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RESEARCH ON THE CORRELATION BETWEEN THE POROSITY OF PLANT GRANULAR MATERIALS AND THE SELECTED PARAMETERS OF SURFACE TEXTURE

BADANIA NAD KORELACJĄ POROWATOŚCI SYPKICH MATERIAŁÓW ROŚLINNYCH Z WYBRANYMI PARAMETRAMI WARSTWY WIERZCHNIEJ

Key words:

3D scanning, surface roughness parameters, granular materials

Słowa kluczowe:

skanowanie 3D, topografia powierzchni, materiały sypkie

Abstract

The issues concerning porosity of granular materials, especially plant materials, are considered very important matters in respect of their transport, storage, precise dosing, and tribological properties. The classic method of measuring porosity requires specialized equipment and takes time, thus often being of

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little use in dynamic production processes. Therefore, there is a growing need for developing new methods for fast porosity measurement.

In the article, the authors present an attempt to define a correlation between the selected parameters of the surface texture of plant granular materials and their porosities. To digitize the surface, an optical 3D scanner and specialized software for analysis of the surface topography were used. The results should provide a basis for the development of innovative methods for measuring porosity based on digital image processing (DIA).

INTRODUCTION

Biological materials, in particular granular materials, constitute a form of matter that causes the greatest difficulties when it comes to a theoretical description of their physical properties and behaviour. A heterogeneous structure and susceptibility to changing environmental conditions (e.g., humidity) affect the results of measurements, making analysis quite difficult. Due to the fact that granular materials are used on a massive scale (either as final products or semi-products) in a number of manufacturing processes, investigation into their physical properties has become the focus of attention for numerous material scientists **[L. 1–4]**. This research is primarily driven by the desire for understanding the phenomena that is taking place during the course of many technological operations involving these materials. The gained information provides the foundation for the design of new processes or development of existing operations, equipment, machines, means of transport, storage methods, bulk packaging, etc. **[L. 5, 6, 8]**.

Another issue that concerns biological granular materials is the assessment of their basic quality parameters, such as the degree of fragmentation, the degree of specimen homogeneity, and porosity. These issues are discussed at length in many publications, among others **[L. 9–11]**.

The porosity of granular material determines the nature of contact between the granular material and the contact area (i.e. the way of grain packaging, the real contact surface of the granular material), thus affecting the tribological properties of the friction pair.

The knowledge of both presented areas makes up the core of the design and maintenance as well as laying the basis for proper and safe food production and the processing of plant materials intended for non-food purposes. Since these processes are dynamic and most often automated, the search for alternative and quick measuring methods of basic quality parameters has become a priority. The development and increased use of many applications related to 3D imaging, digital image processing (DIA), and data analysis has encouraged the authors to determine if there is any link between the basic parameters of the surface of granular material and its porosity.

POROSITY OF GRANULAR MATERIAL

The porosity of granular material is directly related to a measure of the void spaces between the particles of the material. The issues concerning the measurement of porosity and the change it undergoes over the course of processing (the coefficient of dynamic compaction) are vital to the design of different devices (e.g., conveyors) aimed for precise automated bulk solid dosing as well as packaging and storing of granular material.

While the prediction of the porosity of the materials exhibiting a regular, repeating shape (sphere, cylinder, etc.) **[L. 12]** can become a purely mathematical task concerning the size and distribution of the particles, for biological materials whose constituents often differ considerably within the same cluster; it is exceedingly difficult to create such an equation. Consequently, without the application of appropriate measuring methods, satisfactory results cannot be achieved. However, these methods often take a great deal of time; therefore, their application in industrial engineering might be discouraged. This problem has been already addressed by a multitude of authors **[L. 13]**.

Porosity can be defined as the following ratio:

$$\varepsilon = \frac{V_p}{V_m + V_p} = 1 - \frac{V_m}{V} \qquad 0 \le \varepsilon \le 1, \tag{1.1}$$

where: V_p – the volume of pores,
V_m – the volume of material,
V – total bulk volume.

