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The Influence of Water Content on Selected Physical Properties of Cereal Seeds to Improve the Precision of DEM Simulation

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ABSTRACT

This article presents the results of research on the influence of moisture on changes in selected physical properties, i.e. the length, width, thickness and weight of dressed and untreated cereal seeds in order to improve the simulation process based on the discrete element method (DEM). The research was conducted on the seeds of three winter cereals, i.e. triticale, rye, and barley. The seeds with an initial moisture content of about 7% were moistened to 5 levels, ranging from 9.5% to 17.5%, at an increment of 2%. The statistical analysis showed that moisture significantly influenced the physical properties of the seeds, i.e. their length, width, thickness, and weight. As the moisture content of the seeds increased, there were greater differences in their weight. The average increase in the thousand kernel weight resulting from the increase in their moisture content ranged from 4 to 6 mg. The change in the seed moisture content from 9.5% to 17.5% significantly increased the volume of rye seeds from 3.10% to 14.99%, the volume of triticale seeds from 1.00% to 13.40%, and the volume of barley seeds from 1.00% to 15.33%. These data can be used as a parameter to improve the DEM simulation process.

Keywords: moisture, cereal seeds, physical properties, DEM simulation, simulation parameters

Introduction

According to the data of the Central Statistical Office ¹, the average share of certified seeds in the total amount of cereal seeds used for sowing in Poland in 2020 amounted to only 17.7%. It was even lower, i.e. 15.4 %, when cereal mixtures were taken into account. These shares were also similar in 2018, when they amounted to 17.1% and 14.7%, respectively ². These data show that uncertified seeds stored directly on farms are sown in more than 80% of farmland in Poland. Globally, this is not an isolated case. According to Masyitah et al.³, unclassified seeds from previous harvests are used in more than 60% of the area of rice plantations in Indonesia.

Unclassified seeds from previous harvests are stored in flat (usually brick granaries) or vertical warehouses (metal silos), where they come into contact with the atmospheric air of different humidity, which depends on variable weather conditions. Research conducted in Spain ⁴ revealed a close dependence between air humidity and changes in the moisture content of seeds stored in *hórreos* (traditional grain storage buildings), which ensure natural ventilation. The researchers observed that when the relative air humidity exceeded 90%, the average humidity inside the warehouse buildings was 5.2% lower. If the relative air humidity was lower than 65%, the humidity inside the warehouse was 3.2% higher. The research showed that the geographical location, altitude, and exposure to wind influenced changes in relative humidity inside the grain warehouse⁴.

It is important to store healthy, dry, clean, and pest-free cereal grains. The moisture content is an important parameter affecting the quality of stored seeds. It is taken into account in grain quality standards⁵. Too high moisture content causes biochemical and microbiological changes in seeds, which

limit the time of their safe storage. In consequence, seeds warm up, become infested by fungal pathogens, mould, and other microorganisms. On the other hand, too low humidity may increase the susceptibility of seeds to mechanical damage and result in a loss^{6, 7}. Inappropriate storage conditions reduce the quality of seeds. As a result, they can neither be sown nor used as food or feed⁵. Contemporary storage of cereal grains involves a sequence of treatments protecting them from unfavourable processes lowering their quality. The drying and cooling of seeds enable their long-term storage⁸.

Numerous studies have shown that the physical properties of cereal grains depend mainly on their water content⁹ and change significantly with it^{10, 11}. It is necessary to know the physical properties of agricultural products to predict the quality of the raw material before, during and after processing. It helps to design technological processes and determine use-by dates¹²⁻¹⁴. The knowledge of changes in the physical properties of biomaterials caused by moisture is necessary to design technological lines for the sorting, cleaning, separation, transport, storage, processing and packaging of seeds. It is also necessary for engineers constructing sowing, planting, and cereal harvesting machinery¹⁵⁻²⁰.

