hanka	OLZNAS-CN Potato Breeding and Seed Production Center in Olsztyn	11.8
Pea	Eureka	GRANUM seed farm, J. Manias, S. Menc, J. Szymański Sp. j., Wodzierady	12.1
Lupin	Emir	OLZNAS-CN Potato Breeding and Seed Production Center in Olsztyn	11.5
Faba bean	Nadwiślański	OLZNAS-CN Potato Breeding and Seed Production Center in Olsztyn	10.9

A survey sampling method (GREŃ 1984) was used to randomly select 120 seeds representing every tested species. In the analyzed seed samples, the standard error of the mean did not exceed:

– for three basic seed dimensions – 0.1 mm (0.2 mm for faba bean),

– for the angle of external friction – 0.4° for buckwheat, lupine and faba bean, 0.6° for vetch, 0.8° for pea,

– for seed weight – 2 mg for buckwheat and vetch, 8 mg for pea and lupine, 24 mg for faba bean.

The length and width of seeds were determined with the accuracy of 0.02 mm under the MWM 2325 laboratory microscope, and seed thickness was measured using a dial indicator device with measurement precision of 0.01 mm. The above measurements were performed in accordance with the methodology described by KALINIEWICZ et al. (2011).

Seeds were weighed on WAA 100/C/2 laboratory scales with the accuracy of 0.1 mg.

The measured parameters were used to determine the arithmetic D_a and geometric mean diameter D_g, aspect ratio R and sphericity index Φ (MOHSENIN 1986):

$$D_a = \frac{T + W + L}{3} \tag{1}$$

$$D_g = (T \cdot W \cdot L)^{\frac{1}{3}} \tag{2}$$

$$R = \frac{W}{L} \cdot 100 \tag{3}$$

$$\Phi = \frac{(T \cdot W \cdot L)^{\frac{1}{3}}}{L} \cdot 100 \tag{4}$$

A flat friction plate with an adjustable angle of inclination was used in the study, therefore the coefficient of static friction μ (both the coefficient of sliding friction μ_s for seeds sliding on the surface, and the coefficient of rolling resistance μ_t for seeds rolling on the surface) of seeds was calculated from a universally applied formula (GROCHOWICZ 1994, MOLENDA et al. 1995, KRAM 2006, YALÇIN et al. 2007, LAWROWSKI 2008, RAZAVI, FARAHMANDFAR 2008, RIYAHI et al. 2011, TARIGHI et al. 2011, DARVISHI 2012, NOSAL 2012, SOLOGUBIK et al. 2013):

$$\mu = \tan\alpha \tag{5}$$

The angles of external friction at which seed motion was initiated through sliding or rolling were determined for each seed on two types of friction surfaces: steel and rubber. Surface porosity was described by parameter R_a measured by the Hommel Tester T1000 device. The average value of R_a was 0.48 μm for steel and 0.79 μm for rubber. The device and the method for measuring the angle of external friction were described by KALINIEWICZ (2013b). Seeds were placed with their longitudinal axis parallel to the inclined plane. The angle of inclination was measured with the precision of 0.01°, and seed travel time – with the precision of 1 ms. Due to irregular seed shape and the momentary detachment of seeds from the friction surface, the time of travel was determined only for sliding seeds. Having passed labile equilibrium (FRĄCZEK 1999), seeds move on the friction surface in sliding motion, rolling motion or a combination of both. The analysis was performed only on seeds whose motion could be classified as typically sliding or rolling. For sliding seeds, the coefficient of kinetic friction was determined based on time t required for traveling the distance of $S = 140$ mm on a plane inclined at angle α_s (GROCHOWICZ 1994):

$$\mu_k = \tan\alpha_s - \frac{2S}{gt^2 \cos\alpha_s} \tag{6}$$

For rolling seeds, the coefficient of rolling friction f was calculated from the below equation (LAWROWSKI 2008, NOSAL 2012):

$$f = \mu_t \cdot r = r \cdot \tan\alpha_t \tag{7}$$

where r is the radius of a rolling seed. Based on the expected seed distribution on a given friction surface, it was assumed that radius represents the average half thickness and length of a given seed, and it equals:

