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Experimental characteristics for deformation properties of backfill mass

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Abstract

Purpose. Determining the deformation properties of backfill mass used to preserve the continuity of the coal-rock stratum enclosing mine workings.

Methods. To achieve the purpose set, laboratory studies have been performed on crushed rock samples with different granulometric composition, which are exposed to uniaxial compression in a steel cylinder. The experimental data are processed using the mathematical statistics methods.

Findings. As a result of performed laboratory studies, it has been determined that during compression pressure of the backfill material from crushed rock, the deformation modulus is a variable value and depends on the value of the applied load, which means that it cannot be used as a physical characteristic of the backfill mass. It has been proven that the deformation modulus characterizes the backfill mass rigidity, that is, its ultimate stress state. The rigidity value under a constant external load, can be regulated using the granulometric composition of the crushed rock. It has been revealed that the maximum shrinkage of the backfill mass is achieved when repacking crushed rock fractions of different sizes under volume compression of the backfill material. In the case when the backfill material is a homogeneous fraction of crushed rock, when increasing the constrained modulus, the backfill mass rigidity increases, and shrinkage decreases.

Originality. It has been proven that the values of the crushed rock compaction coefficient, which characterizes the shrinkage of the backfill mass, are correlated with a parabola and depend on the granulometric composition of the source material. With inhomogeneous granulometric composition, the compaction coefficient values are maximum, and for backfill material with the similar fraction, they decrease with a change in the bulk density of the crushed rock.

Practical implications. To ensure the side rocks stability and to maintain mine workings in an operational state, it is necessary to ensure a uniform by volume granulometric composition inhomogeneity of the crushed rock. This determines the ability of the roof and bottom of the coal seam to effectively respond to the impact of external factors that are manifested in the mass of sedimentary rocks during mining operations.

Keywords: *stability, roof, coal seam, stope face, stress-strain state, modelling, equivalent materials*

1. Introduction

Performance of the majority of domestic deep coal mines, especially in difficult mining-and-geological conditions, has relatively low technical and economic indicators. Besides, during mining operations, collapse of side rocks and blockage of mine workings are possible, which leads to the miners' injury. In most cases, the causes of accidents and emergency situations are the lack of reliable means of ensuring the stability of mine workings.

One of the conditions for guaranteeing high indexes of coal production is to ensure mine workings stability in the coal mine. The efficiency of mining-out the coal seams and the safety of mining operations largely depends on the method used to control the roof in the stope face. As evidenced by the world experience of coal seams mining in difficult mining-and-geological conditions, the state of side rocks and the mine workings preservation in a sedimentary rock mass are most favourably influenced by the method of controlling the roof through backfilling of the mined-out space [1]-[3]. Therefore, in order to avoid emergency situations and reduce the probability of negative rock pressure manifestations in mine workings, especially when mining the coal seams at great depths, it is necessary to focus on backfilling of the mined-out space as a way to control the roof in the stope face. By using backfilling of the mined-out space, the state of side rocks will be improved and blockage in mine workings will be eliminated.

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1.1. Recent research and publications analysis

Rock waste dumps of mines are the main source of environmental pollution in coal-mining areas. Currently, they should be considered as objects that present the prospect of subsequent processing and use [4], for example, for backfilling of the mined-out space.

More than 1000 rock waste dumps have been accumulated over the entire period of functioning the mining enterprises on the territory of Ukraine. These dumps occupy an area of about 20 thousand hectares of highly fertile chernozem soils [5].

Analysis of the world experience in underground mining of mineral deposits shows that up to 35% of mines use systems of mining with backfilling of the mined-out space. In coal mines, the method of controlling the roof by backfilling of the mined-out space is used in exceptional cases, for example, when it is necessary to reduce the endogenous fire hazard and for mining the coal seams under security facilities [6].

Indeed, the substantial experience of using the backfilling with crushed rock has been obtained in the mines of Ukraine in cases of solving complex issues of protecting industrial, residential objects and water bodies on the surface, when managing geomechanical processes during mining the reserves in difficult mining-and-geological conditions, and, when it is necessary to reduce the volume of rock output from mines [7]-[10].

