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Analysis of frictional properties of cereal seeds

Zdzisław Kaliniewicz

Department of Heavy Duty Machines and Research Methodology, University of Warmia and Mazury, Oczapowskiego 11/3A, 10-719 Olsztyn, Poland.

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The thickness, width, length and weight of cereal seeds (wheat, rye, barley, oats and triticale) and their external friction angles on three types of surfaces – steel, methyl polyacrylate and rubber – were determined. The experiment was performed with the use of a new device 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, sphericity index, specific weight, volume and density of seeds. The correlations between the analyzed parameters were evaluated by analysis of variance, correlation analysis and linear regression analysis. The dimensions, weight and the calculated indicators of the examined seeds did not affect their angles of friction or the coefficients of static and kinetic friction. The studied parameters were significantly influenced by the type of friction surface, and significantly lower average values were reported for the steel surface. An inversely proportional correlation between static and kinetic friction coefficients was also observed for the steel surface.

Key words: Physical attributes, coefficient of external friction, correlation.

INTRODUCTION

Friction is a set of phenomena observed at the point of contact between two materials. It leads to the loss of energy between moving objects and the wear of surfaces that come into contact, which increases surface temperature and can even produce acoustic effects (Grochowicz, 1994). The knowledge of frictional properties of plant material is essential for designing mechanical units in machines and for selecting harvesting, cleaning, sorting, storage and processing parameters (Altuntas and Demirtola, 2007; Horabik, 2001; Jouki and Khazaei, 2012; Kabas et al., 2007; Kram, 2008; Riyahi et al., 2011; Sologubik et al., 2013). The processes that occur between a particle and the friction surface are termed as external friction, whereas internal friction takes place between particles (Grochowicz, 1994).

An analysis of published sources (Afzalinia and Roberge, 2007; Altuntas and Demirtola, 2007; Horabik, 2001; Izli et al., 2009; Kalkan and Kara, 2011; Kram, 2006, 2008; Łukaszuk et al., 2009; Mohsenin, 1986; Sharobeem, 2007; Tarighi et al., 2011; Yalçin and Özarslan, 2004) indicates that the frictional parameters of plant materials are determined by species (variety), ripeness, moisture content, velocity, orientation relative to the direction of motion, structural material of the friction surface, surface roughness, normal pressure exerted on particles and variations in particle shape. External friction conditions can be expressed by the angle and the coefficient of static and kinetic friction. Various methods and devices are applied to measure to above parameters. In the simplest approach, an adjustable inclined plane and a friction plate are used. The angle of static friction is

E-mail: arne@uwm.edu.pl

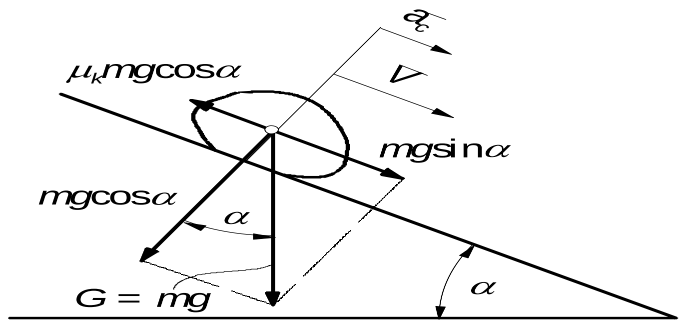

Figure 1. Forces acting upon a particle moving along an inclined plane.

measured by placing the analyzed material on a horizontally adjusted friction plate and by slowly increasing the angle of inclination until the seed begins to move (Grochowicz, 1994; Jouki and Khazaei, 2012; Kabas et al., 2007; Riyahi et al., 2011).

Frictional properties of granular material can also be determined with the use of Żeligowski's apparatus, Jenike shear tester, a device with an adjustable measuring lathe and a static container, devices with a rotating disc, a device with a moving roller inside a container filled with granular material and others (Afzalinia and Roberge, 2007; Altuntas and Demirtola, 2007; Grochowicz, 1994; Horabik, 2001; Ibrahim, 2008; Łukaszuk et al., 2009; Rusinek and Molenda, 2007; Sharobeem, 2007).

Friction is a complex phenomenon, and the angles and coefficients of friction given by researchers vary considerably, including for the same species and variety of seeds. Those variations can be attributed to the non-homogenous nature of granular material as well as different testing conditions (Grochowicz, 1994; Horabik, 2001). The available literature on the topic, reviewed for the purpose of this study, provides scant information about the kinetic friction coefficients of seeds. The influence of seed dimensions and weight on friction properties has not been investigated in detail. The relationships presented in the paper and the ranges of variation of friction parameters should be determined to aid the design and modeling of processes that rely on seed motion. The objective of this study was to determine the external friction coefficients of cereal seeds and to identify the correlations between those parameters and selected physical attributes of seeds.

