УДК 004.942; 631.3

4.3.1. Технологии, машины и оборудование для агропромышленного комплекса (технические науки

ОПРЕДЕЛЕНИЕ ФИЗИКО-МЕХАНИЧЕСКИХ ПАРАМЕТРОВ ГРАНУЛИРОВАННЫХ МИНЕРАЛЬНЫХ УДОБРЕНИЙ ДЛЯ ИСПОЛЬЗОВАНИЯ В ЦИФРОВЫХ ДВОЙНИКАХ

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В данной статье были определены физико-механические параметры 5 наименований образцов гранулированных минеральных удобрений для использования в цифровых двойниках. Представлены результаты экспериментальных исследований по определению геометрических размеров, гранулометрического состава, плотности угла естественного откоса, угла обрушения, коэффициента статического трения,

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4.3.1. Technologies, machinery and equipment for the agro-industrial complex (technical sciences)

DETERMINATION OF PHYSICAL AND MECHANICAL PARAMETERS OF GRANULAR MINERAL FERTILIZERS FOR USE IN DIGITAL TWINS

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In this article, the physical and mechanical parameters of 5 names of samples of granular mineral fertilizers for use in digital doubles were determined. The results of experimental studies on the determination of geometric dimensions, granulometric composition, density of the angle of natural slope, angle of collapse, coefficient of static friction, coefficient of reduction of granular mineral fertilizers are presented: nitroammophoska, carbamide with trace elements, diammonium коэффициента восстановления гранулированных минеральных удобрений: В качестве образцов были взяты: нитроаммофоска, карбамид с микроэлементами, диаммонийфосфат, азофоска (нитроаммофоска), карбамид (мочевина)

phosphate, azofoska (nitroammophoska), carbamide (urea) were taken as samples

Ключевые слова: ЦИФРОВОЙ ДВОЙНИК, СИТОВЫЙ КЛАССИФИКАТОР, МЕТОД ДИСКРЕТНЫХ ЭЛЕМЕНТОВ, ФИЗИКО-МЕХАНИЧЕСКИЕ ПАРАМЕТРЫ, КОНТАКТНАЯ МОДЕЛЬ, ГРАНУЛИРОВАННЫЕ МИНЕРАЛЬНЫЕ УДОБРЕНИЯ

Keywords: DIGITAL DOUBLE, THE SIEVE CLASSIFIER, DISCRETE ELEMENT METHOD, PHYSICAL AND MECHANICAL PARAMETERS, CONTACT MODEL, GRANULAR MINERAL FERTILIZERS

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Introduction. To create a digital twin of the working element of a seeding soil-cultivating machine for sowing seeds with simultaneous application of granulated mineral fertilizers, it is necessary to select a contact model, calibrate and evaluate the significant parameters of the contact model of fertilizers, taking into account their physical, mechanical and geometric parameters.

In the work of Mudarisov S.G. an analysis of foreign and domestic literature is carried out, and information is presented containing key physical and mechanical characteristics of parameters and models of contacts of granular fertilizers for the creation of digital twins using discrete element methods [1]. When creating digital twins of tillage seeding machines, it is necessary to select the parameters of the contact model of granular mineral fertilizers taking into account their physical and mechanical parameters.

Having reviewed the literature, it was found that for different names of granulated mineral fertilizers, their physical and mechanical parameters differ significantly. Therefore, 5 names of mineral granulated fertilizer samples were considered, widely used in farms of the Republic of Bashkortostan, suitable for soil conditions. For the research, both simple fertilizers were selected, which include 1 nutrient element such as nitrogen, and complex or complex fertilizers with several nutrient elements such as nitrogen, phosphorus and potassium with different percentages.

The bulk of the produced fertilizers is ammonium nitrate from 34% to 41%, while urea occupies at least 4% - 5% [2]. Distinctive properties of granulated mineral fertilizers are the presence of nutrients and, accordingly, various physical and geometric parameters.

For effective use of fertilizers, it is necessary to comply with technical requirements for packaging, transportation and storage. Granulated mineral fertilizers must be stored in closed warehouses and not exposed to precipitation [3]. In the works of Kochetov I. M., Sokolov V. V., the influence of changes in humidity on such physical and mechanical properties of granulated mineral fertilizers (hygroscopicity, caking, strength) under various storage and transportation conditions was established [4,5] .

In the research of V. A. Chernovolov, results are presented on the change in physical and mechanical parameters of some types of fertilizers. Increased humidity is unacceptable for granulated mineral fertilizers, since in this case it becomes impossible to scatter them over the surface of the field, move them along seed pipes, and dose them in seeding machines.

During storage, caking and clod formation may occur, which will reduce the effectiveness when applied to the soil during sowing. [6]. However, if the conditions are met and fertilizers are used within the standard (factory) humidity, the change in parameters is insignificant: diammonium phosphate 1.5-2.9%, ammonium phosphate 5.7%, granulated urea 0.1-2.6%, superphosphate 2.9-3.2%. At the same time, the humidity of powdered fertilizers reaches 9-10% due to their significant hygroscopicity.