The determination of an individual volume can be done in several different ways. Most often, an examined specimen is saturated with a given volume of fluid, the type of which depends on the tested material (mercury, oil, water). A volume of displaced liquid equals to the volume of the material.

Porosity can also be calculated from density as per the ratio below:

$$\varepsilon = 1 - \frac{V_m}{V} = 1 - \frac{\dfrac{m_m}{\rho_m}}{\dfrac{m_m}{\rho}} = 1 - \frac{\rho_m}{\rho} \qquad 0 \le \varepsilon \le 1, \tag{1.2}$$

where: m_m – material density,
ρ_m – particle density,
ρ – bulk density.

If granular material is immersed in the liquid of accurately known density, the mass of displaced liquid can be easily determined, and porosity can be written as the following equation:

$$\varepsilon = \frac{m - m_n - m_m}{V \rho_c} \qquad 0 \le \varepsilon \le 1, \tag{1.3}$$

where m_n – the mass of a container,
ρ_c – fluid density.

According to the above formulas, the methods for the determination of external porosity can be divided into displacement and immersion types.

THE AIM AND THE SCOPE OF THE STUDY

The measurements of surface geometric structure (SGS) constitute the principal source of knowledge about machining processes that the surface has been subjected to at the time of its formation (technological surface layer) as well as providing information on wear processes triggered by the operation of a technical device (operational surface layer) **[L. 14–16]**. Measuring techniques concerning SGS have been increasingly contributing to research on biological materials, undertaken in the field of agriculture and physics **[L. 17]**.

Taking into account that the surface texture of granular materials reveals some similarities to machined or worn surfaces with respect to surface geometric structure, and it can be successfully described with the use of roughness parameters.

Assuming that the porosity of granular material surface largely depends on the shape of an individual grain, which determines the shape of the material surface layer, a working hypothesis can be put forward that there must be a relationship between the surface texture and the actual void spaces in the tested material.

The aim of this study was to demonstrate the relationship between the selected parameters of roughness and the porosity of examined granular materials.

TEST METHODS AND THEIR RESULTS

The study was conducted for four biological granular materials exhibiting different geometry, i.e. peas, wheat, and basket willow pellets, basket willow woodchips. The material moisture was estimated at 7%. The step-by step set of operations performed is depicted in **Figure 1**.

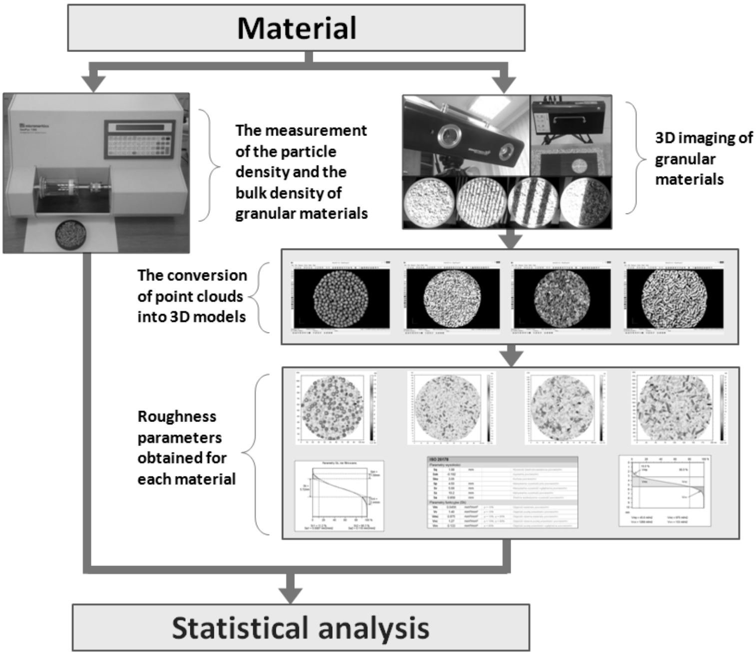

Fig. 1. Research plan
Rys. 1. Plan badań

The first step was to determine the porosity of the selected materials. A unique displacement technique was followed, making use of the examined porosity of individual granules and the bulk (envelope) porosity. These values were measured with the Envelope Density Analyzer GeoPyc 1360 **(Fig. 2)**, using a quasi-fluid pycnometer. The measurement procedures were repeated ten times for each specimen. The accumulated results were used to calculate the porosity of each material **(Table 1)**.