THEORY

In experiments where the sample is placed on an adjustable inclined plane, the coefficient of static friction μ_s is determined with the use of the below formula:

$$\mu_s = \tan\alpha \qquad (1)$$

Distance S traveled by the particle in expected time t or time t required by the particle to travel distance S are measured to determine the coefficient of kinetic friction μ_k. If the particle travels in uniformly accelerated motion and air drag is negligibly small, the force causing sliding motion (Figure 1) is described by the following formula:

$$ma_c = mg(\sin\alpha - \mu_k\cos\alpha) \qquad (2)$$

If the particle's initial velocity equals zero, its acceleration can be calculated from the below formula:

$$a_c = \frac{2S}{t^2} \qquad (3)$$

Formula (3) was substituted into Equation (2), and particle weight was reduced and transformed to produce (Grochowicz, 1994):

$$\mu_k = \tan\alpha - \frac{2S}{gt^2\cos\alpha} \qquad (4)$$

MATERIALS AND METHODS

Sample preparation

The experimental material comprised seeds of principal cereals (wheat, rye, barley, oats and triticale) obtained from three sources: the Educational and Research Station in Tomaszkowo of the University of Warmia and Mazury in Olsztyn, the Potato Breeding and Seed Production Center in Olsztyn and a farm in Żuromin. The relative moisture content of seeds was determined at 11.4 to 13.2%, and it was appropriate for long-term storage (Kaleta and Górnicki, 2008; Rudziński, 2011). Relative moisture content was measured with the Radwag Max 5-/WH moisture analyzer equipped with a halogen heating element.

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 0.25 mm for the three basic seed dimensions, 1° for the angle of external friction and 2.5 mg for seed weight.

Physical properties

At the first stage of the study, the length and width of cereal seeds were determined under the MWM 2325 laboratory microscope with 0.02 mm readability (each parameter was determined based on two readings from the micrometer screw gauge accurate to 0.01 mm), and seed thickness was measured with a dial indicator device to the nearest 0.01 mm. The above measurements were performed in accordance with the methodology described by Kaliniewicz et al. (2011).

The angles of external friction were determined with the use of a device (Figure 2) equipped with two phototubes at the top and bottom of an adjustable arm. Friction plates made of ST3S steel (GPS – *Ra*=0.48 µm), methyl polyacrylate – plexiglass (GPS – *Ra*=0.22 µm) and EPDM synthetic rubber (GPS – *Ra*=0.79 µm) were fixed to the adjustable arm. The arm was connected to an electric motor by worm gear. Seeds were placed on a horizontally inclined plate just above the light level of the top phototube, the motor was activated, and the angle of inclination of the adjustable arm and the friction plate was increased. The angular velocity of a moving plate was $1.25°\cdot s^{-1}$. When particle motion was initiated, the plate was stopped, and it crossed the light beam produced by the photo-emitter. The stopper was activated simultaneously. Having traveled the distance of 14 cm (distance between top and bottom phototubes), the seed crossed the light beam produced by the bottom photo-emitter, the stopper was paused, and the time of seed travel between phototubes was read. The angle of inclination was measured with the precision of 0.01°, and seed travel time – with the precision of 1 ms. Seeds were placed with their longitudinal axis parallel to the inclined plane, which corresponds to the their position in a string sieve. Seeds were weighed on WAA 100/C/2 laboratory scales with the accuracy of 0.1 mg. At the second stage of the study, the measured parameters were used to determine the following seed indicators:

(i) Arithmetic D_a and geometric mean diameter D_g, aspect ratio R and sphericity index Φ (Mohsenin, 1986):

$$D_a = \frac{T + W + L}{3} \tag{5}$$

$$D_g = (T \cdot W \cdot L)^{1/3} \tag{6}$$

$$R = \frac{W}{L} \times 100 \tag{7}$$

$$\Phi = \frac{(T \cdot W \cdot L)^{1/3}}{L} \times 100 \tag{8}$$

(ii) Specific weight:

$$m_D = \frac{m}{D_g} \tag{9}$$

(iii) Volume (on the assumption that seed shape resembled an ellipsoid):

$$V = \frac{\pi \cdot T \cdot W \cdot L}{6} \tag{10}$$

(iv) Density:

$$\rho = \frac{m}{V} \tag{11}$$

The seeds' coefficients of external friction for every analyzed friction surface were determined with the use of Formulas (1) and (4).

Statistical analysis

The results were processed in the Statistica PL v. 10 application at a significance level of α=0.05. The differences in friction coefficients of the analyzed seed species on various friction surfaces were determined by one-way 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 mean values of friction coefficients 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, and Spearman's rank correlation was used to calculate the coefficients of static and kinetic friction. The correlations between the analyzed parameters were determined by linear regression analysis (Luszniewicz and Słaby, 2008; Rabiej, 2012).

