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THE INFLUENCE OF THE EXTERNAL SURFACE TOPOGRAPHY OF GRANULAR PLANT MATERIALS ON EXTERNAL FRICTION

WPŁYW TOPOGRAFII POWIERZCHNI ZEWNĘTRZNEJ ZŁOŻA ROŚLINNYCH MATERIAŁÓW ZIARNISTYCH NA SIŁĘ TARCIA ZEWNĘTRZNEGO

Key words:

external friction, granular material, 3D scanning

Słowa kluczowe:

tarcie zewnętrzne, materiał ziarnisty, skanowanie 3D

Abstract

The results of studies on external friction concerning granular plant materials that include, among others, grains, seeds of various plants, and powdered plant material, have been applied to the design of machines and devices for transport, sorting, cleaning, and blending. A separate and equally important matter is the storage of these materials in silos.

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The article presents the influence the surface topography of selected granular materials has upon the force of external friction. The research was performed with a specially designed adapter attached to the testing machine MTS, which is used to determine the external friction force of granular materials rubbing against various surfaces in a function of displacement. To define the topography of the external surface, a 3D scanner and specialized software were used. The authors have attempted to develop a model of friction taking into account the topography of the surface.

INTRODUCTION

Granular plant materials comprise, among others, conglomerations of grain crops, crushed fruits, seeds, and plants. They form a separate group that is counted among a broad class of bulk materials. Due to three distinctive factors, i.e. the existence of stiction, inelastic collisions, and virtually zero kinetic energy by comparison with gravitational potential energy, granular materials are often considered to constitute a separate state of matter **[L. 1]**.

The behaviour of this type of materials results from a variety of already known and still unrecognized relationships. Their number is so significant that obtained measurement results concerning the physical properties of granular plant materials show huge discrepancies **[L. 2]**.

Still, little is known about phenomena taking place between particles composing a conglomeration and a construction material. This refers especially to friction occurring at the contact surface, so-called external friction. Prediction of it is needed in many cases, especially when making calculations regarding transport and storage of granular plant materials.

Although various authors have conducted research on the process of friction, interaction models developed by them resemble real conditions only to a limited extent. Difficulties associated with predicting friction forces arise chiefly from the complexity of properties exhibited by plant materials (dependent largely on water content) with special emphasis on their anisotropy. Based on the results obtained from previous studies, the following factors should be considered major determinants of the friction process **[L. 1, 3]**:

- **Motion conditions** - the value of pressure, the duration of body contact, relative velocity of objects, temperature; and,
- **Properties of materials composing a friction pair** – water content in a plant material, the shape and spatial orientation of a single grain, material density, surface topography and roughness, actual contact area, the density of asperity vertices across the surface, the elastic modulus, and material hardness.

Despite the fact that friction is primarily affected by the parameters and size of contacting surfaces, this research relies largely on Amonton's laws of friction that do not take into account the contact surface.

Among others, Asli-Ardeh et al. **[L. 4]** studied the impact of moisture, velocity, and the type of rubbing surfaces (three types of construction material) on the coefficient of kinetic friction for three varieties of rice. The analysis results showed that, with the increase of grain moisture and the cylinder peripheral speed, the coefficient of kinetic friction increased from approx. 0.260 to 0.661. However, the authors did not propose any mathematical model, having their calculations limited to the analysis of variance.

Research on friction was also carried out, among others, by Alibas and Koksal **[L. 5]** who determined the static friction coefficient (by measuring the static friction angle) for different varieties of pepper cultivar seeds with the moisture content estimated at approx. 7%, which rubbed against various surfaces. The coefficient of friction varied from 0.554 to 1.205.

Subramanian and Viswanathan **[L. 6]**, in turn, determined the coefficient of static friction for millet grains, which ranged from 0.26 to 0.62.

Amin et al. **[L. 7]** distinguished static and kinetic coefficients of friction for grain legume seeds (chickpea, black-eyed pea, field pea, green gram, grass pea, and lentils) on different friction surfaces, such as smooth concrete, galvanized steel, cast iron, plywood, and glass sheet.