Fig. 2. Envelope Density Analyzer GeoPyc 1360
Rys. 2. Analizator gęstości GeoPyc 1360

Table 1. Average values of porosity for the selected materials
Tabela 1. Średnie wartości porowatości dla poszczególnych materiałów

Material	Particle density	Bulk density	Porosity	Standard deviation ε
	ρ_m $\left[\frac{g}{cm^3}\right]$	ρ $\left[\frac{g}{cm^3}\right]$	$\varepsilon = 1 - \frac{\rho_m}{\rho}$	
Peas	1.31	0.7298	0.7298	0.00085
Pellets	1.2	0.6434	0.4639	0.0057
Wheat	1.259	0.7088	0.437	0.0011
Woodchips	0.675	0.2157	0.6753	0.0035

The following step was to acquire 3D images of the surface layer of the examined materials. 3D surface imaging was made with the use of an optical white light 3D scanner (Scan3D Universe 5Mpix LED) with a measurement uncertainty of 0.04 mm, which allowed for collecting up to 164 points/mm^2 **(Figure 3)**. The scanner projects structured stripe patterns or any other raster images from the data projector **(Fig. 3c)**. The camera records the distorted pattern on the measured sample, based on which the geometry of the sample is reconstructed. The advantage of the applied technique is that the sample is measured across the entire field of view simultaneously. Therefore, the technique is said to be the fastest method for coordinate measuring.

The use of 3D scanning, however, poses a few problems. The accuracy of measurement depends primarily on the contrast ratio of the stripes to the measured sample. Therefore, the measurement of reflective surfaces, without

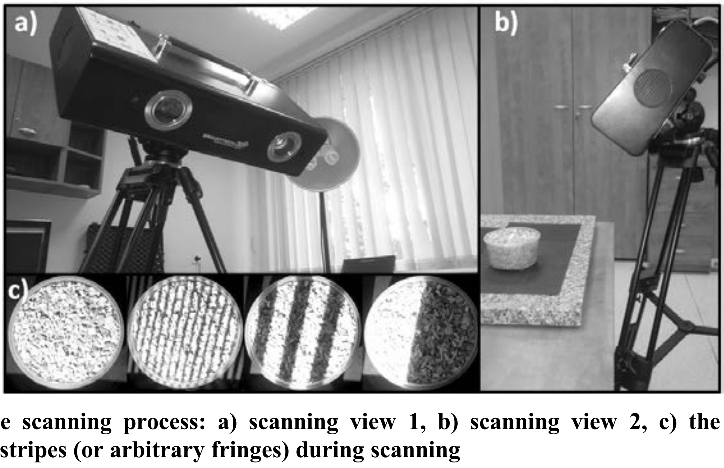

Fig. 3. The scanning process: a) scanning view 1, b) scanning view 2, c) the projection of stripes (or arbitrary fringes) during scanning
Rys. 3. Proces skanowania powierzchni: a) skanowanie widok 1, b) skanowanie widok 2, c) projekcja prążków podczas skanowania

the application of relevant anti-reflection coating, is virtually impossible. The materials that exhibit changeable surface texture and texture discontinuity cause major problems. Illumination is also of vital importance **[L. 18, 19]**.

The examined granular materials presented an enormous challenge due to their complex geometry, large discontinuity, and glass-like external layers (especially wheat). For these reasons, the determination of proper measurement parameters required a number of preliminary measurements to be taken. With a view of collecting a maximum number of data points, each specimen was scanned from four directions, and the acquired views of the surface were then converted into a single 3D model. An example of the scanned area is shown in **Figure 4**.