$$r = \frac{T + L}{4} \tag{8}$$

The results were processed in the Statistica PL v. 10 application at the significance level of $\alpha = 0.05$. The differences in friction coefficients of the analyzed seed species on various friction surfaces were determined by ANOVA. The normality of each group was determined by the Shapiro-Wilk test, and the equality of variances was assessed with Levene's test. Where the null hypothesis of equal population means was rejected, multiple comparisons were performed post-hoc to examine the differences and identify homogenous groups with the use of Duncan's test. A correlation analysis was performed to determine the strength and direction of correlations between friction coefficients and physical parameters of seeds. The degrees of correlation were evaluated with the use of Pearson's correlation coefficients (RABIEJ 2012).

Results

The physical parameters of the analyzed seeds are presented in Table 2. The lowest width and thickness values were noted in buckwheat, and the highest – in faba bean. The latter species was also characterized by the highest average length. Vetch seeds were the shortest with average length of 4.4 mm. The seeds were also characterized by the smallest arithmetic and geometric mean diameter and the highest aspect ratio. The highest values of arithmetic and geometric mean diameter were noted in faba bean, and the highest sphericity index was reported in pea seeds. The lowest average values of the aspect ratio and sphericity index were observed in buckwheat seeds.

The coefficient of external friction was determined upon the initiation of seed motion. The percentage share of seeds sliding or rolling on a given friction surface is given in Figure 1. All buckwheat seeds were characterized by sliding motion on both tested surfaces. An analysis of seed motion on friction surfaces revealed that significantly more seeds were set into motion by rolling on a rubber surface than on a steel surface. Pea seeds were most susceptible to rolling (approximately 62% on steel and approximately 88% on rubber). The susceptibility of the remaining seed species was determined by the type of friction surface.

Table 2

Statistical parameters of physical attributes of seeds

Parameter	Seed species				
	buckwheat $x \pm SD$	vetch $x \pm SD$	pea $x \pm SD$	lupin $x \pm SD$	faba bean $x \pm SD$
m	24.9 ± 4.92	44.1 ± 9.38	249.2 ± 43.68	171.8 ± 30.47	478.2 ± 132.02
T	3.6 ± 0.25	3.3 ± 0.30	6.2 ± 0.45	5.2 ± 0.34	7.4 ± 0.72
W	4.1 ± 0.30	4.2 ± 0.29	7.0 ± 0.51	6.3 ± 0.44	8.5 ± 0.85
L	6.0 ± 0.53	4.4 ± 0.32	7.6 ± 0.48	7.5 ± 0.53	10.2 ± 1.12
D_a	4.6 ± 0.28	4.0 ± 0.27	7.0 ± 0.42	6.3 ± 0.38	8.7 ± 0.83
D_g	4.4 ± 0.27	3.9 ± 0.27	6.9 ± 0.42	6.3 ± 0.37	8.6 ± 0.82
R	69.0 ± 6.54	94.0 ± 3.73	92.4 ± 4.57	84.0 ± 4.43	84.2 ± 5.47
Φ	74.7 ± 4.83	88.9 ± 2.93	91.3 ± 2.76	83.3 ± 2.62	85.1 ± 3.81