Frączek and Rule **[L. 8]** analysed the phenomenon of kinetic and static friction for shredded giant miscanthus sprouts. They observed that friction force was influenced by the humidity of sprouts, pressure force, and the type of construction material. It all led to the conclusion that humidity exerts a significant impact on the values of friction coefficients calculated according to *Coulomb friction* and Amonton's friction model for static and kinetic friction, respectively.

Given sample results clearly show that research on friction with respect to granular plant materials is conducted on various materials, with friction coefficients ranging widely in values. It should also be emphasized that the methods for measuring the friction force or friction angle are usually very simple, and the authors often do not discuss the accuracy of measurement.

External dry friction, which the mentioned research refers to, is a complex, heterogeneous process. Despite many attempts made, no general theory on this phenomenon has been developed so far, which should include a formula allowing one to determine the value of a friction coefficient, experimentally verifiable under any test conditions **[L. 9]**.

As it has been already mentioned, when doing research on dry friction with respect to plant materials, Amonton's friction model is most often followed (despite the fact that it seems not entirely accurate), which assumes that sliding bodies are perfectly rigid. In real conditions, however, under the influence of external load, asperities of bodies in contact undergo plastic deformation, which especially affects plant materials less resistant to such force. As a result, the actual contact surface and adhesive forces are increased. Therefore, this should be incorporated into calculations.

THE AIM AND RANGE OF RESEARCH

Amonton's law was expanded on by Coulomb who took into consideration the adhesion factor.

A more detailed theory about adhesion was formulated by Bowden and Tabor. It assumed that bodies brought into contact touch not at the nominal contact area, but at the real contact area. As a result of the applied load, surface asperities are deformed, which leads to the occurrence of so-called half-bridge circuits. Surface asperities are subject to deformation. The friction force, therefore, is necessary for breaking adhesive junctions.

Given the above, the presented study aimed at determining the influence the external surface topography has upon a granular plant material. Coulomb friction and Amonton's theory were compared to discover which of the models gives a more accurate prediction of a friction coefficient relating to selected granular plant materials. It was assumed that adhesion would depend on the top surface topography.

The real contact area is a certain portion of the area at which solids come into direct contact with each other. When it comes to granular mass, the real contact surface is considered to be the sum of discrete micro-contact areas, the magnitude of which makes up a fairly small fraction of the nominal contact surface **(Figure 1)**.

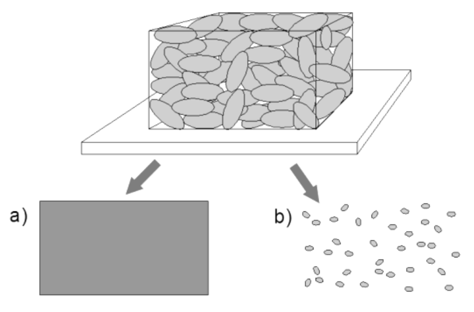


Fig. 1. The contact surface of granular material: a) nominal, b) real
Rys. 1. Powierzchnia styku materiału ziarnistego: a) nominalna, b) rzeczywista

A relation between the material ratio and corresponding height (a function of the material ratio) counts among a set of functional parameters that are derived from roughness parameters. In a 3D-representation, it is displayed as a cumulative expected value of coordinates (x, y, z) **[L. 10–13]**. For such a defined curve, further parameters can be calculated, including the following:

- Kernel roughness depth (roughness depth of the core) Sk, mm,
- Reduced peak height (roughness depth of the peaks) Spk, mm,
- Reduced valley depth (roughness depth of the valleys) Svk, mm,
- Upper **real material ratio** Smr1 (expressed as a percentage), and
- Lower **real material ratio** Smr2 (expressed as a percentage).

Their graphic representation is shown in **Figure 2**.