A significant part of the parameters of contact models are determined through calibration, which includes comparison of data from natural experiments and modeling results to achieve identical results. When creating digital twins of soil-cultivating seeding machines with simultaneous application of granulated mineral fertilizers, their physical properties should be assumed to be identical. In the absence of such data, use the scientific results of research by other scientists working in this area, and produce difficult-to-determine parameters through calibration in a digital twin.

Purpose and objectives of the study. The purpose of this study is to determine the physical and mechanical parameters of granulated mineral fertilizers . The objectives of the research are: laboratory and model experiments are carried out within the framework of a digital twin using the ROCKY DEM software package based on the discrete element method. Determine the physical and mechanical parameters for using data when creating digital twins using the discrete element method.

Material and methods of research. The physical and mechanical properties of 5 types of granulated mineral fertilizer samples (geometric dimensions, granulometric composition of fertilizers, density of fertilizers, density of fertilizer granules, angle of natural repose, angle of collapse (arch) of fertilizers), coefficient of static friction, elasticity, coefficient of recovery were determined.

The following dry complex fertilizers were used as samples: nitroammophoska with a percentage content of microelements of nitrogen in the amount of 16%, phosphorus 16%, potassium 16%; diammonium phosphate with a percentage content of microelements of phosphorus in the amount of 47%, nitrogen 18%); azophoska (nitroammophoska) with a percentage content of microelements in the amount of nitrogen 16%, phosphorus 16%, potassium 16%. Dry simple fertilizers containing one element: urea with a percentage of nitrogen microelements of 46%; urea with a percentage of nitrogen microelements of 46.2% from another manufacturer.

Research results and their discussion. After analyzing the scientific research of various authors, 4 contact models are mainly used [9, 10, 11]: Hertz-Mindlin, which takes into account the elastic contact of spherical particles of fertilizer granules when modeling the storage process; the linear adhesion model, which takes into account the dependence of the contact force on the contact area and the adhesion coefficient of the granule particles; the Coulomb model, which takes into account the friction forces between the particles of fertilizer granules and various surfaces; the Johnson-Kennedy-Clark (JKR) model, which takes into account the influence of surface forces on contact pressure and the size of the contact zone

By calibrating the particle diameter, different granule diameters can be used for more accurate calculations, resulting in a more realistic digital twin result.

Table 1 presents the results of the sample granulometric composition by particle fractions of granules.

Table 1 - Samples of granulometric composition by fractions of granule particles

Fertilizer name	Fertilizer fractions
Simple fertilizers that contain one element	
Dry simple fertilizers: urea (carbamide) with a nitrogen content of 46.2%	
Complex (complex fertilizers) which contain several elements	
Dry complex fertilizers: diammonium phosphate with a percentage of microelements of phosphorus of 47%, nitrogen 18%	
urea with trace elements	
azofoska (nitroammophoska) with a percentage content of microelements in the amount of nitrogen 16%, phosphorus 16%, potassium 16%	

When modeling, it is necessary to take into account the granulometric composition of granulated mineral fertilizers using a set of sieves. In this case, cells with a diameter of 1 mm, 2.5 mm, 3 mm, 3.5 mm, 4.25 mm, 4.5 mm were used to separate the fraction of granules less than 1 mm, 1-2.5 mm, 2.5-3 mm, 3-3.5 mm, 3.5-4.25 mm, 4.25-4.5 mm, more than 4.5 mm. It was found that the granulometric composition of fertilizers is heterogeneous. Table 1 presents samples of granulometric composition by fractions of granule particles. Accordingly, it is necessary to determine the percentage content by granule size in different types of fertilizers. Since different sized particles have different physical and mechanical parameters. Samples of fertilizers were selected and prepared according to GOST 21560.0-82, 250 g of each fertilizer sample. Then, shaking was performed to sift the fertilizer sample in a sieve classifier. Granules of fertilizers of different sizes remain on the cells, while their mass is weighed and calculated as a percentage.

In further studies we will consider the bulk density of granulated mineral fertilizers. The volume occupied by the mass of bulk granulated mineral fertilizers depends on the density of the fertilizers, the size of the granule particles and the presence of voids between the granule particles. To determine the density, a glass cylinder was used in which samples of fertilizers were placed (Figure 1), scales were used to measure the mass (Figure 2).

The ratio of the fertilizer mass to the working volume of the glass cylinder determines how, the density of the fertilizer in kilograms per cubic decimeter. When filling the measuring glass cylinder, the sample of granulated mineral fertilizers was subjected to uniform shaking and compaction.

Table 2 presents the results of the granulometric composition of fertilizers when divided into fractions.