Some specialists believe that if the rock is left in the mine, then the complex issues of managing geomechanical processes in the coal-rock mass enclosing the mine workings can be solved during the development of stope and preparatory works [11]. It is noted that it is the backfilling of the mined-out space that provides the least shrinkage of the underworked stratum and restrains the side rocks displacement in the mass. However, with such statement of a situation, there are no requirements for backfill mass, which reflect their deformation properties and ensure the stability of the coal-rock mass [12].

It is known [13] that backfilling of the mined-out space has a positive influence on the state of the side rocks in the vicinity of the stope working and adjacent extraction drifts. This is not only due to the influence of reducing the effective thickness of the seam. When mining the longwall faces with complete roof collapse or complete backfilling of the mined-out space, under the condition of the similar effective thickness of the seam, the geomechanical pattern in the coal-rock mass enclosing the mine workings is different [14]-[15]. Probably, the improvement in the nature of the side rocks state when using backfilling of the mined-out space from crushed rock is conditioned by the nature of the roof and bottom interaction with the backfill mass.

As it has been determined before [16], the change in the stress-strain state of side rocks when using yielding supports for mine workings security occurs as a result of their shrinkage or compression. To achieve a favourable geomechanical situation in the coal-rock mass enclosing the mine workings, it is necessary to provide a smooth deflection of side rocks. Then, other factors being equal, the probability of natural hazards in the mine workings will always be less.

It is believed [17] that the use of backfilling of the mined-out space ensures safe and effective minerals extraction. In real conditions of mining the coal seams with backfilling of the mined-out space, the backfill mass perform the functions of a supporting structure. They provide supporting of side rocks in the mined-out space behind the longwall face and prevent dangerous rock pressure manifestations, such as sudden collapse of the stratified rock stratum [18]. The world experience of mines and pits that use backfilling of the mined-out space to protect mine workings and surface objects indicates that a change in the geometry of the backfill mass significantly influences on its compressibility. In the rubble band used to protect the drifts, the backfill material functions in the conditions close to uniaxial compression, and in the compact mass, when the method of roof control is used through backfilling of the mined-out space, in the conditions of volume loading [19]. It is evident that the compression of the backfill mass under the action of own weight of the overlying layers occurring across a certain area is carried out when the lateral expansion is impossible. Such a particular case of triaxial pressure influence is called compression [20], [21].

To maintain mine workings with limited volumes of rock in underground conditions, it is proposed to use a solidifying backfill [22]. Such a solution in certain mining-and-geological conditions, ensures the maintenance of mine workings due to the use of a solidifying support, in comparison with other protecting methods. At the same time, there are still unresolved issues related to the regulation of the backfill solidifying processes and the preparation of multi-component solidifying mixtures, as well as the influence of solidifying supports on mine workings stability [23], [24]. Proceeding from this, the backfill mass from crushed rock, as a means of restraining the displacements of side rocks, must have certain properties and characteristics. This will maintain the mine workings in an operational state and increase the safety of mining operations, while meeting the requirements for the source backfill material.

1.2. Purpose and objectives of research

The purpose of research is to determine the deformation properties of the backfill mass used to preserve the continuity of the coal-rock stratum enclosing the mine workings.

To achieve this purpose, the following objectives are set:

– to determine the physical and mechanical characteristics of backfill mass from crushed rock with different granulometric composition;

– to study the deformation properties of backfill mass from crushed rock under compression pressure to substantiate the side rocks stability.

2. Materials and methods of research

The backfill mass consists of the source material – crushed rock of various sizes. Such mass very rarely are an accumulation of any single faction. Usually, all fractions in the backfill mass are in certain proportions, which means that particles of various sizes that compose the backfill mass system have certain properties. To study the physical and mechanical properties of the backfill mass, the granulometric composition of the backfill material from crushed rock is analysed in this research.