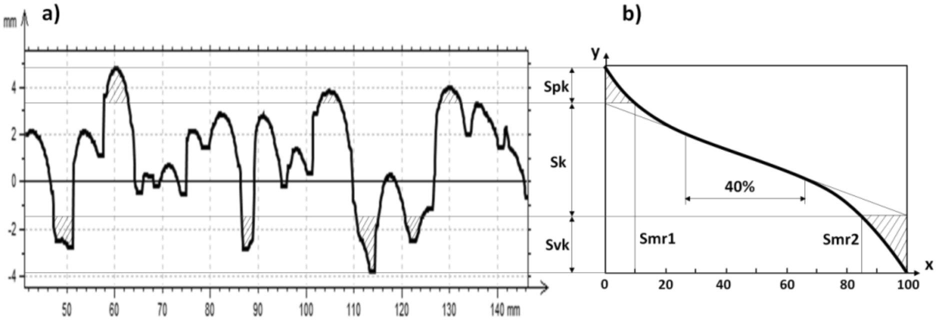


Fig. 2. Surface topography: a) surface profile, b) bearing ratio curve
Rys. 2. Topografia powierzchni: a) profil powierzchni, b) krzywa nośności

Having analysed the physical meaning of the above-mentioned parameters, a hypothesis was made that dry friction exerted on granular plant materials would be most influenced by the reduced peak height denoted by Spk. This parameter is defined as the mean height of the peaks protruding above the core roughness, thus implying the mean height of the upper part of the surface profile, which determines the behaviour of the surface geometric structure at short-term contact (usually occurring during the transport of grain).

The measurements of frictional forces were performed at low, constant humidity (approx. 7%). This ensured the occurrence of dry friction. As our own studies have shown, at increased humidity and high pressure, a liquid facilitating a slide emerges.

The measurements were carried out for three different materials: pea, wheat, and basket willow (woodchips and pellets made from it). Such a selection of materials provided an opportunity to conduct research on plants significantly different in terms of shape, morphology, and chemical composition.

MEASUREMENT METHODOLOGY

Measurements of frictional forces were performed with the use of MTS Insight 2 Material Testing Machine with a special adapter to accommodate testing needs **(Figure 3)**. As a rubbing surface, galvanized steel was employed (used, among others, in the pneumatic transport system intended for this type of raw materials). Due to the correct construction of the adapter and the ball bearings on which it rides, friction exerted on a surface by it was considered so insignificant that it was not taken into consideration. Frictional forces were measured at four values of pressure: at zero load and with 19.70 [N], 39.34 [N], and 59.04 [N] load cells. Load was the sum of the weight of a sample and a load cell. The speed of a slide was held at 0.06 $m \cdot s^{-1}$, while the length of the distance was 100 mm.

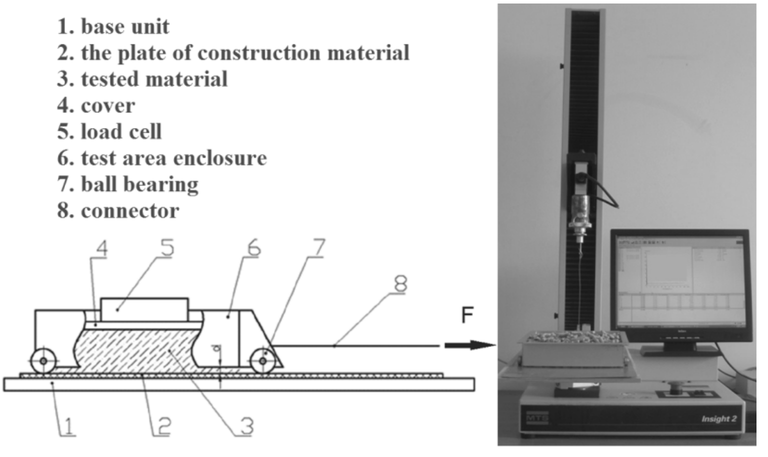


Fig. 3. Adapter for external friction measurement: a) scheme, b) the view of the measuring station

Rys. 3. Przystawka do pomiaru siły tarcia zewnętrznego: a) schemat, b) widok stanowiska pomiarowego

The change in the value of frictional forces was recorded at a frequency of 100 Hz, and the TestWork 4 software cooperating with the material testing machine produced a line chart visualizing a dependency relationship between this force and adapter displacement. A sample graph is shown in **Figure 4**. The maximum force (F_1) recorded during trials is the force of static friction, while the mean frictional force (F_{sr}) exerted at the measuring distance denoted by L is the force of kinetic friction.