Table 2 results of granulometric composition of fertilizers when separated into fractions

Name And compound fertilizers	Size factions granules, mm	cell	Mass of granules, G	Fraction yield, %
Nitroammophoska (nitrogen – 16%, phosphorus – 16%, potassium -16%)	less 1		0.8	0.32
	1-2.5	1	114.6	45.84
	2.5-3	2.5	68.5	27.4
	3-3.5	3	33.5	13.4
	3.5-4.25	3.5	26.8	10.72
	4.25-4.5	4.25	2.0	0.8
	more 4.5	4.5	3.8	1.52
Urea with microelements (Nitrogen -46%)	less 1		1,2	0.48
	1-2.5	1	136.1	54.44
	2.5-3	2.5	69.4	27.76
	3-3.5	3	28.2	11.28
	3.5-4.25	3.5	13.2	5.28
	4.25-4.5	4.25	0.4	0.16
	more 4.5	4.5	1.4	0.56
Diammonium phosphate (Phosphorus – 47% nitrogen 18%)	less 1		0.9	0.36
	1-2.5	1	96.9	38.76
	2.5-3	2.5	36.6	14.64
	3-3.5	3	47.6	19.04
	3.5-4.25	3.5	58.5	23.4
	4.25-4.5	4.25	3.6	1.44
	more 4.5	4.5	5.9	2.36
Azofoska (nitroammophoska) (Nitrogen – 16% phosphorus – 16 potassium -16%)	less 1		1,1	0.44
	1-2.5	1	141.7	56.68
	2.5-3	2.5	60.0	24.0
	3-3.5	3	27.4	10.96
	3.5-4.25	3.5	17.3	6.92
	4.25-4.5	4.25	1,1	0.44
	more 4.5	4.5	1,1	0.44
Urea (urea) (Nitrogen -46.2)	less 1		14.7	5.88
	1-2.5	1	169.7	67.88
	2.5-3	2.5	43.5	17.4
	3-3.5	3	15.4	6.16
	3.5-4.25	3.5	5.9	2.36
	4.25-4.5	4.25	0.4	0.16
	more 4.5	4.5	0	0

Based on the calibration carried out, for urea particles with microelements, a diameter in the range from 1 to 3 mm can be selected, since 82 % of all particles fall within this range.

Figure 1 - Determining the sample volume

Figure 2 - Determination of sample mass

The results of determining the bulk density of 5 types of granulated mineral fertilizer samples are presented in Table 3. The average density of the fertilizers was: nitroammophoska - 1.12 kg/ dm^3 ; diammonium phosphate - 1.03 kg/dm^3 ; azophoska - 1.12 kg/dm^3 . At the same time, the density of urea samples varied among different manufacturers, so urea with microelements 1.02 kg/dm^3; urea (carbamide) 0.76 kg/ dm^3 .

In the research of V. A. Chernovolov, the results of density changes depending on humidity for different types of fertilizers are presented. Thus, for granulated superphosphate with 7% humidity, the density is 1100 kg/m^3; with an increase in humidity to 14%, the density reaches 1150 kg/m^3. Thus, for urea with 3% humidity, the density is 600 kg/m^3; with an increase in humidity to 6%, the density reaches 650 kg/m^3 [6].

Data on the density of fertilizers are necessary for modeling when setting up the parameters of mineral fertilizer granule particles in the ROCKY DEM program, as well as for determining the lifting capacity of seed drill bins and the supply of fertilizers to soil-cultivating seeding working bodies.

The following studies will examine the granule density. To determine the density, a pre-calibrated 10 ml measuring cup was used, into which 10 g samples of fertilizers were placed. The granule density was calculated by dividing the fertilizer mass by the change in volume ΔH. The measurements of the fertilizer sample mass are shown in Figure 3. The results of determining the granule density of 5 samples of granulated mineral fertilizers are presented in Table 3. At the same time, the average density of fertilizer granules ranged from 1.25 to 1.69 grams per cubic centimeter.

Figure 3 - Measurement of volume change after adding fertilizer sample

Granule density is used to calibrate fertilizer particle parameters in ROCKY DEM software.

In further research we will consider static coefficient friction. There are many devices for measuring the coefficient of static friction. The handle of the screw mechanism is carefully turned until the sample with fertilizer begins to slide along the pad (see Figure 4).