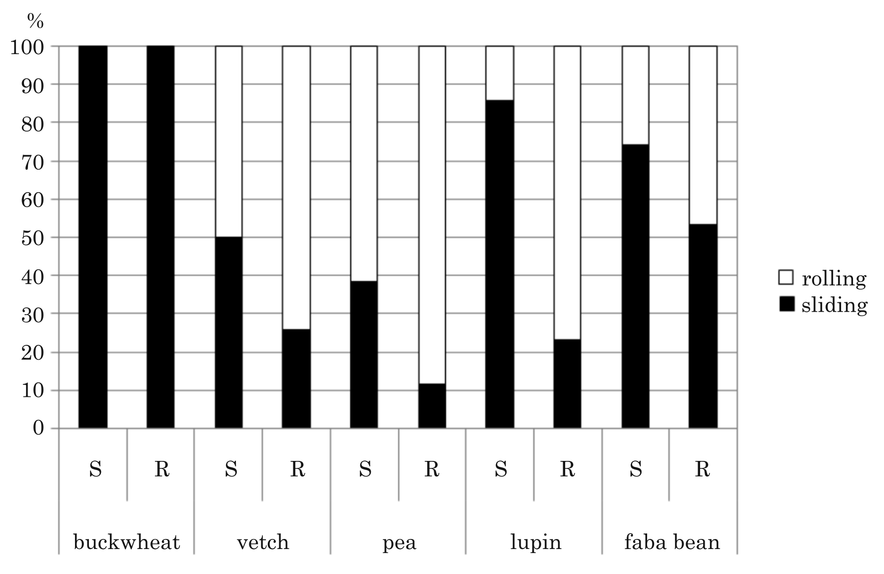

Fig. 1. Percentage share of seeds sliding or rolling on a given friction surface: S – steel, R – rubber

The coefficients of static friction (Table 3) of the analyzed seeds ranged from 0.187 (faba bean) to 0.426 (vetch) on steel, and from 0.267 (faba bean) to 0.582 (buckwheat) on rubber. Based on the average values of the coefficient of static friction on a steel surface, the analyzed species were sorted in the following rising sequence: faba bean (0.220), lupine (0.281), vetch (0.297), buckwheat (0.315) and pea (0.339). The average values of the coefficient of static friction on a rubber surface were determined in the range of 0.327 (faba bean) to 0.465 (buckwheat). No significant differences in the average values of the coefficient of static friction were observed between buckwheat and pea seeds or between vetch and lupine seeds. The greatest variations in the coefficient of rolling resistance on steel were reported for vetch (from 0.148 to 0.378). The studied seed species were arranged in the following rising sequence based on the average values of the coefficient of rolling resistance: faba bean (0.198), lupine (0.252), vetch (0.259) and pea (0.286). No significant differences in the average values of the coefficient of rolling resistance were noted between vetch and lupine. On a rubber surface, the coefficient of rolling resistance ranged from 0.170 (faba bean) to 0.529 (pea). Faba bean and pea were also

Table 3

Statistical distribution of the coefficients of static friction and the coefficients of rolling resistance of the analyzed seeds

Seed species	Coefficient of friction	x_{min}	x_{max}	x	SD
Buckwheat	μ_{s1}	0.218	0.419	0.315^{Da}	0.041
	μ_{s2}	0.375	0.582	0.465^{Cb}	0.042
Vetch	μ_{s1}	0.228	0.426	0.297^{Ca}	0.042
	μ_{s2}	0.314	0.459	0.381^{Bb}	0.036
	μ_{t1}	0.148	0.378	0.259^{Ba}	0.048
	μ_{t2}	0.178	0.482	0.312^{Bb}	0.061
Pea	μ_{s1}	0.286	0.418	0.339^{Ea}	0.031
	μ_{s2}	0.372	0.559	0.460^{Cb}	0.053
	μ_{t1}	0.183	0.369	0.286^{Ca}	0.041
	μ_{t2}	0.182	0.529	0.353^{Cb}	0.077
Lupin	μ_{s1}	0.227	0.364	0.281^{Ba}	0.028
	μ_{s2}	0.333	0.455	0.386^{Bb}	0.030
	μ_{t1}	0.199	0.305	0.252^{Ba}	0.026
	μ_{t2}	0.255	0.434	0.344^{Cb}	0.037
Faba bean	μ_{s1}	0.187	0.358	0.220^{Aa}	0.025
	μ_{s2}	0.267	0.385	0.327^{Ab}	0.032
	μ_{t1}	0.155	0.242	0.198^{Aa}	0.018
	μ_{t2}	0.170	0.376	0.277^{Ab}	0.042

A, *B*, *C*, *D*, *E* – different letters in the superscript represent statistically significant differences between seeds of different species

a, *b* – different letters in the superscript represent statistically significant differences between friction surfaces characterized by the lowest and highest average values of the coefficient of rolling resistance at 0.277 and 0.353, respectively. Similar average values of the above coefficient were reported for pea and lupine. In a comparison of the coefficient of external friction, significant differences in average object values were observed for the analyzed friction surfaces as well as for sliding and rolling motion of every seed species. Lower values of the coefficient of external friction were reported for the steel surface and rolling motion.