In order to obtain the bearing ratio curve, the surface of the studied materials was digitized with the use of the 3D optical scanner Scan3D Universe 5Mpix LED by SMARTTTECH3D, using white LED light technology. Measurement uncertainty was calculated at 0.04 mm, which made it possible to obtain 164 points/mm^2 **(Fig. 5)**.

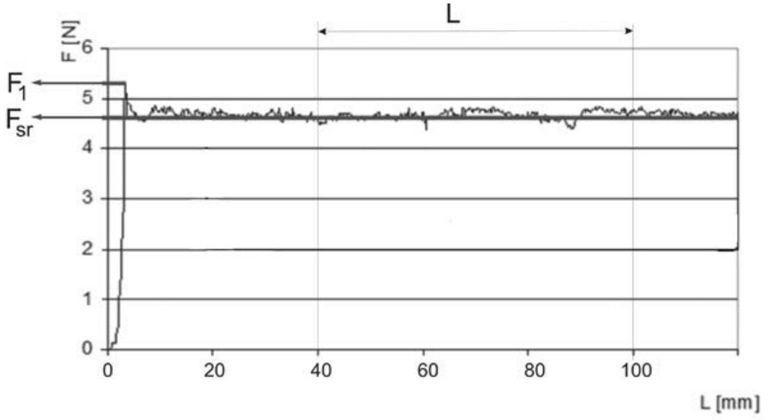


Fig. 4. External friction force versus adapter displacement: F_1 – Force of static friction; F_{sr} – Force of kinetic friction; L – Measuring distance of the kinetic friction force

Rys. 4. Zależność siły tarcia zewnętrznego od przemieszczenia: F_1 – siła tarcia statycznego; F_{sr} – siła tarcia kinetycznego; L – odległość pomiaru siły tarcia kinetycznego

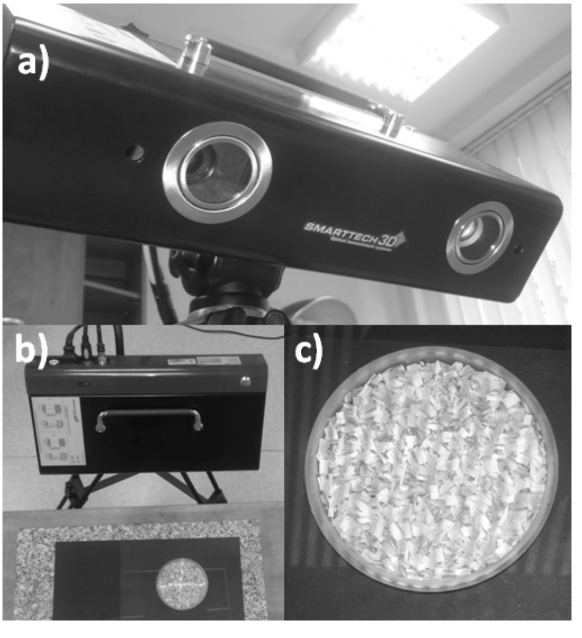


Fig. 5. The surface scanning: a) scanner Scan 3D Universe, b) measuring station, c) scanning process