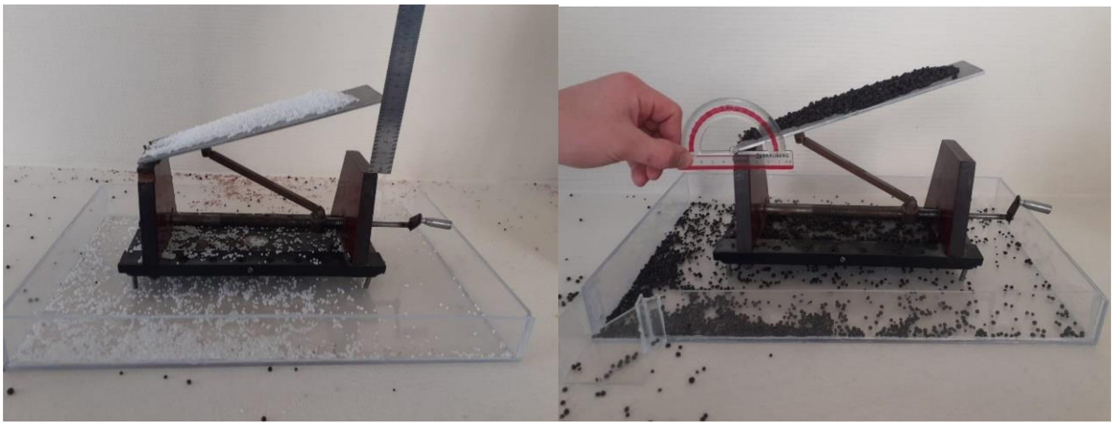
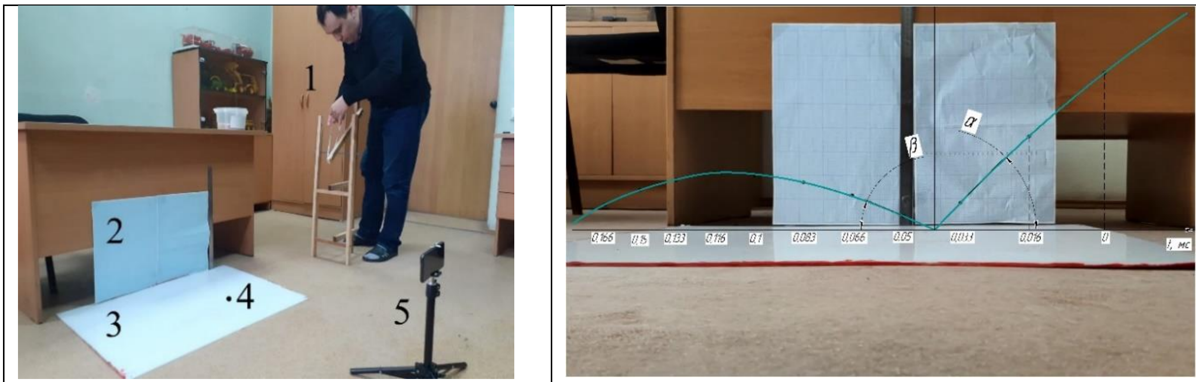


Figure 4 – Laboratory setup for determining the coefficient of static friction

The coefficient of friction between the studied samples was calculated as the tangent of the angle of inclination of the board at the moment when the fertilizer sample began to move along the pad. The obtained experimental data on determining the coefficient of static friction of 5 types of granulated mineral fertilizer samples are presented in Table 3. The average coefficient of static friction (static friction) is: nitroammophoska - 0.29; urea with microelements - 0.32; diammonium phosphate - 0.41; azophoska - 0.24; urea (carbamide) - 0.43. The coefficient of static friction (static friction) is used when calibrating the parameters of particles of mineral fertilizer granules in the ROCKY DEM software package.

In further studies we will consider the coefficient of restoration. This parameter depends on the elastic properties of the particles of fertilizer granules, taking into account what part of the initial relative velocity of these bodies was restored by the end of the impact. The coefficient of restoration reflects the loss of mechanical energy of the colliding bodies due to the occurrence of residual deformations. The elastic properties of fertilizers are estimated by the coefficient of restoration upon impact, i.e. the ratio of the normal components of the velocities of the granule particle before and after the collision with a different surface.

Collisions in working bodies occur during different processes: in seeders - when fertilizers move along seed pipes, in coulters, especially if fertilizer guides and reflectors are installed there, and also when fertilizers fall to the bottom of the furrow in the sowing strip. Figure 5 shows a laboratory stand for determining the recovery coefficient.



A) b)

Figure 5 – a) Laboratory stand for determining the coefficient of restitution, b) measurement of the angle of incidence and rebound of a fertilizer particle

The laboratory setup consists of: 1 – laboratory setup for determining the coefficient of recovery, 2 – graph paper, 3 – rebound surface (plastic), 4 – fertilizer granule particle (shown conditionally), 5 – slow-motion camera. Various materials (plastic, metal) were used as the rebound surface. Figure 5 shows a photo of a fertilizer particle rebound and determination of the angle of incidence and rebound of the fertilizer particle.

To find the recovery coefficient for fertilizer granule particles, we can use the following well-known formula:

$$к = \frac{\tan\alpha}{\tan\beta},$$

α – the angle that a fertilizer particle forms with the normal to the inclined surface, measured in degrees;

β is the angle formed between the fertilizer particle and the normal to the inclined surface after impact, also measured in degrees.

We find the angles α and β based on the diagram in Figure 5 b. The angle α depends on the angle of inclination of the surface and is determined by the formula:

$$\alpha = 90 - \gamma,$$

Corner γdetermined using a photo in the Compass software package. For this, we used the method of slow-motion shooting from a mobile phone equipped with an optical stabilization system with matrix shift compensation. Then the photo from the still frame was loaded into the Compass software package, where the angle was measured.