Simulation methods such as the Finite Element Method (FEM) and Discrete Element Method (DEM) are increasingly often used to design machinery for sorting, cleaning, separation, transport, storage, processing, and packaging. The FEM is used both for strength tests²¹ and to test contacts between machine elements²². The DEM is used to simulate transport²³, milling²⁴, crushing, screening and many other processes involving granular material. Numerous studies have shown that the DEM is an effective tool simulating the behaviour of granular materials. The accuracy of the simulation largely depends on the contact models, the physical parameters of particles and the input parameters²⁵. There are no available scientific publications with the results of research on the influence of the moisture content in cereal grains on their dimensions, i.e. their length, width, thickness, and the shape factor. These physical parameters of seeds can be used as input data in the DEM simulation of specific technological processes (dosing, transport, milling, etc.). The water content in seeds stored on farms ranges very widely, from less than 10% to about 17-18%. Due to such high variability in the seed moisture content the authors of this study decided to investigate this issue.

The knowledge of the physical properties of the seeds of cereals and other crops can also be used to determine the efficiency of machines, assess the quality of end products, and to classify cultivars and distinguish between them²⁶. The geometric traits determining the dimensions and shape of seeds are an important group of physical properties of cereal raw materials^{27, 28}. It is important to know them when constructing machines and devices (e.g. for the pneumatic transport, sorting, hulling, and grinding of seeds) and selecting the parameters of their operation^{29, 30}.

The aim of the study was to determine the influence of the moisture content on the selected physical properties of grains of three winter cereals, i.e. triticale, rye, and barley in order to improve the simulation of seed dosage and transport in the sowing unit of a pneumatic seed drill and to select the simulation parameters based on the discrete element method (DEM).

Research methodology

The research was conducted on the seeds of three winter cereals, i.e. triticale (Gringo cultivar – Danko Company, Poland), rye (Agata cultivar – Danko Company, Poland), and barley (LG Veronika cultivar) – which come from the seed farm: Top Farms Nasiona, Runowo, Poland.

Both dressed and untreated seeds were used in the research. The seeds were wet-dressed with Syngenta³¹ Vibrance Gold fungicide in September 2019. Before the experiment the initial seed moisture content measured with a RADWAG MAX 50/WH moisture analyser was about 7%. Next, the moisture content in the samples was increased to levels of about 9.5%, 11.5%, 13.5%, 15.5%, and 17.5% by adding an appropriate amount of water M_w on the basis of the equation below (1)³²⁻³⁴:

$$M_w = \frac{W_2 - W_1}{100 - W_2} \cdot M_p \quad (1)$$

where:

M_w – the amount of water necessary to increase the moisture content, g;

M_p – the weight of the moistened sample, g;

W_1 – the initial moisture content of the sample, %;

W_2 – the assumed moisture content of the sample, %.

The moisture content was increased by adding an appropriate amount of water to samples weighing 20 g. Next, the samples were refrigerated for 24 hours at a temperature of 3-4°C. Then, 100 seeds of each cereal species were randomly selected from each moistened sample and their physical parameters were measured. The other seeds were used for measurements of the moisture content.

The physical properties of seeds were measured in accordance with the methodology described by Kaliniewicz et al.³⁵. The physical characteristics such as the length and width of the seeds were measured with an MWM 2325 workshop microscope with an accuracy of 0.02 mm. The thickness of the seeds was measured with an accuracy of 0.01 mm by means of a thickness gauge with a dial sensor. The weight of the seeds was measured with an accuracy of 0.1 mg by means of a RADWAG WAA 100/C/2 laboratory balance.