RESULTS AND DISCUSSION

The physical parameters of the examined seeds are presented in Table 2. An analysis of the weight and volume of the studied kernels and a comparison with other cereal varieties (Cacak-Pietrzak et al., 2010; Chrząstek et al., 2010; Hebda and Micek, 2005, 2007; Kociuba et al., 2007; Markowski et al., 2013; Szwed-Urbaś and Segit, 2007; Zdybel et al., 2009) indicates that rye seeds were characterized by low plumpness, wheat, barley and triticale seeds – by average plumpness, and oat seeds – by high plumpness. The analyzed seed species were sorted in the following rising sequence based on their average density values: barley, oats, triticale, rye and wheat. The highest values of thickness and width were noted in barley, and the smallest – in rye seeds. Oat seeds were longest, and wheat seeds were shortest. When the dimensions of the analyzed grain were compared with those reported for other varieties (Boac et al., 2010; Hebda and Micek, 2005, 2007; Kalkan and Kara, 2011; Sadowska and Żabiński, 2009; Segit et al., 2003; Sologubik et al., 2013; Zdybel et al., 2009), the resulting correlations were similar to those noted in the analysis of seed weight. A comparison of the dimensions of wheat seeds of the same variety indicates that the material evaluated in this study was characterized by greater plumpness than that analyzed by Geodecki and Grundas (2003). The highest average values of all shape factors were reported for wheat, and the lowest – for oats. The values of arithmetic and geometric mean diameters, aspect ratio and sphericity index correspond to the data presented by other authors (Boac et al., 2010; Frączek and Wróbel, 2006; Kalkan and Kara, 2011; Kusińska et al., 2010; Markowski et al., 2013; Sadowska and Żabiński, 2009; Segit et al., 2003; Sologubik et al., 2013; Zdybel et al., 2009). The analyzed seed species were arranged in the following descending order based on their average specific weight: wheat, barley and triticale, oats and rye.

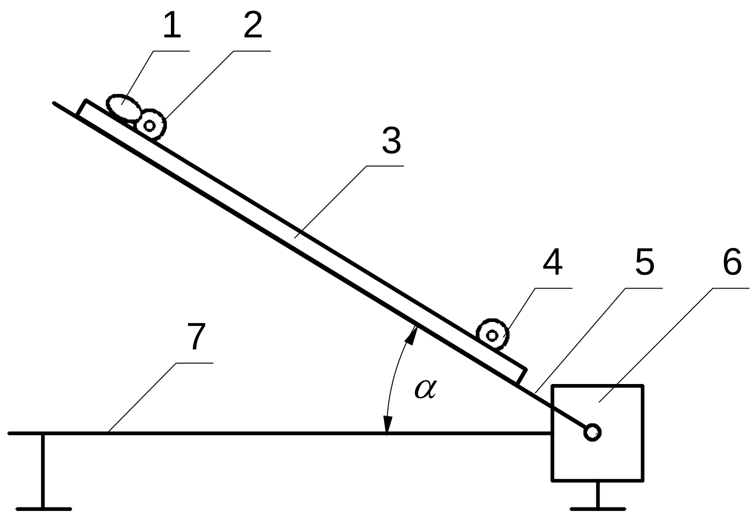

Figure 2. Device for measuring the angle of external friction: 1 – seed, 2 – top phototube, 3 – friction plate, 4 – bottom phototube, 5 – adjustable arm of inclined plane, 6 – power transmission (motor + worm gear), 7 – base of inclined plane.

Table 1. Experimental material.

Cereal species	Cereal variety	Producer	Relative moisture content [%]
Wheat	Nawra	Educational and Research Station in Tomaszkowo	12.8
Rye	Dańkowskie Diament	Educational and Research Station in Tomaszkowo	12.5
Barley	Skarb	OLZNAS-CN Potato Breeding and Seed Production Center in Olsztyn	12.6
Oats	Kasztan	Educational and Research Station in Tomaszkowo	11.4
Triticale	Atletico	Farm in Żuromin	13.2

When seeds were placed with their longitudinal axis parallel to the inclined plane, they always traveled in sliding motion. The smallest average angle of external friction was observed on a steel surface, and the highest – on rubber (rye, barley and oats) and methyl polyacrylate (wheat, triticale). No significant differences (Table 3) were observed between the average friction angle of wheat, rye and barley seeds on a steel surface, rye and oat seeds on a methyl polyacrylate surface and wheat, rye and oat seeds on a rubber surface. Significant differences were not reported between the average angle of external friction of rye and oat seeds on rubber and methyl polyacrylate surfaces. The friction angle of the analyzed cereal seeds (whose relative moisture content is given in Table 1) varied within the following range:

(i) On steel – from 13° to approximately 29°,
(ii) On methyl polyacrylate– from approximately 14° to approximately 37°,
(iii) On rubber– from approximately 19° to approximately 38°.