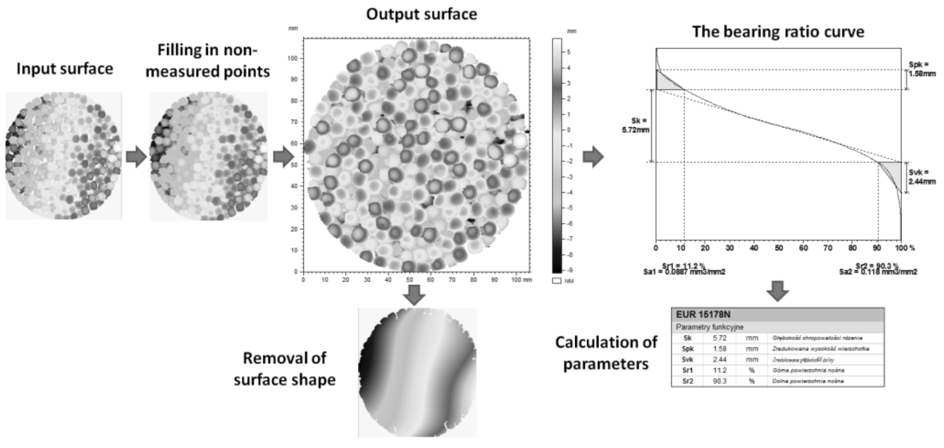
Rys. 5. Skanowanie powierzchni: a) skaner Scan 3D Universe, b) stanowisko pomiarowe, c) skanowanie

In order to record a maximum number of data points from the studied surface, scanning was made in all directions, and subsequently the obtained 3D images were fused together to form a single model. The measurements were repeated ten times.

For the purpose of performing analysis of the surface texture of the studied granular material, TalyMap 6.0 software was used. This made it possible to generate the bearing ratio curve and surface parameters listed in the previous section.

Since the tested materials were characterized by great surface variation, the images obtained from surface scanning exhibited a number of non-measured points found especially in cavities. Therefore, it was necessary to fill them in.

A heap of granular material is formed randomly, with its outer layer showing waviness. However, owing to the fact that it is subject to constant change, e.g., motion, its analysis seems to be unjustifiable. Additionally, the research focuses on a granular plant material sliding against the flat surface of a construction material. If the surface of granular material is to be referred to the surface of the cooperating body, a waviness indicator has to be removed from the measured surface. The diagram of the applied procedure is shown in **Fig. 6**.



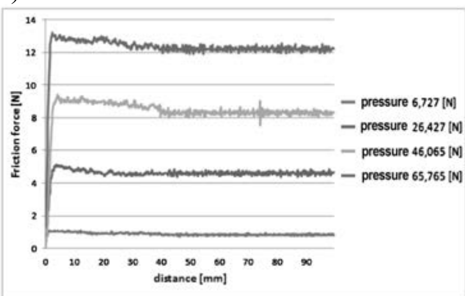
Input surface – filling in non-measured points – output surface – the bearing ratio curve – removal of surface shape – calculation of parameters

Fig. 6. The steps of the surface preparation and analysis with TalyMap 6.0
Rys. 6. Etapy przygotowania i analizy powierzchni w TalyMap 6.0

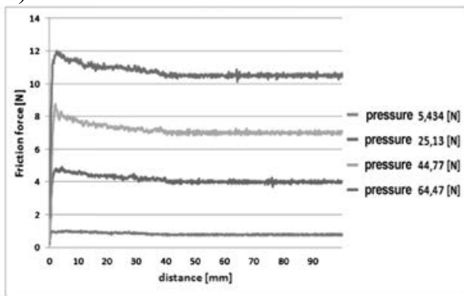
RESEARCH RESULTS

Sample results of tests performed on the studied materials are shown in **Figure 7**.