The angle β is determined using the formula

$$\beta = 90 - \varepsilon$$

The results obtained for determining the recovery coefficient of 5 types of granulated fertilizers are presented in Table 3. The average recovery coefficient is: from 0.322 to 0.492; azophoska – 0.414; urea – 0.348.

In further research we will consider the angle of natural repose and the angle of collapse, which are important characteristics in the design of bunkers, tanks of various agricultural machines. The angle of natural repose reflects the degree of mobility of fertilizer particles and is determined by the level of internal friction and adhesion between them, the size and shape of the particles, as well as the properties of their surface, density and moisture of the fertilizer.

The angle of repose (or the coefficient of static friction between fertilizer particles) is an important characteristic. Currently, various types of devices are used to measure the angle of repose 7. A special laboratory setup was developed to determine the angles of repose and repose. (Figure 6 , 7). It consists of: 1 upper part, 2 lower part, 3 damper, 4 partition, 5 passage channel, 6 pusher, 7 fertilizer.

For this purpose, a rectangular container was made from transparent organic glass plates with the following dimensions: length 340 mm, width 80 mm and height The transparent organic glass plate had a thickness of 4 mm. The procedure for conducting full-scale tests included the following stages. First, 1000 grams of fertilizers were poured into the upper part of the rectangular container 1 (Figure 6). Then, by pressing the pusher 6, the valve 3 moved back and the fertilizers 7 poured out through the passage channel 5 under the force of gravity into the lower part 2.

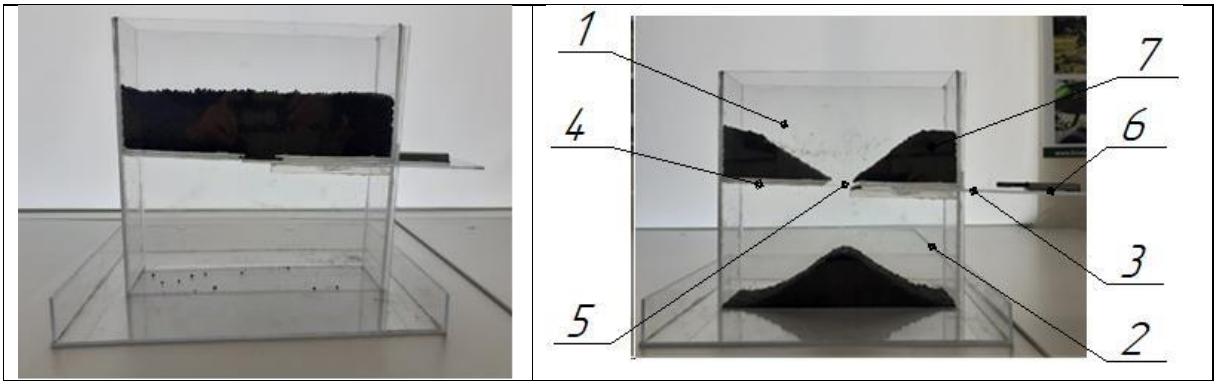


Figure 6 Laboratory setup for determining the angle of natural slope and the angle of collapse (arch angle).

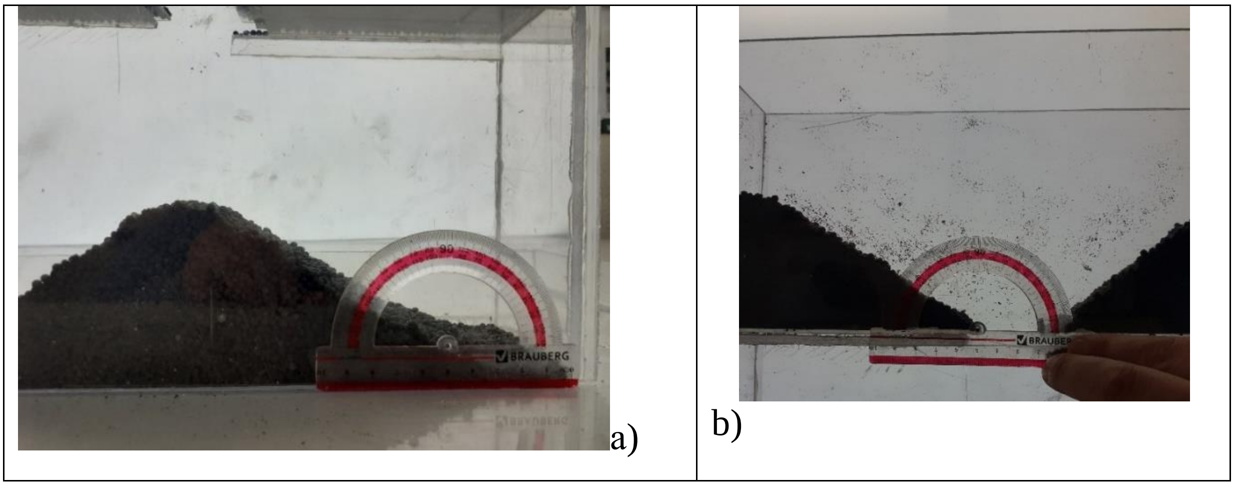


Figure 7 A) Measurement of the angle of natural slope, b) measurement of the angle of collapse (arch angle)

The results of determining the angle of natural slope and the angle of collapse (arch angle) of 5 types of granular fertilizers are presented in Table 3.