The above results indicate that cereal grains are set into motion when the angle of inclination of a steel surface exceeds 30° and the angle of inclination of methyl polyacrylate and rubber surfaces exceeds 40°.

Similar correlations were noted in an analysis of the coefficient of static friction (Table 4). Smaller differences in the values of friction coefficients of wheat, rye and barley seeds were noted on a steel surface, which enabled to create a homogenous group comprising seeds

Table 2. Statistical distribution of the physical parameters of seeds.

Parameter	Cereal species				
	Wheat ***X ± SD***	**Rye** ***X ± SD***	**Barley** ***X ± SD***	**Oats** ***X ± SD***	**Triticale** ***X ± SD***
m	44.4 ± 8.91	28.7 ± 6.94	45.3 ± 8.62	38.6 ± 8.02	40.0 ± 11.67
V	33.6 ± 6.58	25.3 ± 6.39	52.5 ± 9.62	44.0 ± 8.71	35.4 ± 9.71
ρ	1.3 ± 0.06	1.1 ± 0.10	0.9 ± 0.07	0.9 ± 0.09	1.1 ± 0.09
T	2.9 ± 0.21	2.4 ± 0.25	2.9 ± 0.22	2.6 ± 0.15	2.7 ± 0.33
W	3.3 ± 0.31	2.7 ± 0.28	3.8 ± 0.30	3.2 ± 0.25	3.2 ± 0.38
L	6.7 ± 0.39	7.5 ± 0.68	9.0 ± 0.65	10.4 ± 1.20	7.6 ± 0.60
α_1	17.1 ± 1.71	16.7 ± 2.37	17.3 ± 1.77	19.3 ± 3.00	20.6 ± 3.02
α_2	25.7 ± 3.03	23.5 ± 2.86	20.1 ± 2.95	23.5 ± 4.11	26.7 ± 4.03
α_3	23.7 ± 2.58	24.1 ± 2.18	27.0 ± 3.03	23.9 ± 2.31	28.6 ± 3.20
D_a	4.29 ± 0.26	4.18 ± 0.35	5.24 ± 0.33	5.36 ± 0.48	4.50 ± 0.39
D_g	3.99 ± 0.26	3.61 ± 0.31	4.63 ± 0.30	4.36 ± 0.31	4.04 ± 0.39
R	48.9 ± 3.76	35.4 ± 3.19	42.6 ± 3.06	30.6 ± 2.82	42.7 ± 3.98
Φ	59.2 ± 2.40	48.3 ± 2.61	51.3 ± 2.54	42.3 ± 2.71	53.4 ± 3.16
m_D	11.0 ± 1.53	7.8 ± 1.32	9.7 ± 1.35	8.8 ± 1.40	9.7 ± 2.06

Table 3. Statistical distribution of the external friction angles of seeds.

Cereal species	**Angle of external friction**	x_{min}	x_{max}	x	***SD***
Wheat	α_1	13.08	22.05	17.14^{ABa}	1.713
	α_2	19.91	35.48	25.74^{Cb}	3.027
	α_3	19.49	30.73	23.68^{Ac}	2.581
Rye	α_1	13.00	22.61	16.66^{Aa}	2.327
	α_2	16.76	30.86	23.53^{Bb}	2.863
	α_3	19.89	29.90	24.05^{Ab}	2.182
Barley	α_1	13.77	22.16	17.32^{Ba}	1.774
	α_2	14.89	28.78	20.12^{Ab}	2.950
	α_3	20.55	33.50	26.95^{Bc}	3.025
Oats	α_1	12.86	25.49	19.30^{Ca}	3.001
	α_2	14.07	32.84	23.45^{Bb}	4.108
	α_3	18.66	30.11	23.87^{Ab}	2.314
Triticale	α_1	14.79	28.78	20.58^{Da}	3.017
	α_2	18.28	36.57	26.67^{Db}	4.029
	α_3	23.04	37.54	28.61^{Cc}	3.201

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

of the above cereal species. The average coefficients of static friction were significantly higher on a rubber surface than on a steel surface. Similar results were reported in other studies (Haciseferoğullari et al., 2011; Izli et al., 2009; Jouki and Khazaei, 2012; Kabas et al., 2007; Razavi and Farahmandfar, 2008; Razavi and Milani,

Table 4. Statistical distribution of the external friction coefficients of seeds.