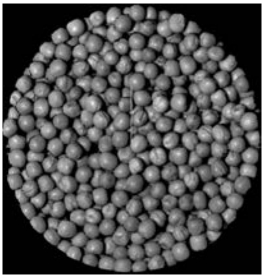

Fig. 4. Example of a 3D surface image (peas)
Rys. 4. Przykład obrazu powierzchni 3D (groch)

As a result of scanning, a series of 40 3D surfaces (10 for each type of material) were captured. These surfaces were loaded to the TalyMap 6.0 analysis software by means of which the non-measured points were filled in **(Fig. 5)** and the surface form was removed **(Fig. 5b)**. For such prepared data, a set of parameters describing surface topography was generated, and the average values are displayed in **Table 2**.

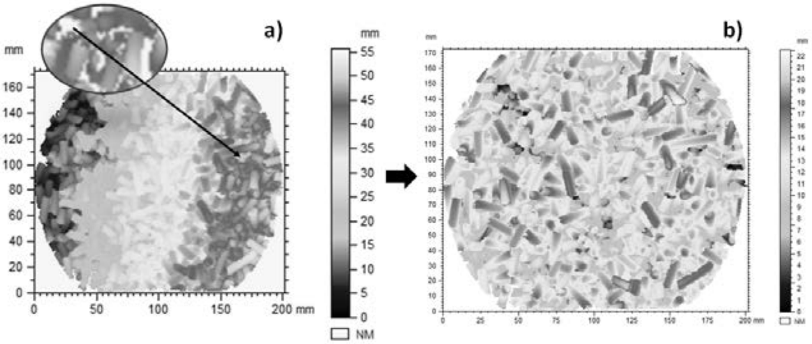

Fig. 5. An example of a loaded surface (Taylor Map 6.0): a) the fill-in of non-measured points, surface before form removal, and b) surface after form removal
Rys. 5. Przykład wczytanej powierzchni (TaylorMap 6.0): a) wypełnienie punktów niezmierzonych, powierzchnia przed usunięciem kształtu, b) powierzchnia po usunięciu kształtu

Table 2. Average values of the measured surface topography
Tabela 2. Średnie wartości parametrów topografii powierzchni zmierzonych

		Average values of parameters			
Parameter	**Unit**	**wheat**	**peas**	**pellets**	**woodchips**
Root mean square height of the surface Sq	mm	1.118	2.312	3.248	1.921
Skewness of the height distribution Sq	<no unit>	-0.217	-0.403	-0.296	-0.276
Kurtosis Sku	<no unit>	2.900	2.825	2.875	3.165
Maximum peak height Sp	mm	4.012	5.553	9.607	7.166
Maximum valley height Sv	mm	5.031	9.204	13.514	8.838
Maximum height Sz	mm	9.042	14.756	23.121	16.004
Arithmetical mean height Sa	mm	0.900	1.880	2.615	1.529
Material volume of the surface Vm	mm^3/mm^2 (p = 10%)	0.043	0.063	0.114	0.076
Void volume of the surface Vv	mm^3/mm^2 (p = 10%)	1.454	2.983	4.204	2.470
Core material volume of the scale limited surface Vmc	mm^3/mm^2 (p = 10%, q = 80%)	1.036	2.190	3.022	1.743
Core void volume of the scale limited surface Vvc	mm^3/mm^2 (p = 10%, q = 80%)	1.320	2.689	3.798	2.227
Valley void volume of the scale limited surface Vvv	mm^3/mm^2 (p = 80%)	0.134	0.294	0.406	0.243
Głębokość chropowatości rdzenia Sk Core Roughness Depth Sk	mm	2.918	6.351	8.775	4.649
Reduced peak height Spk	mm	0.852	1.212	2.239	1.468
Reduced valley depth Svk	mm	1.271	2.584	4.324	2.201
Upper bearing area Sr1	%	8.462	7.557	7.963	8.772
Lower bearing area Sr2	%	88.357	89.332	88.023	88.552

It should be noted that, for each parameter of surface texture, a relatively high repeatability of measuring results was observed. In most cases, the ratio of the arithmetic mean to standard deviation was close to 5%.