Table 3 Experimental data on the physical and mechanical parameters of fertilizers

Name And compound fertilizers		Granule density g/ ^{cm3}	Density, kg/ ^{dm3}	Angle of natural slope, deg	Angle of collapse, deg (coefficient of static friction fertilizer on fertilizer)	Coefficient of static friction	Coefficient of recovery (rebound surface plastic)
Nitroammophoska (nitrogen – 16%, phosphorus –	average	1.69	1,12	32	36	0.29	0.391
	Wed. sq. off	0.067	0.03435	1,536	1,476	0,014	0,00477
	Dispersion	0.0045	0.00118	2,3593	2,17858	0.0002	0.0000151
	Coeff. k $_{v}$ variations	3.99	3.06	4.8	4.1	4.9	1.11
Urea with microelements (Nitrogen - 46%)	average	1.64	1.02	31	34	0.32	0.322
	Wed. sq. off	0,0172	0.03	1,426	0.697	0,012	0,01448
	Dispersion	0,0003	0,00088	2,03348	0.48581	0.00016	0.000185
	Coeff. k $_{v}$ variations	1.05	2.9	4.6	2.05	3.9	4.5
Diammonium phosphate (Phosphorus – 47% nitrogen	average	1.61	1.03	30	35	0.41	0.492
	Wed. sq. off	0,0216	0,019	1,407	0.655	0,019	0,01437
	Dispersion	0,00047	0,00037	1,97965	0.42837	0.00036	0.000208
	Coeff. k $_{v}$ variations	1.34	1.86	2.05	1.87	4.62	3.04
Azofoska (nitroammophoska) (Nitrogen –	average	1.67	1,12	25	31	0.24	0.414
	Wed. sq. off	0.0631	0.049	1,245	1,442	0,012	0,01912
	Dispersion	0.00399	0.00242	1,55003	2,07792	0.00014	0,000373
	Coeff. k $_{v}$ variations	3.79	4.38	4.98	4.65	4.88	4.62
Urea (urea) (Nitrogen -46.2)	average	1.25	0.76	35	40	0.43	0.348
	Wed. sq. off	0.0089	0.034	1,393	1,680	0,018	0,01732
	Dispersion	0,0008	0,00117	1,94045	2,82240	0.00032	0.00027
	Coeff. k $_{v}$ variations	0.72	4.51	3.98	4.2	4.15	4.98

It was found that the collapse angle is an effective parameter in calibrating and assessing the accuracy of the selected model when developing a digital twin. This indicator is affected by the coefficient of static friction and the coefficient of rolling friction between mineral fertilizer granules.

To create a virtual computer model of the technological process of subsurface fertilization based on the discrete element method, the parameters of fertilizer particles were calibrated in the ROCKY DEM software package. To create a digital twin of the measurement of the angle of collapse and the angle of natural slope, the data obtained during laboratory studies and analysis of scientific data were used. These model parameters are presented in Table 4.

Table 4 – Model parameters for the digital twin

№p/p	Parameter	Meanings
1	Young's modulus E, Pa	1.23 - 9.0x10 ^{6}
2	Poisson's ratio, v	0.25
3	Coefficient of static friction between particles of fertilizer granules f_{st}	0.24 - 0.43
4	Coefficient of dynamic friction between fertilizers f_d	0.03 - 0.18
5	Restitution coefficient k_{vost} based on experimental data according to table 3	0.322-0.492
6	Particle diameter d, mm based on experimental data according to table 3	1-4.25
7	Coefficient of static friction of fertilizer granules on material f_{stk}: between the fertilizers and the bunker, between fertilizer granules and acrylic plate, between the fertilizer granules and the walls of the seeding apparatus, between fertilizer granules and steel	0.32 0.07-0.23 0.41 0.28
8	Dynamic friction coefficient of fertilizer granules $f_{d\,k}$	0.03…0.18

In the research of Farkhutdinov I.M. an assessment of significant factors is presented and when selecting specific parameters of the contact model for modeling pea seeds in digital twins it was found that the angle of natural repose and the angle of collapse depend on the coefficient of dynamic friction for seeds of leguminous crops such as peas [8].

After creating a three-dimensional model of the laboratory installation to determine the angle of repose and the angle of collapse, we import it into the ROCKY DEM software package in stl format. Figure 9 shows the measurement of the angle of collapse and the angle of repose using a digital twin of the laboratory installation in the ROCKY DEM program.