Cereal species	Coefficient of external friction	x_{min}	x_{max}	x	SD
Wheat	μ_{s1}	0.232	0.405	0.309^{Aa}	0.033
	μ_{s2}	0.362	0.713	0.484^{Cc}	0.067
	μ_{s3}	0.354	0.594	0.440^{Ab}	0.055
	μ_{k1}	0.132	0.280	0.220^{Ca}	0.029
	μ_{k2}	0.202	0.567	0.377^{Dc}	0.064
	μ_{k3}	0.148	0.366	0.263^{Bb}	0.050
Rye	μ_{s1}	0.231	0.416	0.300^{Aa}	0.045
	μ_{s2}	0.301	0.597	0.437^{Bb}	0.060
	μ_{s3}	0.362	0.575	0.447^{Ab}	0.046
	μ_{k1}	0.109	0.245	0.194^{Ba}	0.035
	μ_{k2}	0.157	0.452	0.308^{Bc}	0.064
	μ_{k3}	0.187	0.367	0.286^{CDb}	0.036
Barley	μ_{s1}	0.245	0.407	0.312^{Aa}	0.034
	μ_{s2}	0.266	0.549	0.368^{Ab}	0.059
	μ_{s3}	0.375	0.662	0.510^{Bc}	0.067
	μ_{k1}	0.121	0.296	0.225^{Ca}	0.034
	μ_{k2}	0.116	0.427	0.272^{Ab}	0.069
	μ_{k3}	0.190	0.438	0.293^{Dc}	0.056
Oats	μ_{s1}	0.228	0.477	0.351^{Ba}	0.059
	μ_{s2}	0.251	0.645	0.437^{Bb}	0.086
	μ_{s3}	0.338	0.580	0.443^{Ab}	0.049
	μ_{k1}	0.067	0.286	0.161^{Aa}	0.045
	μ_{k2}	0.123	0.515	0.330^{Cc}	0.086
	μ_{k3}	0.142	0.408	0.276^{BCb}	0.049
Triticale	μ_{s1}	0.264	0.549	0.377^{Ca}	0.061
	μ_{s2}	0.330	0.742	0.505^{Db}	0.090
	μ_{s3}	0.425	0.768	0.548^{Cc}	0.074
	μ_{k1}	0.048	0.326	0.188^{Ba}	0.058
	μ_{k2}	0.102	0.583	0.321^{BCc}	0.094
	μ_{k3}	0.105	0.437	0.240^{Ab}	0.067

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

2006; Riyahi et al., 2011; Taser et al., 2005; Yalçin and Özarslan, 2004). The cited authors did not indicate the surface roughness of the investigated friction materials,and for this reason, those results cannot be directly compared with the present findings. Significant variations in the average values of the static friction coefficient on different surfaces could be attributed to differences in the roughness and frictional properties of the analyzed materials. Similar correlations were noted by Horabik (2001). The variations in the values of the static friction coefficient of wheat, barley and oat seeds on a steel surface are similar to the range of values given by Boac et al. (2010). The analyzed species were classified in a rising sequence based on the average values of static friction coefficients on different friction surfaces:

(i) Steel: rye, wheat, barley, oats, triticale,
(ii) Methyl polyacrylate: barley, rye and oats, wheat, triticale,
(iii) Rubber: wheat, oats, rye, barley, triticale. In this study, the average values of the static friction coefficient were somewhat different from those reported by Kram (2006). In the cited study, the average values of the

analyzed parameters were both higher and lower than those observed in our experiment. The variations in the static friction coefficient of cereal seeds on steel, methyl polyacrylate and rubber were determined in the range of 0.23-0.48, 0.25-0.74 and 0.34-0.77, respectively.

A comparison of the average coefficients of kinetic and static friction indicates that the former parameter takes on significantly lower values. In all analyzed cereal species, the smallest differences between the analyzed coefficients were noted on methyl polyacrylate. On a steel surface, no significant differences between the average coefficients of kinetic friction were observed for the following pairs of grain species: rye and triticale, and wheat and barley. The highest average coefficient of kinetic friction on steel was reported for barley (0.23), and the lowest – for oats (0.16). The variations in the value of the friction coefficient were determined in the range of 0.05 to 0.33. On a methyl polyacrylate surface, statistically equivalent average values of the kinetic friction coefficient were observed for triticale and rye and for triticale and oats. The highest average value of the studied parameter was noted for wheat (0.38), and the lowest – for barley (0.27). The kinetic friction coefficient varied in the range of 0.10 to 0.58. No significant differences between the average coefficients of kinetic friction were observed on a rubber surface for wheat and oats, rye and oats, and rye and barley. On a rubber surface, the variations in the values of this parameter were determined in the range of 0.11 to 0.44, and the lowest average value was reported for triticale (0.24) and the highest – for barley (0.29). Significant differences in the coefficients of kinetic friction were noted between the analyzed surfaces, and the value of the tested coefficient was significantly lower on steel than on methyl polyacrylate and rubber. In the majority of the analyzed grain species, the average coefficient of kinetic friction was lower on rubber than on methyl polyacrylate (with the exception of barley) despite a reverse correlation in their roughness values. This phenomenon remains unexplained, but it could be attributed to the presence of static electricity on the plexiglass plate which could affect the value of the friction coefficient.