Similarly to the coefficient of static friction, lower values of the coefficient of kinetic friction were reported on a steel surface (Table 4). The lowest values of the coefficient of kinetic friction were determined for faba bean on both tested surfaces. The highest average value of the above coefficient was observed for pea (steel) and buckwheat (rubber). No significant differences in the average values of the coefficient of kinetic friction were reported between vetch and lupine on both friction surfaces.

The coefficient of rolling friction ranged from 0.29 mm (vetch) to 1.34 mm (pea) on a steel surface, and from 0.33 mm (vetch) to 1.80 mm (pea and lupine)

Table 4
Statistical distribution of the coefficients of kinetic friction and the coefficients of rolling friction of the analyzed seeds

Seed species	Coefficient of friction	x_{min}	x_{max}	x	SD
Buckwheat	μ_{k1}	0.164	0.314	0.233^{Ca}	0.033
	μ_{k2}	0.213	0.479	0.346^{Db}	0.049
Vetch	μ_{k1}	0.140	0.319	0.217^{Ba}	0.034
	μ_{k2}	0.198	0.344	0.262^{Bb}	0.032
	f_1	0.29	0.76	0.51^{Aa}	0.10
	f_2	0.33	0.97	0.60^{Ab}	0.13
Pea	μ_{k1}	0.185	0.336	0.262^{Da}	0.032
	μ_{k2}	0.134	0.368	0.286^{Cb}	0.071
	f_1	0.63	1.34	0.99^{Da}	0.14
	f_2	0.68	1.80	1.22^{Cb}	0.26
Lupin	μ_{k1}	0.156	0.286	0.220^{Ba}	0.024
	μ_{k2}	0.187	0.355	0.264^{Bb}	0.038
	f_1	0.56	0.96	0.78^{Ba}	0.10
	f_2	0.78	1.42	1.09^{Bb}	0.15
Faba bean	μ_{k1}	0.145	0.234	0.198^{Aa}	0.014
	μ_{k2}	0.148	0.284	0.221^{Ab}	0.028
	f_1	0.64	1.09	0.85^{Ca}	0.11
	f_2	0.73	1.80	1.21^{Cb}	0.22

A, *B*, *C*, *D* – different letters in the superscript represent statistically significant differences between seeds of different species
a, *b* – different letters in the superscript represent statistically significant differences between friction surfaces

on a rubber surface. Statistically equal average values were noted only for pea and faba bean seeds moving on a rubber surface.

An analysis of the data presented in Table 5 suggests that the analyzed physical attributes (weight, dimensions and the calculated indicators) were weakly correlated with friction coefficients. The smallest number of significant correlations with friction coefficients was noted for the coefficient of proportionality (5 out of 36 comparisons), and the highest – for seed weight (15 out of

Table 5

Pearson's coefficients of correlation between external friction coefficients and the remaining physical parameters of seeds