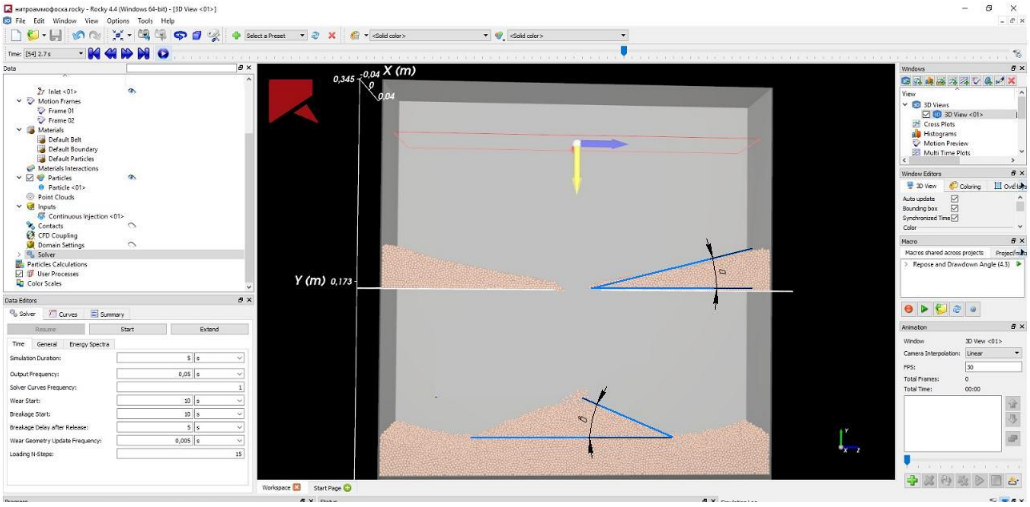


Figure 9 - Measuring the angle of collapse and the angle of natural repose in the ROCKY DEM program

The modeling process confirmed that the collapse angle is a significant parameter for adjusting and assessing the accuracy of the selected model when creating a digital twin. This indicator depends on the coefficients of static friction and rolling friction between particles of mineral granulated fertilizers.

To calibrate the diameter of the fertilizer particle, a digital twin of the sieve classifier was created. For this purpose, a set of three-dimensional models with a sieve diameter of 200 mm and a sieve flow section with a diameter d_1 equal to 1 mm, 2.5 mm, 3 mm, 3.5 mm, 4.25 mm, 4.5 mm was created in the Kompas-3 D program. After that, the three-dimensional model of the sieve classifier is imported into the ROCKY DEM software package in stl format (Figure 10).

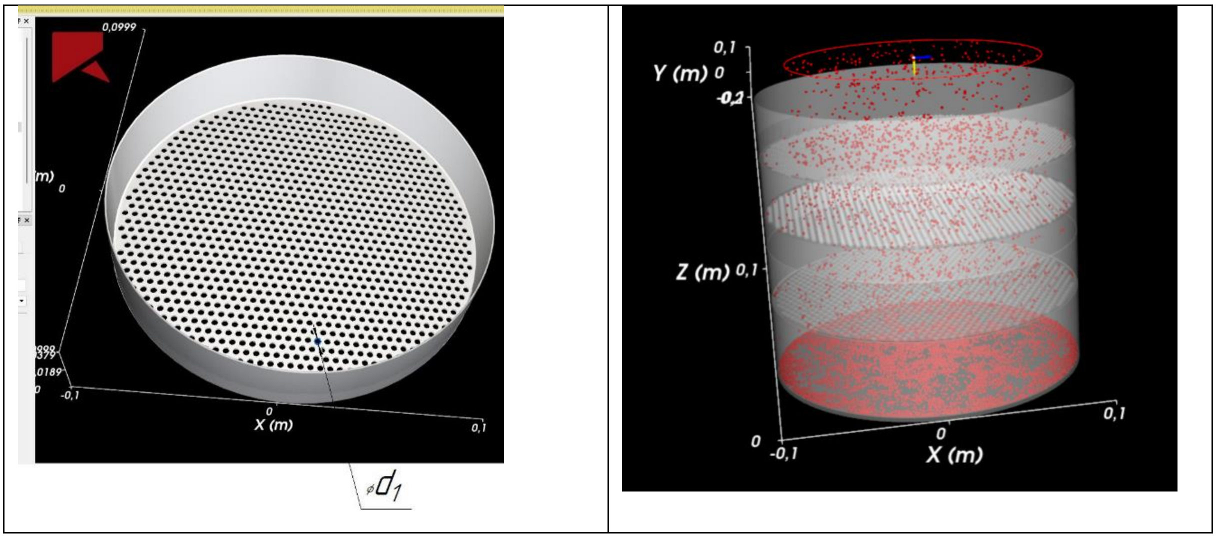
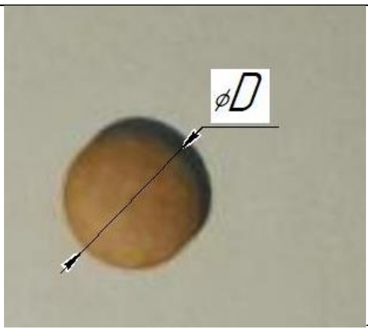