An analysis of the data presented in Table 5 suggests that the physical parameters of seeds (weight, volume, density, dimensions, arithmetic and geometric mean diameter, aspect ratio, sphericity index and specific weight) were not correlated with the coefficients of kinetic and static friction. The presence of significant correlations can probably be attributed to the ellipsoidal shape of seeds and seed rocking which prevented seeds from moving with uniform acceleration. An absence of correlations between the frictional parameters and other physical attributes of seeds was also noted in studies investigating different types of seed material, including forest tree seeds (Kaliniewicz and Poznański, 2013; Kaliniewicz et al., 2011).

The coefficients of static and kinetic friction of all seed species were significantly correlated only on a steel surface (Table 6). For this reason, regression equations were derived only for steel. The coefficient of kinetic friction decreased with an increase in the coefficient of static friction (Figure 3) in all grain species analyzed in this study, but the coefficient of determination varied widely from 0.43 for rye to 0.13 for oats.

Conclusions

The dimensions, weight, arithmetic and geometric mean diameter, aspect ratio, sphericity index, specific weight, volume and density of seeds did not affect their angles and the coefficients of static and kinetic friction.

Significant correlations were noted sporadically, and they could result from a relatively unstable position of ellipsoidal seeds on the tested friction plates, seed rocking during the initiation of motion and the movement of seeds along an inclined plane. The external friction angle for the studied cereal seeds varied in the range of 13° to approximately 29° on steel surface, approximately 14° to approximately 37° on methyl polyacrylate surface, and approximately 19° to approximately 38° on rubber surface.

The variations in the static friction coefficient of cereal seeds were determined in the range of 0.23-0.48 on steel, 0.25-0.74 on methyl polyacrylate and 0.34-0.77 on rubber. The coefficient of kinetic friction for the analyzed seeds varied in the range of 0.05 to 0.33 on a steel surface, 0.10 to 0.58 on a methyl polyacrylate surface, and 0.11 to 0.44 on a rubber surface. The values of the kinetic friction coefficient accounted for 44 to 78% of the values of the static friction coefficient.

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Symbols: D_a – arithmetic mean diameter, mm, D_g – geometric mean diameter, mm, m – seed weight, mg, m_D – specific seed weight, g·m^{-1}, R – aspect ratio, %, T, W, L – seed thickness, width and length, mm, V – seed volume, mm^3, x, SD – average value and standard deviation of trait, x_{min}, x_{max} – minimum and maximum value of trait, α_1, α_2, α_3 – angle of static friction of seeds on steel, methyl polyacrylate and rubber, respectively, °, μ_{k1}, μ_{k2}, μ_{k3} – coefficient of kinetic friction of seeds on steel, methyl polyacrylate and rubber, respectively, μ_{s1}, μ_{s2}, μ_{s3} – coefficient of static friction of seeds on steel,

Table 5. Pearson's coefficients of correlation between external friction coefficients and the remaining physical parameters of cereal seeds.