Seed species		m	T	W	L	D_a	D_g	R	Φ
Buckwheat	μ_{s1}	**-0.39**	-0.08	0.12	0.09	0.08	0.07	-0.02	-0.08
	μ_{s2}	**-0.22**	-0.04	0.03	**-0.19**	-0.12	-0.09	**0.21**	0.17
	μ_{k1}	**-0.21**	-0.02	0.05	**0.18**	0.13	0.10	-0.14	-0.16
	μ_{k2}	**-0.20**	0.06	0.17	**0.19**	**0.20**	**0.19**	-0.06	-0.10
Vetch	μ_{s1}	-0.15	-0.24	-0.10	-0.13	-0.17	-0.18	0.09	-0.08
	μ_{s2}	-0.14	-0.13	-0.16	-0.27	-0.21	-0.21	0.26	0.19
	μ_{k1}	**0.27**	0.15	0.25	**0.38**	**0.31**	**0.31**	**-0.27**	**-0.26**
	μ_{k2}	-0.21	**-0.41**	0.02	0.08	-0.09	-0.14	-0.12	**-0.48**
	μ_{t1}	-0.16	-0.19	-0.01	-0.09	-0.10	-0.11	0.15	-0.03
	μ_{t2}	-0.09	**-0.23**	0.06	0.15	-0.01	-0.03	-0.15	-0.42
	f_1	0.20	0.16	**0.30**	**0.27**	**0.26**	**0.26**	0.08	-0.06
	f_2	**0.24**	0.09	**0.34**	**0.45**	**0.33**	**0.31**	-0.21	**-0.37**
Pea	μ_{s1}	**-0.30**	**-0.31**	**-0.40**	**-0.39**	**-0.41**	**-0.40**	-0.14	-0.07
	μ_{s2}	-0.03	0.08	0.02	0.14	0.09	0.09	-0.14	-0.11
	μ_{k1}	-0.19	-0.23	**-0.36**	-0.27	**-0.32**	**-0.32**	-0.23	-0.13
	μ_{k2}	0.42	0.44	0.48	0.16	0.38	0.39	0.45	0.43
	μ_{t1}	**-0.26**	**-0.29**	**-0.29**	-0.16	**-0.27**	**-0.28**	-0.21	-0.23
	μ_{t2}	-0.16	**-0.31**	-0.16	-0.06	**-0.20**	**-0.21**	-0.17	**-0.31**
	f_1	0.12	0.08	0.01	0.22	0.11	0.11	**-0.27**	**-0.29**
	f_2	0.09	-0.07	0.04	**0.19**	0.06	0.05	-0.17	**-0.29**
Lupin	μ_{s1}	-0.17	**-0.32**	-0.10	-0.05	-0.16	-0.18	-0.07	**-0.25**
	μ_{s2}	-0.19	-0.16	-0.11	-0.10	-0.14	-0.14	0.01	-0.03
	μ_{k1}	**0.20**	**0.20**	0.14	0.15	0.18	0.19	-0.01	0.05
	μ_{k2}	-0.31	-0.19	-0.33	-0.24	-0.30	-0.30	-0.11	-0.04
	μ_{t1}	0.36	0.07	**0.50**	0.43	0.42	0.41	0.19	-0.17
	μ_{t2}	0.16	-0.09	0.09	0.34	0.16	0.14	**-0.32**	**-0.60**
	f_1	**0.71**	0.46	**0.67**	**0.77**	**0.74**	**0.73**	0.05	-0.30
	f_2	**0.60**	**0.38**	**0.44**	**0.74**	**0.60**	**0.58**	**-0.40**	**-0.64**
Faba bean	μ_{s1}	0.09	0.11	0.11	0.09	0.11	0.11	-0.01	-0.01
	μ_{s2}	**0.25**	0.21	0.13	**0.27**	0.22	0.22	-0.22	-0.17
	μ_{k1}	**0.33**	**0.32**	**0.32**	**0.30**	**0.34**	**0.34**	-0.03	-0.02
	μ_{k2}	-0.09	-0.13	-0.05	-0.07	-0.09	-0.09	0.03	-0.03
	μ_{t1}	-0.05	-0.12	-0.01	0.13	0.01	-0.01	-0.26	**-0.40**
	μ_{t2}	0.05	-0.12	0.15	0.13	0.07	0.06	0.04	-0.25
	f_1	**0.68**	**0.60**	**0.64**	**0.79**	**0.72**	**0.71**	-0.22	-0.30
	f_2	**0.56**	**0.39**	**0.61**	**0.62**	**0.58**	**0.57**	-0.11	**-0.39**

Bold font indicates that the correlation coefficient has exceeded critical value

36 comparisons). In the dimensions, frictional properties were most significantly correlated with seed length (14 out of 36 comparisons). The highest number of significant correlations with the remaining physical attributes was observed for the coefficient of rolling friction of lupine (8 out of 8 comparisons), faba beans (7 out of 8 comparisons) and vetch (6 out of 8 comparisons) on a rubber surface. The use of other, non-linear correlation models did not lead to a significant increase in the values of correlation coefficients, which indicates that the analyzed traits and the calculated coefficients had a minor influence on the seeds' frictional properties.

The coefficients of static and kinetic friction were significantly correlated in only 6 out of 30 cases (Table 6). A low number of significant correlations and the variability in the signs of correlation coefficients testify to an absence of correlations between the analyzed friction coefficients. The use of other correlation models did not lead to major improvement in the analyzed parameters either.