The following parameters were calculated on the basis of geometric measurements of the seeds:

- geometric equivalent diameter D_g (2), aspect ratio R (3) and sphericity index Φ (4)²⁷:

$$D_g = (T \cdot W \cdot L)^{\frac{1}{3}} \quad [mm] \quad (2)$$

$$R = \frac{W}{L} \cdot 100 \quad [\%] \quad (3)$$

$$\Phi = \frac{(T \cdot W \cdot L)^{\frac{1}{3}}}{L} \cdot 100 \quad [\%] \quad (4)$$

where:

T – seed thickness [mm],

W – seed width [mm],

L – seed length [mm].

m_D – unit weight (5)³⁶:

$$m_D = \frac{m}{D_g} \quad [g \cdot m^{-1}] \quad (5)$$

where:

m – seed weight [mg].

The following equation was used to calculate the volume of seeds V_g , whose shape resembles a rotational ellipsoid (6)³⁷:

$$V_g = \frac{\pi \cdot T \cdot W \cdot L}{6} \quad [mm^3] \quad (6)$$

The results of measurements and calculations were statistically processed with the Statistica program (version 13) at a significance level of 0.05, using the module of descriptive statistics and analysis of variance. The differences between the physical characteristics and the level of moisture were determined

by means of one-way analysis of variance (ANOVA). Statistically significant differences were determined with Duncan's test ^{38, 39}.

Results and discussion

Tables 1-3 show the results of measurements of the physical characteristics of the seeds of three types of winter cereals: triticale, barley, and rye, depending on their moisture content. The analysis of their dimensions showed that as their moisture content increased, so did their dimensions (length, width, and thickness) and weight. In extreme cases, the differences in the length between the winter triticale seeds with the highest and the lowest moisture content were as large as about 0.11 mm, or even 0.25 mm for dressed seeds. The width of the seeds decreased slightly as their moisture content increased, whereas their thickness increased slightly by 0.04-0.13 mm. The weight of the seeds also increased along with the increase in their moisture content. In extreme cases the thousand kernel weight increased from about 4 mg to 6 mg. As far as the seeds of the other two types of cereals are concerned, i.e. both untreated and dressed barley and rye seeds, their width and thickness increased along with the increase in their moisture content. The weight of the seeds also increased along with their moisture content. The differences in the nature of changes in the dimensions of winter triticale, barley and rye seeds may have been caused by differences between individual seeds in their ability to absorb water as well as differences in their chemical composition, morphological structure and the endosperm structure. The water absorption capacity of cereal seeds is important not only during their storage but also during their conditioning before milling. Flourish seeds absorb water faster than vitreous seeds, they are softer and do not require long maturing ^{40, 41}.

Additionally, in order to increase the legibility of the results of the significance of the differences between the values of physical traits and the weight of triticale, barley and rye seeds depending on their moisture content they were illustrated in graphs (Fig. 1-3).

Seeds	Moisture [%]	Length [mm]		Width [mm]		Thickness [mm]		Weight [mg]	
		<i>X</i>	<i>SD</i>	<i>X</i>	<i>SD</i>	<i>X</i>	<i>SD</i>	<i>X</i>	<i>SD</i>
Untreated	9.5	8.20 ^{a, b}	0.447	3.56 ^a	0.771	2.84 ^{a, b}	0.232	47.80 ^{b, c}	8.698
	11.5	8.07 ^b	0.622	3.45 ^a	0.638	2.77 ^b	0.272	46.59 ^c	10.458
	13.5	8.37 ^a	0.602	3.52 ^a	0.363	2.91 ^a	0.255	51.43 ^a	10.643
	15.5	8.30 ^a	0.646	3.49 ^a	0.434	2.87 ^a	0.254	49.89 ^{a, b}	11.338
	17.5	8.31 ^a	0.874	3.52 ^a	0.356	2.88 ^a	0.258	51.63 ^a	12.648
Dressed	9.5	7.33 ^{a, b}	0.640	3.35 ^b	0.335	2.93 ^a	0.255	43.16 ^a	9.428
	11.5	7.30 ^{a, b}	0.418	3.37 ^b	0.288	2.93 ^a	0.211	43.32 ^a	7.478
	13.5	7.23 ^a	0.744	3.24 ^a	0.442	2.89 ^a	0.238	40.88 ^a	9.166
	15.5	7.46 ^{b, c}	0.576	3.48 ^c	0.334	3.03 ^b	0.263	48.10 ^b	10.561
	17.5	7.58 ^c	0.657	3.53 ^c	0.303	3.06 ^b	0.260	49.07 ^b	9.619