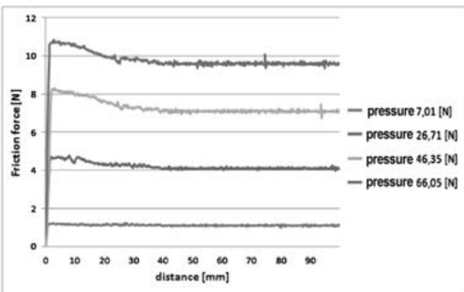
a)



b)



c)



d)

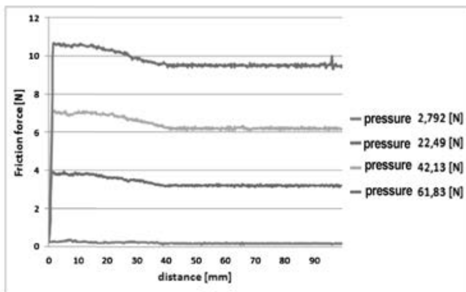


Fig. 7. The change in the force of friction at the time of measurement: a) peas, b) pellets, c) wheat, and d) woodchips

Rys. 7. Zmiana wartości siły tarcia w czasie pomiaru: a) grochu, b) pelety, c) pszenicy, d) zrębki

After taking measurements, the results were analysed with the use of data analysis software system StatSoft, Inc. (2014), STATISTICA, version 12. The estimation was carried out at the significance level $\alpha = 0.05$.

First, the friction coefficients were calculated from the Amonton's model:

$$T_{s(k)} = \mu_{s(k)} \cdot N \tag{1.1}$$

where: μ_s – static friction coefficient,
μ_k – kinetic friction coefficient,
N – normal force [N],
T_s – static friction force [N],
T_k – kinetic friction force [N].

The calculation results are displayed in **Table 1**.

Table 1. The values of the coefficient of friction according to the Amonton's model
Tabela 1. Wartości współczynnika tarcia. Model Amontonsa

Material	Friction coefficient	Standard error Std	Coefficient of determination R2	Statistical significance p value
STATIC FRICTION, model: $T = \mu_s N$ *[N]*				
Peas	0.215	0.0016	0.9978	0.0000
Pellets	0.190	0.0022	0.9944	0.0000
Wheat	0.176	0.0032	0.9835	0.0000
Woodchips	0.174	0.0012	0.9983	0.0000
Altogether	0.189	0.0026	0.9678	0.0000
KINETIC FRICTION, model: $T = \mu_k N$ *[N]*				
Peas	0.197	0.0010	0.9962	0.0000
Pellets	0.169	0.0011	0.9984	0.0000
Wheat	0.155	0.0020	0.9226	0.0000
Woodchips	0.148	0.0019	0.9950	0.0000
ALTOGETHER	0.166	0.0025	0.9628	0.0000

The calculations revealed a very high goodness of fit of the model to the results – the coefficient of determination, denoted R^2, ranged from 0.9226 to 0.9984. All the designated friction coefficients were statistically significant. The coefficient of static friction was greater than the kinetic friction coefficient by 9.13% to 11.75%. The lowest friction force was recorded for woodchips, the highest – for peas.

The research showed that the application of Amonton's model separately for each type of material had its justification in the high accuracy of the model. However, when trying to determine a universal friction coefficient (plant materials), the goodness of fit measure dropped dramatically. For kinetic friction, R^2 was decreased to 0.9628. This seemed to be justified, since the studied materials comprised various plant specimens.

Therefore, an attempt was made to try out the modified Coulomb model of friction. According to the assumptions, adhesive forces are dependent on the selected parameters of surface topography as follows:

$$T_{s(k)} = \mu_{s(k)} \cdot N + (S)^a \tag{1.2}$$

where: μ_s – static friction coefficient,
μ_k – kinetic friction coefficient,
N – normal force [N],
T_s – static friction force [N],
T_k – kinetic friction force [N],
S – surface topography parameters (Sk, Spk, Svk, Smr1, Smr2),
a – exponent.

The results of least square estimation at a 95.0% confidence level are displayed in **Tables 2a** and **2b**.