ANALYSIS OF RESULTS

The obtained results were subjected to statistical analysis, the aim of which was to find the relationship between the dependent variable, i.e. porosity, and the values of surface texture parameters recorded for each material **(Tab. 2)**. With this end in view, StatSoft, Inc. (2014) STATISTICA (data analysis software system), version 12, was used. All tests were performed at the significance level $\alpha = 0.05$.

First, the analysis of variance was performed, which allowed the rejection of non-significant results. For other parameters (Sp, Vv, Vvc, Sr1), non-linear approximation with a few different functions was performed, using the least squares method. It showed that only the maximum peak height Sp allows for the prediction of the value of material porosity with appropriate confidence. In other cases, the correlation between the model and the observed values indicated a low goodness of fit (0.5> R2) or model constants were statistically non-significant.

For the Sp parameter, two models with the highest goodness of fit were obtained (R2> 0.94): a logarithmic function (5.1) and a polynomial function of degree 3 (5.2).

Model 1

$$\varepsilon_1 = a \cdot (logSp)^b \tag{5.1}$$

Model 2

$$\varepsilon_2 = a \cdot Sp^3 + b \cdot Sp^2 + 4.3044 \tag{5.2}$$

The results of estimation are displayed in **Tab. 3**.

Table 3. The results of nonlinear estimation for Sp parameter
Tabela 3. Wyniki estymacji nieliniowej dla czynnika Sp

Model	Constants						Ratio of explained variation R^2
	a			b			
	value	standard error	statistical significance p value	value	standard error	statistical significance p value	
5.1	2.192	0.377	0.0283	-1.858	0.406	0.0447	0.944
5.2	0.358	0.0072	0.0004	-1.497	0.0214	0.0002	0.984

The construction of an explanation taking into account the physical aspect of the discovered relationship is difficult. The influence of Sp parameter does not seem so evident, although the statistical analysis has clearly pointed to it. Assuming that the porosity of granular materials affects the shape and the mutual distribution of the grains, the dependence of the porosity on the maximum peak height of the surface seems to be in question. However, it may be argued that the peak height of the surface might be related to the mutual arrangement of the particles, which, in case of elongated grains (e.g., pellets), may be an indicator of their more or less chaotic, multidirectional distribution. In authors' opinion, this correlation appears to be weak and requires further investigation.

CONCLUSIONS

The study has yielded very promising results. It has confirmed that there exists a relationship between surface roughness parameters (Sp) and the porosity of the examined materials. The highest goodness of fit was recorded for the polynomial function of degree three (R2 = 0.984). It should be noted, however, that this research is at a preliminary stage and needs further refinement as far as the measurement methodology of surface parameters with respect to the specimen preparation (including the scanning technique) and the measurement of porosity are concerned. This treatment should be aimed at developing standard methods ensuring enhanced repeatability and reproducibility in the measurement system. Analysis should also encompass other parameters of surface topography in terms of their relationship to the porosity. The determination of alternative parameters of surface texture, more accurately describing the shape and the distribution of grains, remains an open question.

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Streszczenie

Zagadnienia porowatości materiałów sypkich, w tym w szczególności materiałów roślinnych, są bardzo istotnym elementem związanym z ich transportem, przechowywaniem, precyzyjnym dozowaniem. Klasyczne metody pomiaru tej porowatości wymagają specjalistycznej aparatury i są czasochłonne, a zatem często są mało przydatne w dynamicznych procesach produkcyjnych. Istotne staje się więc opracowanie nowych metod szybkiego pomiaru porowatości.

W artykule autorzy przedstawiają próbę określenia korelacji wybranych parametrów warstwy wierzchniej złoża sypkich materiałów roślinnych z jego porowatością. Do akwizycji złoża wykorzystano skaner optyczny 3D oraz specjalistyczne oprogramowanie do analizy topografii powierzchni. Uzyskane wyniki powinny dać podstawę do opracowania innowacyjnej metody pomiaru porowatości opartej o Digital Image Analysis (DIA).