X – mean value, *SD* – standard deviation, a, b, c – statistically significant differences at $\alpha = 0.05$

Table 1. The statistical parameters of the physical characteristics of winter triticale seeds

Figure 1. The physical parameters (mean value and standard deviation) of winter triticale seeds. Note: a, b, c – different letters indicate significant differences at $p < 0.05$ in the group of dressed and untreated seeds (Duncan's test).

Seeds	Moisture [%]	Length [mm]		Width [mm]		Thickness [mm]		Weight [mg]	
		X	SD	X	SD	X	SD	X	SD
Untreated	9.5	9.29 ^a	1.435	3.63 ^a	0.327	2.96 ^a	0.257	51.19 ^a	8.904
	11.5	9.71 ^b	1.215	3.66 ^a	0.294	2.96 ^a	0.208	50.47 ^a	7.151
	13.5	9.58 ^{a, b}	1.317	3.74 ^b	0.245	3.02 ^{a, b}	0.220	54.27 ^b	8.423
	15.5	9.28 ^a	0.976	3.77 ^b	0.272	3.04 ^{b, c}	0.262	55.10 ^b	8.886
	17.5	9.54 ^{a, b}	1.192	3.92 ^c	0.353	3.10 ^c	0.253	58.50 ^c	9.963
Dressed	9.5	9.10 ^b	0.991	3.65 ^a	0.349	2.78 ^a	0.181	48.53 ^a	6.687
	11.5	8.69 ^a	1.368	3.66 ^a	0.275	2.86 ^a	0.657	47.99 ^a	7.758
	13.5	9.07 ^b	0.770	3.80 ^b	0.606	2.79 ^a	0.204	49.15 ^a	8.074
	15.5	8.89 ^{a, b}	0.815	3.71 ^{a, b}	0.324	2.81 ^a	0.223	49.00 ^a	8.246
	17.5	8.96 ^{a, b}	0.665	3.72 ^{a, b}	0.279	2.79 ^a	0.204	49.44 ^a	8.683

X – mean value, SD – standard deviation, a, b, c – statistically significant differences at $\alpha = 0.05$

Table 2. The statistical parameters of the physical characteristics of winter barley seeds

Figure 2. The physical parameters (mean value and standard deviation) of winter barley seeds. Note: a, b, c – different letters indicate significant differences at $p < 0.05$ in the group of dressed and untreated seeds (Duncan's test).

Seeds	Moisture [%]	Length [mm]		Width [mm]		Thickness [mm]		Weight [mg]	
		X	SD	X	SD	X	SD	X	SD
Untreated	9.5	7.66 ^a	0.959	2.64 ^a	0.203	2.51 ^a	0.186	33.39 ^a	6.074
	11.5	7.81 ^{a, b}	0.481	2.72 ^b	0.267	2.53 ^{a, b}	0.175	33.15 ^a	5.637
	13.5	7.94 ^{b, c}	0.525	2.72 ^b	0.211	2.58 ^{b, c}	0.196	35.03 ^{a, b}	6.505
	15.5	7.82 ^{a, b}	0.537	2.66 ^a	0.239	2.51 ^a	0.212	33.88 ^a	7.378
	17.5	8.05 ^c	0.661	2.73 ^b	0.253	2.60 ^c	0.225	36.48 ^b	7.918
Dressed	9.5	8.02 ^b	0.549	2.75 ^{a, b}	0.256	2.56 ^b	0.215	35.99 ^b	7.142
	11.5	8.40 ^c	0.628	2.89 ^c	0.279	2.68 ^c	0.215	41.21 ^c	8.185
	13.5	7.67 ^a	0.912	2.65 ^a	0.288	2.48 ^a	0.249	32.74 ^a	8.330
	15.5	8.11 ^b	0.610	2.83 ^{b, c}	0.440	2.62 ^b	0.205	37.42 ^b	6.999