Table 6

Coefficients of linear correlation describing the relationship between coefficients of static and kinetic friction

Seed species		μ_{s2}	μ_{k1}	μ_{k2}
Buckwheat	μ_{s1}	0.129	0.053	**0.239**
	μ_{s2}	1	0.088	0.094
	μ_{k1}		1	**0.322**
Vetch	μ_{s1}	**0.605**	-0.250	0.202
	μ_{s2}	1	-0.191	-0.065
	μ_{k1}		1	0.244
Pea	μ_{s1}	-0.078	**0.360**	0.005
	μ_{s2}	1	0.021	-0.478
	μ_{k1}		11	-0.211
Lupin	μ_{s1}	0.123	**-0.383**	0.071
	μ_{s2}	1	0.057	-0.078
	μ_{k1}		1	-0.240
Faba bean	μ_{s1}	0.081	0.054	0.141
	μ_{s2}	1	-0.016	**-0.400**
	μ_{k1}		1	0.023

Bold font indicates that the correlation coefficient has exceeded critical value

In most comparisons, significant correlations were noted between the coefficients of rolling resistance and rolling friction (Table 7). The critical value of the linear correlation coefficient was not exceeded only in three cases, all of which involved the same seed species (faba bean), which implies that the analyzed correlation coefficients were not statistically significant at the adopted level of significance. The strongest correlations were observed between coefficients of rolling resistance and rolling friction of seeds moving on a given surface.

Table 7
Coefficients of linear correlation describing the relationship between coefficients of rolling resistance and rolling friction

Seed species		μ_{t2}	f_1	f_2
Vetch	μ_{t1}	**0.378**	**0.928**	**0.308**
	μ_{t2}	1	**0.372**	**0.940**
	f_1		1	**0.426**
Pea	μ_{t1}	**0.585**	**0.916**	**0.519**
	μ_{t2}	1	**0.545**	**0.960**
	f_1		1	**0.587**
Lupin	μ_{t1}	**0.659**	**0.904**	**0.659**
	μ_{t2}	1	**0.629**	**0.878**
	f_1		1	**0.793**
Faba bean	μ_{t1}	0.362	**0.693**	0.342
	μ_{t2}	1	0.269	**0.848**
	f_1		1	**0.612**

Bold font indicates that the correlation coefficient has exceeded critical value

Discussion

The lowest sphericity index value was reported for buckwheat seeds, and the highest – for pea, which suggests that the above seeds were least and most likely to resemble a sphere, respectively. The above was validated by the percentage share of seeds whose motion on a given surface was initiated by rolling (Figure 1). The only exception were lupine seeds on rubber, where approximately 77% of seeds rolled on a rubber surface (only 14% on a steel surface). The above could be due to similarities in the porosity of the rubber surface and the surface of lupine seeds. According to MOLENDA et al. (1995), ŚLIPEK et al. (1999) and HORABIK (2001), the greatest changes in the coefficient of external friction induced by adhesive bonding are observed when the irregularities in the height of the friction surface change within a range of values similar to the irregularities in the height of grain surface. This friction pair is characterized by a high coefficient of sliding friction, therefore, after overcoming inertia, seeds initiate their motion mainly by rolling.

The reported values of the coefficient of static friction of pea seeds are somewhat higher than those noted by YALÇIN et al. (2007) and similar to those given by ALTUNTAS and DEMIRTOLA (2007). KRAM (2008) reported similar values of the analyzed coefficient for lupine seeds cv. Radames and somewhat smaller values for lupine seeds cv. Bar on a steel surface. FIROUZI et al. (2012) reported similar average values of the coefficient of static friction of faba bean and SHOUGHY and AMER (2006) observed significantly higher average values (from 0.24 to 0.30) than those noted in this study. With regard to vetch seeds, YALÇIN and ÖZARSLAN (2004) reported somewhat lower values of the analyzed coefficient, whereas higher values were noted by TASER et al. (2005). The observed differences could be attributed to varietal differences as well as differences in growing conditions of the analyzed seed species. The observed differences in surface porosity across varieties can affect the values of the coefficient of friction (MOLENDA et al. 1995, FRĄCZEK 1999, HORABIK 2001). The variations in species-specific values of the coefficient of sliding friction can also be attributed to differences in the geometric structure of friction surfaces. The vast majority of published studies fail to characterize the applied friction surfaces (e.g. porosity parameters), therefore, their results are difficult to compare with our findings. The similarities in the values of the coefficient of static friction between the seeds evaluated in this study and other seed species are given in Table 8.