The simplest way to determine the crushed rock granulometric composition is by sieving the source material through a set of standard sieves with holes 5, 4, 3, 2, 1 and 0.1 mm [25]-[29].

To determine the percentage content of the fractions obtained after sieving the source material of crushed rock, weighing is carried out on a technical weigh scales with an accuracy to 0.01 g. The sum of the weights of all fractions is different from the initial weight of the source material by 1%, which meets the requirements stated in the work [20], [28].

It is known [25], that the bulk weight of crushed rock ρ_b (kg/m^3) is the weight of a unit volume of loose rock mass. During the experiments, the value of ρ_b (kg/m^3) is determined using a special measuring vessel with a volume of $V_v = 10^{-3}$ (m^3) and the weight m_v (kg), in accordance with the methodology described in the work [29].

After performing the experiments, a value of the bulk weight ρ_b (kg/m^3) is found by the expression:

$$\rho_b = \frac{m_{\Pi} - m_v}{V_v}, \quad (1)$$

where:

m_v – the weight of a measuring vessel with crushed rock, kg.

It is believed [30]-[32] that the value of ρ_b (kg/m^3) depends on the rock moisture content and its bulk weight. Therefore, laboratory samples, dried to constant weight, are used for testing.

Void factor M (%) of the backfill material is determined by calculation based on the preliminary found values of the average density ρ (kg/m^3) of the source material and its bulk density ρ_b (kg/m^3) according to the expression from the work [29]:

$$M = \left(1 - \frac{\rho_b}{\rho}\right) \cdot 100. \quad (2)$$

Compression properties of the crushed rock with different granulometric composition are tested in a steel cylinder with a height of $h_{cyl} = 0.075$ m and a diameter of $d_{cyl} = 0.075$ m. In the course of the experiments, a P-50 hydraulic press is used as a test equipment, intended to load experimental samples with a static load (during their testing for compression). The maximum force developed by the press is 50 tons. A steel cylinder filled with crushed rock of a certain fraction with a plunger is set between parallel press plates (Fig. 1a, b). After that, a vertical force F (kN) is applied to it. As a result of this interaction, vertical normal stresses σ_z (MPa) arise in the sample, due to which the crushed rock is compacted and the backfill material shrinks.

***Figure 1.** Photo of experimental equipment for determining the compaction coefficient k_{compa} of crushed rock: (a) press for compressing the steel cylinder; (b) steel cylinder with removable bottom: 1 – steel cylinder; 2 – plunger; 3 – crushed rock*

To determine the compaction coefficient k_{compa}, crushed rock is used, consisting of inhomogeneous fractions and source material dispersed into standard fractions. The compaction coefficient k_{compa} of the crushed rock is calculated as the ratio of the volume occupied by the source material before compaction to the volume that it occupies after compacting [25]-[28].

In this research, the values of the rigidity coefficient C (N/m) of backfill mass is determined based on Hooke's law [18], taking into account the crushed rock of different fractions, when:

$$c = \frac{F}{\Delta h}, \quad (3)$$

where:

Δh – the value of crushed rock compression in a compression device, m.

3. Experimental findings

The data of experimental research on determining the granulometric composition of crushed rock are presented in Table 1.

***Table 1.** Data from laboratory studies of the crushed rock granulometric composition using sieve analysis*

Sieve holes, mm	Fraction size, mm	Percentage content in the total volume, %
5	> 5	4
4	4-5	16
3	3-4	19
2	2-3	24
1	1-2	18
0.1	0.1-1	14
	< 0.1	5

The results of the sieve analysis are shown graphically (Fig. 2) in the form of a grain-size accumulation curve (Fig. 2a), as well as a histogram and differential curves of the crushed rock particles distribution by sizes (Fig. 2b).