	17.5	7.93 ^b	0.737	2.67 ^a	0.324	2.48 ^a	0.263	33.46 ^a	9.653
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X – mean value, SD – standard deviation, a, b, c – statistically significant differences at $\alpha = 0.05$

Table 3. The statistical parameters of the physical characteristics of winter rye seeds

Figure 3. The physical parameters (mean value and standard deviation) of winter rye seeds. Note: a, b, c – different letters indicate significant differences at $p < 0.05$ in the group of dressed and untreated seeds (Duncan's test).

Table 4 shows the mean values of the geometric equivalent diameter D_g , the aspect ratio R and the sphericity ratio Φ , as well as the unit weight m_D calculated on the basis of measurements of the physical traits of the seeds of the species under analysis. The winter barley seeds with a moisture content of 17.5% were characterised by the highest mean value of the equivalent geometric diameter D_g and unit weight, whereas the lowest values of these parameters were noted in the dressed winter rye seeds with moisture content values of 13.5% and 11.5%. The barley seeds with a moisture content of 11.5% were characterised by the highest mean aspect ratio R . The highest mean value of the sphericity index Φ was noted in the dressed winter triticale seeds with a moisture content of 15.5%. The values of these coefficients, calculated on the basis of the dimensions of the seeds, are significant for various separation processes. They also characterise the shape of the seeds to a certain extent, and their numerical value can be used as a criterion for the selection of seeds. As can be read in scientific publications⁴²⁻⁴⁴, the values of the physical characteristics of seeds may vary even within one cultivar due to the significant influence of agrobiological conditions. The conditions of cultivation, climate, fertilisation and other treatments applied to crops affect the individual physical characteristics of seeds, mostly their average length, and to a lesser extent, their thickness and width⁴⁵. They are also important for the selection of appropriate characteristics when separating seeds during cleaning and sorting, and they help to determine the load of machines and devices used in cereal processing. Apart from that, each separation

process is different even if the same species is used as the base material, because there may be differences in the granulometric characteristics, moisture content, botanical composition, purity, and alignment of seeds.

Seeds	W_z [%]	D_g [mm]	R [%]	Φ [%]	m_D [g·m ⁻¹]
Untreated winter triticale	9.5	4.35 ^{a, b}	43.41 ^a	53.02 ^a	10.94 ^b
	11.5	4.25 ^b	42.83 ^a	52.70 ^a	10.85 ^b
	13.5	4.41 ^a	42.14 ^a	52.67 ^a	11.56 ^a
	15.5	4.36 ^a	42.14 ^a	52.58 ^a	11.33 ^{a, b}
	17.5	4.38 ^a	42.59 ^a	52.88 ^a	11.64 ^a
Dressed winter triticale	9.5	4.16 ^b	45.85 ^{a, b}	56.77 ^a	10.28 ^b
	11.5	4.16 ^b	46.24 ^{a, b}	56.99 ^a	10.36 ^b
	13.5	4.07 ^b	45.11 ^b	56.45 ^a	9.97 ^b
	15.5	4.28 ^a	46.61 ^a	57.41 ^a	11.12 ^a
	17.5	4.34 ^a	46.76 ^a	57.38 ^a	11.22 ^a
Untreated winter barley	9.5	4.63 ^c	40.29 ^{a, b}	50.69 ^a	11.02 ^b
	11.5	4.71 ^{b, c}	38.15 ^c	48.91 ^b	10.70 ^b
	13.5	4.76 ^b	39.59 ^{b, c}	50.13 ^{a, b}	11.36 ^a
	15.5	4.73 ^b	40.96 ^{a, b}	51.26 ^a	11.59 ^{a, b}
	17.5	4.87 ^a	41.57 ^a	51.43 ^a	11.96 ^a
Dressed winter barley	9.5	4.51 ^{a, b}	41.46 ^a	50.41 ^b	10.76 ^b
	11.5	4.46 ^b	51.12 ^a	55.56 ^a	10.89 ^b
	13.5	4.57 ^a	42.07 ^a	50.73 ^b	10.70 ^b
	15.5	4.52 ^{a, b}	42.00 ^a	51.02 ^b	10.79 ^a
	17.5	4.52 ^{a, b}	41.64 ^a	50.61 ^b	10.86 ^a
Untreated winter rye	9.5	3.69 ^c	36.28 ^a	49.38 ^a	9.04 ^{a, b}
	11.5	3.77 ^{a, b}	34.94 ^a	48.37 ^a	8.74 ^b
	13.5	3.82 ^a	34.33 ^a	48.15 ^a	9.10 ^{a, b}
	15.5	3.73 ^{b, c}	34.08 ^a	47.78 ^a	8.98 ^b
	17.5	3.85 ^a	33.99 ^a	47.86 ^a	9.39 ^a
Dressed winter rye	9.5	3.83 ^b	34.29 ^a	47.83 ^{a, b}	9.31 ^b
	11.5	4.02 ^a	34.46 ^a	47.90 ^{a, b}	10.18 ^a
	13.5	3.68 ^c	36.34 ^a	49.09 ^a	8.81 ^c