Cereal species	Parameter	Coefficient of external friction					
		μ_{s1}	μ_{s2}	μ_{s3}	μ_{k1}	μ_{k2}	μ_{k3}
Wheat	m	-0.08	-0.05	-0.13	-0.07	-0.05	-0.01
	V	-0.06	-0.03	-0.10	-0.10	-0.01	-0.03
	ρ	-0.10	-0.12	-0.15	0.13	-0.16	0.06
	T	-0.06	-0.10	-0.15	-0.05	0.01	0.01
	W	-0.06	-0.05	-0.06	-0.03	-0.04	-0.04
	L	-0.06	0.09	-0.07	-0.18	0.02	-0.03
	D_a	-0.06	-0.01	-0.10	-0.12	-0.01	-0.03
	D_g	-0.07	-0.03	-0.10	-0.09	-0.01	-0.03
	R	-0.03	-0.13	-0.03	0.09	-0.06	-0.03
	Φ	-0.02	-0.19*	-0.08	0.11	-0.04	-0.01
	m_D	-0.09	-0.06	-0.14	-0.05	-0.05	-0.01
Rye	m	-0.07	-0.12	-0.07	0.01	0.15	0.07
	V	-0.09	-0.08	-0.09	-0.01	0.16	0.10
	ρ	0.05	-0.11	0.13	0.04	-0.01	-0.06
	T	-0.12	-0.16	-0.09	0.04	0.05	0.08
	W	-0.10	-0.03	-0.16	-0.01	0.16	0.04
	L	0.01	-0.07	-0.09	-0.04	0.13	0.17
	D_a	-0.05	-0.09	-0.12	-0.02	0.14	0.14
	D_g	-0.09	-0.10	-0.13	0.01	0.13	0.11
	R	-0.13	0.02	-0.09	0.05	0.07	-0.12
	Φ	-0.15	-0.05	-0.05	0.08	-0.01	-0.11
	m_D	-0.06	-0.14	-0.06	0.01	0.13	0.06
Barley	m	-0.12	-0.43*	0.03	-0.08	-0.01	-0.04
	V	-0.17	-0.38*	0.01	-0.04	0.03	-0.03
	ρ	0.09	-0.12	0.04	-0.06	-0.06	-0.02
	T	-0.15	-0.48*	0.08	-0.03	0.01	0.01
	W	-0.22	-0.38*	0.04	-0.02	0.01	0.01
	L	-0.04	-0.10	-0.05	-0.04	0.11	-0.08
	D_a	-0.13	-0.29*	-0.01	-0.04	0.08	-0.05
	D_g	-0.16	-0.39*	0.03	-0.04	0.05	-0.03
	R	-0.19	-0.32*	0.10	0.02	-0.09	0.08
	Φ	-0.16	-0.36*	0.12	0.01	-0.09	0.07
	m_D	-0.10	-0.43*	0.05	-0.08	-0.01	-0.04
Oats	m	0.03	0.28*	-0.17	0.05	0.34*	-0.06
	V	0.14	0.42*	-0.13	0.03	0.41*	-0.07
	ρ	-0.17	-0.21*	-0.07	0.07	-0.08	-0.01
	T	-0.11	0.03	-0.11	0.16	0.02*	-0.09
	W	0.13	0.39*	-0.04	0.05	0.42*	-0.16
	L	0.21	0.47*	-0.16	-0.06	0.46*	0.01
	D_a	0.19	0.48*	-0.16	-0.02	0.46*	-0.04
	D_g	0.13	0.42*	-0.14	0.03	0.41*	-0.08
	R	-0.14	-0.26*	0.20	0.12	-0.20*	-0.16
	Φ	-0.24	-0.41*	0.17	0.15	-0.38*	-0.12
	m_D	-0.01	0.20*	-0.17	0.06	0.29*	-0.06
Triticale	m	0.02	-0.14	-0.04	0.02	0.12	-0.18
	V	-0.01	-0.17	-0.04	0.01	0.06	-0.14
	ρ	0.08	0.10	-0.01	0.05	0.27*	-0.19*

Table 5. Contd.

T	-0.06	-0.25*	-0.06	-0.01	0.07	-0.13
W	0.03	-0.10	0.02	0.04	0.12	-0.11
L	0.01	-0.08	-0.07	-0.03	-0.08	-0.11
D_a	-0.01	-0.15	-0.05	-0.01	0.02	-0.14
D_g	-0.01	-0.17	-0.04	0.01	0.06	-0.13
R	0.03	-0.06	0.09	0.09	0.22*	-0.05
Φ	-0.03	-0.17	0.03	0.05	0.20*	-0.07
m_D	0.02	-0.12	-0.04	0.02	0.14	-0.19*

*The correlation coefficient has exceeded critical value.

Table 6. Coefficients of correlation between the coefficients of static and kinetic friction.

Cereal species		μ_{s1}	μ_{s2}	μ_{s3}	μ_{k1}	μ_{k2}	μ_{k3}
Wheat	μ_{s1}	1	-0.070	0.232*	-0.472*	0.128	0.089
	μ_{s2}		1	0.072	-0.114	0.153	-0.064
	μ_{s3}			1	-0.170	0.024	-0.512*
	μ_{k1}				1	-0.079	0.132
	μ_{k2}					1	0.103
	μ_{k3}						1
Rye	μ_{s1}	1	-0.007	-0.047	-0.591*	-0.098	-0.112
	μ_{s2}		1	-0.069	0.075	0.162*	-0.108
	μ_{s3}			1	-0.036	0.005	-0.230*
	μ_{k1}				1	0.157	0.100
	μ_{k2}					1	-0.042
	μ_{k3}						1
Barley	μ_{s1}	1	0.168	0.053	-0.379*	0.245	-0.090
	μ_{s2}		1	-0.089	0.051	0.490*	0.104
	μ_{s3}			1	0.007	-0.151	-0.055
	μ_{k1}				1	-0.152	0.207*
	μ_{k2}					1	0.036
	μ_{k3}						1
Oats	μ_{s1}	1	0.235	0.194	-0.425*	0.224	0.098
	μ_{s2}		1	-0.074	-0.045	0.676*	0.043
	μ_{s3}			1	0.046	0.036	0.095
	μ_{k1}				1	0.118	0.004
	μ_{k2}					1	-0.020
	μ_{k3}						1
Triticale	μ_{s1}	1	0.093	0.224	-0.557*	0.040	-0.015
	μ_{s2}		1	0.183	0.065	-0.297*	-0.116
	μ_{s3}			1	0.079	0.062	-0.387*
	μ_{k1}				1	-0.015	0.037
	μ_{k2}					1	0.022
	μ_{k3}						1

*The correlation coefficient has exceeded critical value.