Figure 10 - Sieve classifier in the ROCKY DEM software package

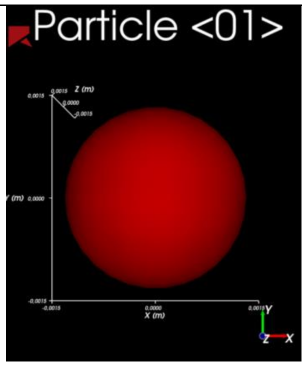
Next in the menu Particles → Create Particles we select the particle shape as a sphere. We add 250 grams of particles for this we calculate the number of fertilizer granules based on the density and volume. We set the density of fertilizers, the recovery coefficient, the friction coefficient, Young's modulus also We set boundary conditions through the Boundaries menu.

When calibrating the physical and geometric parameters of granulated materials, it is necessary to take into account their shape. Thus, the shape of the particles can be conditionally taken as spherical with a certain diameter for dry complex fertilizers nitroammophoska; diammonium phosphate; azophoska (or nitroammophoska), as well as for simple fertilizers urea with microelements and urea (urea). The percentage ratio of particles of different diameters is determined based on Table 2.

We set the initial coordinates of the center of mass and the diameter of the fertilizer granule particles D (particle), mm (Figure 11).



A



b

Figure 11 – Calibration of fertilizer particle parameters

a) Diameter of a natural sample of fertilizer granule (according to Table 3), b) particle - diameter of fertilizer granule in the ROCKY DEM software package

Figure 12 shows a digital twin of a sieve classifier in the ROCKY DEM software package.

Figure 12 – Full-scale sieve classifier

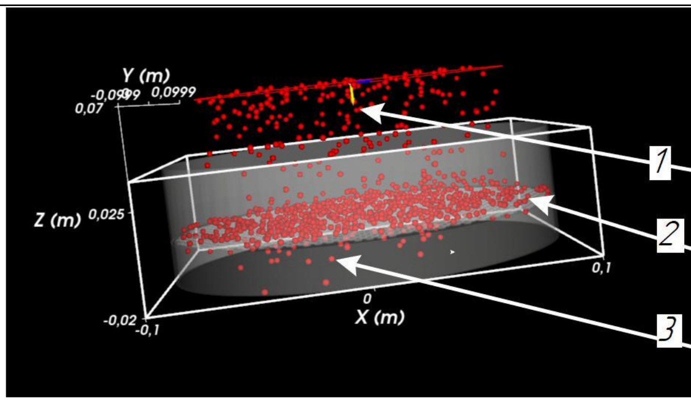


Figure 13 – Digital twin of the sieve classifier in the ROCKY DEM software package

The feed of fertilizer particles 1 of different diameters is presented, the cell of sieve 2 has a diameter of $d_1 = 3$ mm, particles with a diameter of $D \leq 3$ mm.

Conclusions. Based on the experimental studies, the parameters of the contact model were obtained: recovery coefficient of 0.322-0.492. It was found that complex fertilizers containing several microelements have a higher recovery coefficient than simple fertilizers containing one element. The recovery coefficient for diammonium phosphate is 0.492; azophoska - 0.414; for nitroammophoska 0.391; for urea with microelements 0.322; urea (urea) 0.348. Fertilizers with a higher recovery coefficient are more resistant to changes in the process of movement in seed tubes during sowing with the simultaneous application of fertilizers. This property must be taken into account when creating digital twins of seed tubes, coulters of seeding machines. It was also found that the coefficient of static friction between fertilizer particles is 0.24-0.43; the coefficient of dynamic friction between fertilizers is 0.03-0.18.

It has been established that the largest angle of natural slope and the angle of collapse of urea are 35° and 40º. They have an increased level of adhesion between particles, which complicates the process of mixing different fertilizers, the process of emptying bunkers. This must be taken into account when creating a digital twin of the process of moving fertilizer particles in agricultural machinery. The results of the study of granulometric composition allow you to set the sizes of granules in percentage terms.

These experimental physical and mechanical parameters of five samples of granulated mineral fertilizers are given in the table for use in the research process and creation of digital twins of tillage sowing agricultural machines. In further studies, it is planned to investigate the flow modes of fertilizer particles in the pneumatic systems of agricultural machines. To do this, it is necessary to experimentally determine the hovering speed, the speed of movement of fertilizer particles and the required air flow speed.

The developed twin of the sieve classifier, which allows visualizing the process of distribution by fractions of various granulated materials and seeds having a spherical shape, and the use of a rectangular section for distribution by fractions of various agricultural crops. This method of creating a digital twin can be used to study the operation of a grain cleaning sorting machine.

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