	15.5	3.91 ^b	34.97 ^a	48.27 ^{a, b}	9.51 ^b
	17.5	3.74 ^c	33.64 ^a	47.21 ^b	8.79 ^c

Table 4. The mean values of the indexes of the cereal seeds

Due to the ambiguous nature of changes in the physical characteristics of the triticale, barley, and rye seeds as well as the coefficients describing their shape depending on their moisture content, it was necessary to calculate their volume V_g . The results showed that although there were some differences in changes in the volume of the dressed and untreated seeds within the same species, the nature of these changes was generally similar – the volume of the seeds tended to increase along with their moisture content (rye – from 3.10% up to 14.99%, triticale – from 1.00% to 13.40%, barley – from 1.00% to 15.33%). The statistical analysis of changes in the volume of seeds showed that the change in the moisture content of the rye, triticale and barley seeds within 9.5-17.5% caused a significant increase in their volume (Fig. 4). This means that the seed volume can be used as a parameter to improve the DEM simulation process. This fact was confirmed in a study on the volumetric scaling of rice seeds with the discrete element method (DEM) ⁴⁶ and in a study where the volume-to-surface ratio was used to describe and control particles⁴⁷.

Winter triticale

Winter barley

Winter rye

Figure 4. The volume of the dressed and untreated winter triticale, barley, and rye seeds. Note: a, b, c – different letters indicate significant differences at $p < 0.05$ in the group of dressed and untreated seeds (Duncan's test).

Conclusions

The analysis of variance showed that the moisture content of the dressed and untreated winter triticale, barley, and rye seeds significantly affected their physical characteristics, i.e. length, width, thickness, and weight. The greatest differences in the weight of the seeds were observed when their moisture content varied within 9.5-17.5%. The average increase in the thousand kernel weight ranged from 4 to 6 mg. There was also a significant dependence between the seed moisture content W_z and the values of the coefficients describing the shape of the seeds, i.e. the equivalent geometric diameter D_g , aspect ratio R , sphericity index Φ , and unit weight m_D . The values of the coefficients describing the shape of

the seeds tended to change along with the increasing seed moisture content. The nature of these changes depended on the seed species and whether they were dressed or not. The changes in the seed moisture content within 9.5-17.5% significantly increased the volume of the rye (from 3.10% to 14.99%), triticale (from 1.00% to 13.40%), and barley seeds (from 1.00% to 15.33%). This information can be used as a parameter for improvement of the simulation process based on the discrete element method (DEM).

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