The granulometric composition of the crushed rock (Fig. 2a) is characterized by the coefficient of inhomogeneity k_{inhom}, which reflects the scattering of the crushed rock shape and size relative to their average value. Having determined the particle diameters, the value of the coefficient k_{inhom} can be determined, as it is recommended in [29]. Given that the inhomogeneity coefficient values of the rocks forming Donbass coal deposits usually range within the limits of $k_{inhom} = 1.6$, the found experimental value $k_{inhom} = 4.8$ characterizes the inhomogeneity of the crushed rock source material.

To construct a histogram and a differential curve of the particles distribution by sizes, on the granulometric graph, the linear size d (mm) of the measured particles is plotted along the abscissa axis, and their percentage content P (%) in the total volume of the crushed rock source material is plotted along the ordinate axis (Fig. 2b). Volume ratios intervals are presented as bars with height $\Pi_i = \Delta d_i$. In this case, a histogram of the particles distribution by sizes is obtained (Fig. 2b). Having connected the midpoints of the bars upper bases of the distribution diagram, a smooth differential curve is obtained. The resulting dependence characterizes the particles with average sizes enclosed between the right and left edges of one bar (d_i^{av}, mm), which occupy P_i (%) by volume in the crushed rock source material (Fig. 2b, dependence 3).

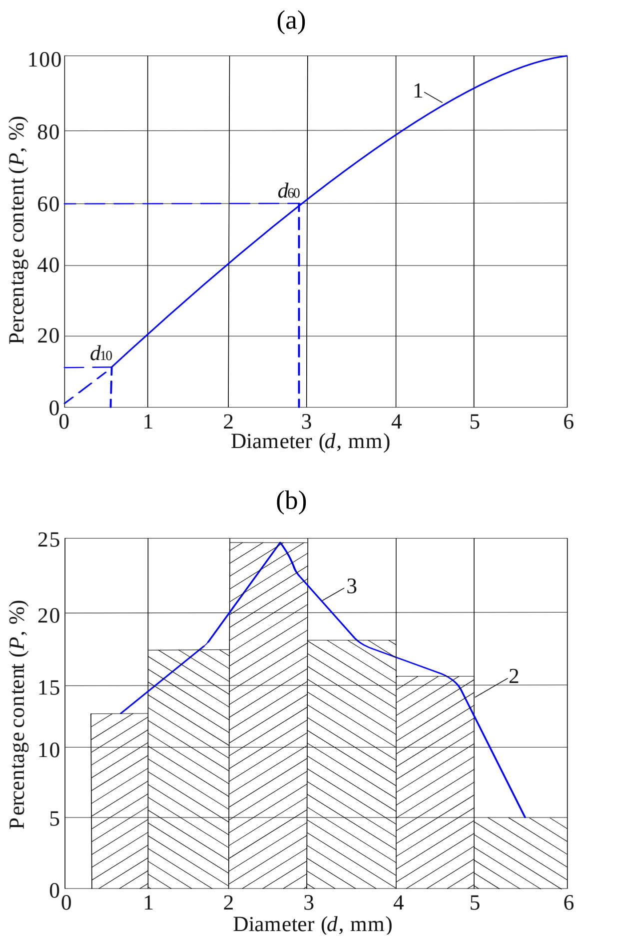

Figure 2. Granulometric composition of crushed rock: (a) in the form of a grain-size accumulation curve; (b) in the form of a histogram and differential curve of the crushed rock particles distribution; 1 – a grain-size accumulation curve; 2 – histogram; 3 – differential curve of the particles distribution

The main statistical characteristics of the differential curves of the particles distribution by sizes are the mean value, median and mode [30]. For a normal distribution, the mean, median and mode coincide, which is confirmed by the obtained experimental data (Fig. 2b).

The physical and mechanical properties of the backfill mass depend on the ratio of the main fractions in them, in accordance with the studied peculiarities of each crushed rock fraction.

Laboratory studies data on determining the value of M (%) are presented in Table 2. Values of ρ_b (kg/m^3) for the crushed rock are given after sieving by fractions. From the data presented in Table 2, it can be seen that with an increase in ρ_b (kg/m^3), the values of void factor M (%) decrease.