Tabela 8

Similarities in the values of coefficients of static friction between the analyzed seeds and other seed species

<table>
<tr><th>Seed species</th><th>Coefficient of static friction</th><th>Similar seed species</th></tr>
<tr><td>Buckwheat</td><td>$\mu_{s1}=0.315 \pm 0.041$
$\mu_{s2}=0.465 \pm 0.042$</td><td rowspan="2">triticale (KRAM 2006)
wheat (KRAM 2006, BOAC et al. 2010, KALINIEWICZ 2013b)
rye (KRAM 2006, KALINIEWICZ 2013b)
cowpea (KABAS et al. 2007)
barley (BOAC et al. 2010, KALINIEWICZ 2013b)
oats (BOAC et al. 2010, KALINIEWICZ 2013b)
castor (GHARIBZAHEDI et al. 2011)
sandbox (IDOWU et al. 2012)
hemp (TAHERI-GARAVAND et al. 2012)</td></tr>
<tr><td>Pea</td><td>$\mu_{s1}=0.339 \pm 0.031$
$\mu_{s2}=0.460 \pm 0.053$</td></tr>
<tr><td>Vetch</td><td>$\mu_{s1}=0.297 \pm 0.042$
$\mu_{s2}=0.381 \pm 0.036$</td><td rowspan="2">cowpea (YALÇIN 2007)
lentil (BAGHERPOUR et al. 2010)
canola (BOAC et al. 2010)
black grape (KILIÇKAN et al. 2010)
barley (SOLOGUBIK et al. 2013)</td></tr>
<tr><td>Lupin</td><td>$\mu_{s1}=0.281 \pm 0.028$
$\mu_{s2}=0.386 \pm 0.030$</td></tr>
<tr><td>Faba bean</td><td>$\mu_{s1}=0.220 \pm 0.025$
$\mu_{s2}=0.327 \pm 0.032$</td><td>melon (SHIESHAA et al. 2007)
soybean (KIBAR, ÖZTÜRK 2008)
Jatropha curcas (KARAJ, MÜLLER 2010)</td></tr>
</table>

The values of the coefficient of rolling resistance are always lower than the values of the coefficient of static friction of seeds whose motion is initiated by sliding, and smaller differences were observed on a steel surface. The differences in the values of the above coefficients ranged from 10% (faba bean) to approximately 16% (pea) on steel, and from approximately 11% (lupine) to approximately 23% (pea) on rubber.

The values of the coefficient of kinetic friction were similar for pea moving on a steel surface and significantly lower for pea moving on a rubber surface in comparison with those reported by ALTUNTAS and DEMIRTOLA (2007). SHAROBEEM (2007) observed significantly higher values of the kinetic friction coefficient for faba bean on both steel and rubber surfaces. The above can be attributed to the use of various friction surface materials and the resulting differences in their porosity. The results presented by KALINIEWICZ (2013b) indicate that lupine and wheat seeds have similar average values of the coefficient of kinetic friction on both friction surfaces. Therefore, it can be assumed that those seeds are characterized by similar surface porosity and microhardness. The similarities in the values of the coefficient of kinetic friction between faba bean and rye seeds and between lupine and barley seeds on a steel surface and between pea seeds vs. rye and barley seeds on a rubber surface are not easy to explain because the components of the molecular-mechanical model of friction, developed by KRAGIELSKI and discussed by MOLENDA et al. (1995), FRĄCZEK (1999), ŚLIPEK et al. (1999) and HORABIK (2001), were not measured. The above could be attributed to similar relations between state of friction surfaces, seed microhardness and the actual area of contact between the seed and the friction surface. The value of the coefficient of kinetic friction of faba bean moving on steel is also comparable to that reported for safflower seeds (KARA et al. 2012).