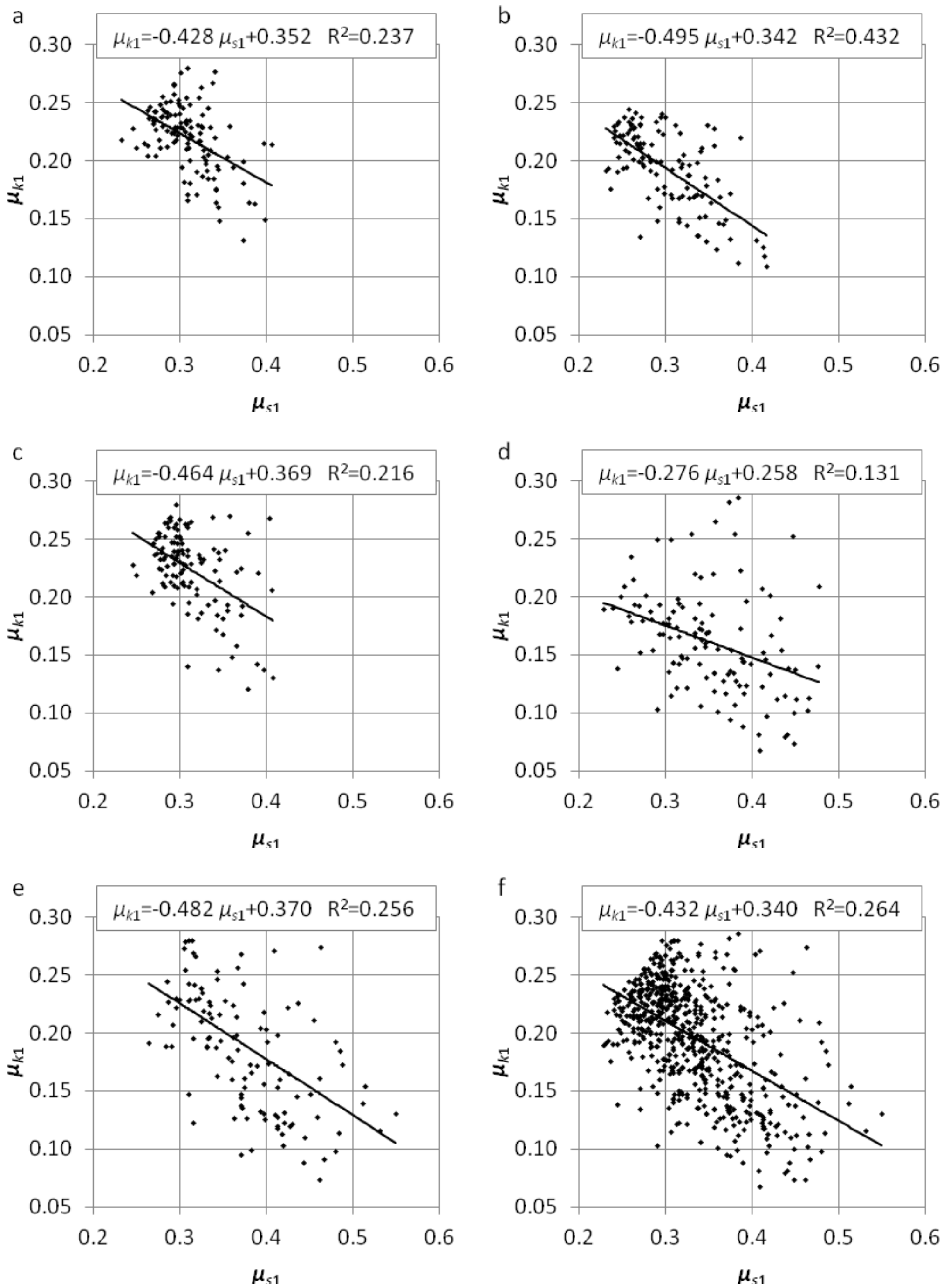

Figure 3. Correlations between the coefficients of kinetic and static friction on a steel surface: (a) wheat, (b) rye, (c) barley, (d) oats, (e) triticale, (f) all cereals.

methyl polyacrylate and rubber, respectively, ***ρ*** – seed density, g·cm^{-3}, ***Φ*** – sphericity index, %.

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