Table 2. Laboratory studies data on determining the bulk density and void factor of the backfill material from crushed rock

Fraction size, mm	Bulk density ρ_b, kg/m^3	Void factor M, %
0.1-5	1820	14
4-5	1680	20
3-4	1720	19
2-3	1860	12
1-2	1880	11
1-0.1	1940	8

The results of tests on compression are represented in the form of a compression diagram, when the value of the external force F, (kN) is plotted along the abscissa axis, and the displacement – change in the height of the sample Δh (m) during compression is plotted along the ordinate axis (Fig. 3).

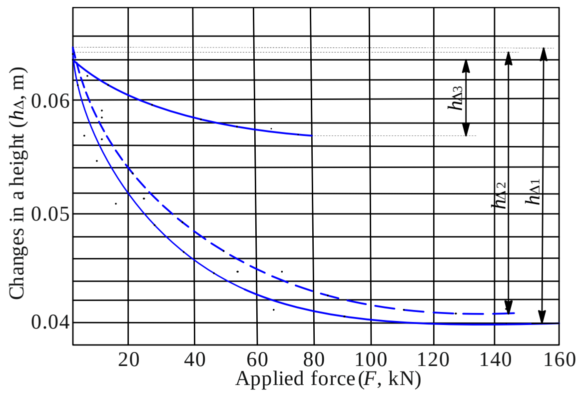

Figure 3. Graphs of changes in a height Δh (m) of a sample from crushed rock with different granulometric composition under uniaxial compression in a steel cylinder depending on the applied force F (kN): 1 – fraction size 0.1-5 mm; 2 – fraction size 4-5 mm; 3 – fraction size 0.1-1 mm; Δh_1 = 0.023 m; Δh_2 = 0.021 m; Δh_3 = 0.007 m – value of samples 1, 2, 3 compression

From Figure 3 it is seen that the compression diagram of the backfill material is curvilinear throughout. However, in a certain limited range of compressive load, the backfill mass can still be considered as a linearly deformable body.

Let us consider compression as a particular case of triaxial pressure impact on a linearly deformable body, when compaction of crushed rock occurs.

Figure 4 shows a scheme of the crushed rock sample deformation in a steel metal cylinder under uniaxial compression. The relative deformation λ_z of a crushed rock sample under compression can be determined from the ratio (Fig. 4):

$$\lambda_z = \frac{\Delta h \cdot A}{h \cdot A} = \frac{\Delta h}{h}, \quad (4)$$

where:

A – cross-sectional area of the sample, m^2.

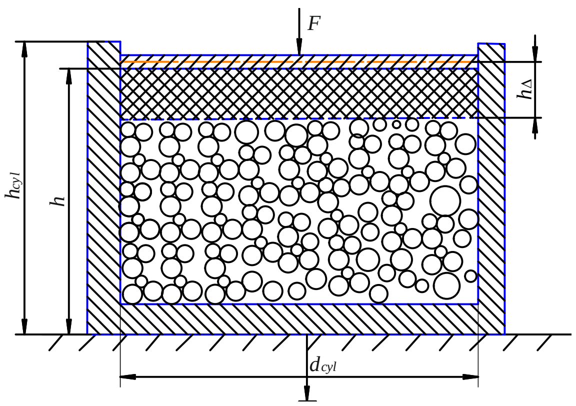

Figure 4. Scheme of the crushed rock sample deformation in a steel metal cylinder: F – compression force (kN); Δh – value of compression (m); h_{cyl} – cylinder height (m); d_c – cylinder diameter (m)

Figure 5 shows the dependences reflecting the change in the compaction coefficient of the crushed rock k_{compa} on its bulk density ρ_b (kg/m^3).

To construct the experimental dependences, the values of the compaction coefficient k_{compa} are plotted along the ordinate axis, and the bulk density of the crushed rock ρ_b (kg/m^3), corresponding to these values, is plotted along the abscissa axis (Fig. 5). To determine the form of the link between the compaction coefficient k_{compa} and the bulk density of the crushed rock ρ_b (kg/m^3), the form of the correlation equation is defined.