A comparison of the coefficients of static and kinetic friction of the analyzed seeds indicates that the latter parameter is always lower, and it accounts from 62% to 90% of the value of the static friction coefficient. The observed decrease in the value of the coefficient of kinetic friction relative to the coefficient of static friction could be explained by the rapid drop in friction force after macro-sliding, which was observed by FRĄCZEK (1999). The authors agree with Frączek that the above results from the system's inertia, which is why the force required to initiate motion is much greater than the force required for its continuation. In this study, greater differences were noted on a rubber surface in most cases (excluding buckwheat). The above could be attributed to somewhat higher porosity of the rubber surface relative to the steel surface as well as lower hardness of the rubber surface.

The dimensions, weight and shape factors of seeds did not significantly affect their coefficients of static and kinetic friction or their coefficients of rolling resistance and rolling friction. The above is due to considerable scatter of the analyzed traits, rather than inadequate selection of the evaluated dependencies, as illustrated by the example in Figure 2. For this reason, the search for more complex models of the analyzed relations is not justified. In a study of cereal grains, no correlations were observed between the physical attributes of seeds and their coefficients of static and kinetic friction

(KALINIEWICZ 2013b). An absence of correlations between frictional parameters and other physical attributes of seeds was also noted in studies investigating other types of seed material, including forest tree seeds (KALINIEWICZ, TROJANOWSKI 2011, KALINIEWICZ et al. 2011, KALINIEWICZ, POZNAŃSKI 2013).

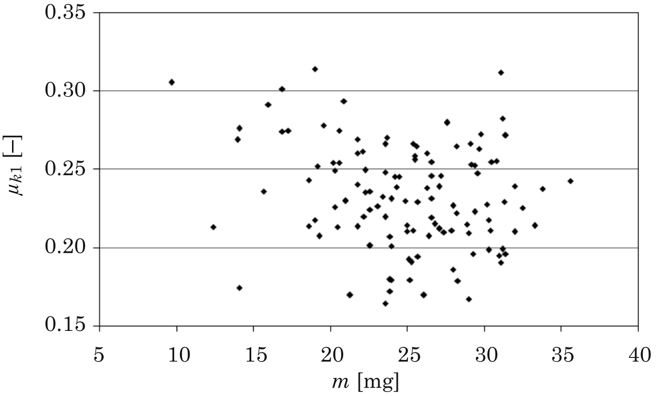

Fig. 2. Relationship between the weight of buckwheat seeds and their coefficient of kinetic friction on a steel friction surface

Significant correlations between the coefficients of static and kinetic friction of seeds moving on a steel surface were reported only for pea and faba beans. Similar correlations were noted in a study of cereal grains (KALINIEWICZ 2013b).

Summary

The analyzed seeds were characterized by a wide range of coefficients of static friction, from 0.187 (faba beans) to 0.426 (vetch) on a steel surface, and from 0.267 (faba beans) to 0.582 (buckwheat) on a rubber surface. Higher values of the analyzed coefficient on a rubber surface than on a steel surface can be explained by higher porosity and lower hardness of rubber.

Buckwheat seeds were the only seeds that moved on friction surfaces in sliding motion. Pea seeds were most susceptible to rolling. Approximately 62% of pea seeds on a steel surface and approximately 88% of pea seeds on a rubber surface initiated their motion by rolling. The values of the coefficient of rolling resistance were determined in the range of 0.148 (vetch seeds on steel) to 0.529 (pea seeds on rubber).

The coefficient of kinetic friction of seeds ranged from 0.140 (vetch) to 0.336 (pea) on a steel surface, and from 0.134 (pea) to 0.479 (buckwheat) on a rubber surface. The average value of the coefficient of kinetic friction was by around 10% to 38% lower than the average value of the coefficient of static friction for seeds of a given species. The coefficient of rolling friction of seeds ranged from 0.29 to 1.34 mm on steel, and from 0.33 to 1.80 mm on rubber.

A statistical analysis revealed that the above frictional parameters were weakly correlated with the dimensions, weight, arithmetic and geometric mean diameter, aspect ratio and sphericity index of the examined seeds. Frictional properties were most significantly correlated with seed weight, although the strength of the observed correlations was relatively low.

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