Table 2a. Coefficient of friction (modified Coulomb friction)
Tabela 2a. Współczynnik tarcia (zmodyfikowany model Coulomba)

Types of friction	Surface parameter	Coefficient of friction μ			Ratio of explained variation R^2
		value	Standard error S_{td}	Statistical significance p value	
Static	Sk	0.081	0.0223	0.0024	0.9786
	Spk	0.1606	0.0068	0	0.9978
	Svk	0.1387	0.0105	0	0.9948
	Sr1	0.0315	0.0296	0.3039	0.9661
	Sr2	0.4093	0.0931	0	0.4341
Kinetic	Sk	0.0577	0.0232	0.0251	0.9771
	Spk	0.138	0.0073	0	0.9975
	Svk	0.1159	0.0111	0	0.9943
	Sr1	0.0072	0.0308	0.8175	0.9625
	Sr2	0.3929	0.0957	0	0.4095

Table 2b. Exponent (modified Coulomb friction)
Tabela 2b. Wykładnik potęgowy (zmodyfikowany model Coulomba)

Types of friction	Surface parameter	Exponent a			Ratio of explained variation R^2
		value	Standard error S_{td}	Statistical significance p value	
Static	Sk	0.9793	0.0102	0	0.9786
	Spk	0.962	0.0034	0	0.9978
	Svk	0.9673	0.0051	0	0.9948
	Sr1	0.9896	0.0127	0	0.9661
	Sr2	-9.47	0	0	0.4341
Kinetic	Sk	0.9848	0.0103	0	0.9771
	Spk	0.9678	0.0035	0	0.9975
	Svk	0.9729	0.0052	0	0.9943
	Smr1	0.995	0.013	0	0.9625
	Smr2	-9.54	0	0	0.4095

The calculations indicated that, for both static and kinetic friction, a more precise friction prediction with respect to plant materials (the whole group) was produced by the Coulomb model, because a parameter depicting the contact area and determining adhesion, Spk (or Svk) should be used. The degree of correlation between predicted and actual values was fairly high and amounted to 0.9978 (0.9948) and 0.9975 (0.9943) for static and kinetic friction, respectively. This confirmed the working hypothesis that had been constructed initially.

It has to be emphasized that, if the proposed model is validated by further research, the parameter for the assessment of the contact area will enable indirect consideration of an array of factors relating to the geometry of granular material (the shape of a single grain and its spatial orientation, the actual contact area, the density of asperity vertices across the surface). This will allow for substantial simplification of analysis.

The presented study should be treated as preliminary, indicating directions for further research. There are plans to expand the research area upon such factors as water content in the plant material and motion parameters.

CONCLUSIONS

From the performed measurements and analysis of the obtained results, the following conclusions have been drawn:

1. The application of the Amonton's model for determining the coefficient of static and kinetic friction for each type of granular plant material is fully sufficient – it is appropriate due to the high accuracy of the model.
2. If a universal model of friction is to be put forward for plant granular materials, it is necessary to consider adhesive forces. In the current research, they were expressed by selected geometrical parameters of surface texturing.
3. The highest degree of correlation between the modified Coulomb friction and the measurement results was recorded for the Spk parameter denoting reduced peak height [mm].
4. Research should be extended by additional factors (material moisture, motion parameters).

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Streszczenie

Wyniki badań dotyczących tarcia zewnętrznego roślinnych materiałów ziarnistych, do których zalicza się m.in. ziarna zbóż, nasiona różnych roślin i rozdrobniony materiał roślinny, znalazły zastosowanie w zagadnieniach dotyczących projektowania maszyn i urządzeń do transportu, sortowania, czyszczenia oraz mieszania. Oddzielnym, równie ważnym zagadnieniem jest magazynowanie tych materiałów w silosach.

W artykule przedstawiono wpływ topografii powierzchni wybranych materiałów ziarnistych na siłę tarcia zewnętrznego. W badaniach wykorzystano specjalnie zaprojektowaną przystawkę pomiarową (do maszyny wytrzymałościowej MTS) służącą do wyznaczania siły tarcia zewnętrznego

materiałów ziarnistych trących o różne powierzchnie w funkcji przemieszczenia. Do określenia topografii powierzchni zewnętrznej złoża wykorzystano skaner 3D oraz specjalistyczne oprogramowanie. Autorzy podjęli próbę opracowania modelu tarcia uwzględniającego topografię powierzchni.