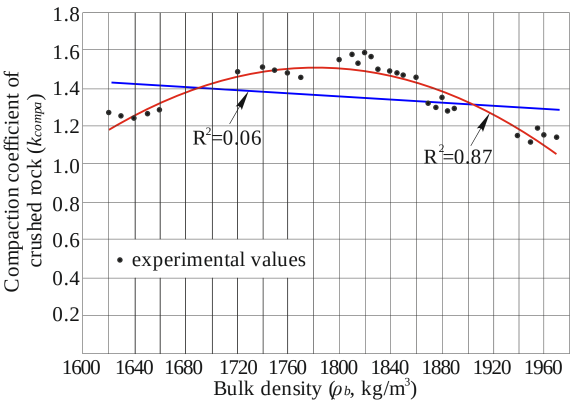

Figure 5. Graphs of the change in the compaction coefficient of crushed rock k_{compa} at different bulk density ρ_b (kg/m^3) of the source backfill material

Let us analyse the correlation field of the obtained experimental data with their subsequent approximation (Fig. 5). As a result of the research performed, it has been determined that the closest link between the considered parameters can be described by a quadratic parabola, the determination coefficient of which is $R^2 = 0.87$. Thus, the resulting regression equation, which has the form:

$$y = ax + bx + c = -0.00001213x^2 + 0.0432x - 36.9\,, \tag{5}$$

explains 87% of the variance of the effective feature, and the share of factors not considered in the experiment is 13% of its variance.

When approximating the experimental data by a linear dependence, the determination coefficient is $R^2 = 0.06$ (Fig. 5).

It has been experimentally determined that with an inhomogeneous granulometric crushed rock composition, the fraction size of which is 0.1-5 mm, and the bulk density ρ_b = 1800-1820 kg/m^3, the compaction coefficient value corresponds to k_{compa} = 1.54-1.57. In the case when the crushed rock is represented by a large sized fraction of 4-5 mm, with a bulk density ρ_b = 1620-1650 kg/m^3, the compaction coefficient values are k_{compa} = 1.24-1.27. In the presence of fine homogeneous fractions with a particle size of 0.1-1 mm in the backfill material, with a bulk density ρ_b = 1940-1970 kg/m^3, the compaction coefficient value decreases to k_{compa} = 1.11-1.16.

From this, it follows that with an inhomogeneous granulometric composition of the crushed rock, as a result of compression, the compaction coefficient values k_{compa} have maximum values in the range k_{compa} = 1.54-1.57.

This is also confirmed by the results of research in [21], [33], where it was determined that soils with a homogeneous granulometric composition, plastic deformations are much less manifested. Constant changes in the structure take place in soils with an inhomogeneous granulometric composition, when plastic deformations develop uniformly.

When the obtained experimental data are processed and the dependences are analysed, the optimal bulk density value of the crushed rock can be determined:

$$\rho_b^{opt} = -\frac{b}{2a} = \frac{0.0432}{2 \cdot 0.00001213} = 1780 \text{ kg/m}^3, \tag{6}$$

at which the compaction coefficient k_{compa} takes maximum values corresponding to k_{compa} = 1.56.

When performing research on determining the compaction coefficient values of the backfill mass k_{compa}, mathematical statistics has been used, which made it possible to assess their accuracy and reliability during processing the experimental results.

The constrained modulus E_{constr} (MPa) of the backfill mass deformation is determined as in the [20], [28] by the expression:

$$E_{constr} = \frac{\sigma h}{\Delta h}, \tag{7}$$

where:

σ – pressure transferred to the crushed rock sample, MPa.

Under compression, the crushed rock sample deformation occurs as a result of volume compression. It has previously been determined [20], [34] that regardless of the type of stress state, when the crushed rock is compressed, its structure is compacted and the contact between particles increases. It is believed [28] that when the sample is compressed in a steel cylinder, the sample diameter does not change, and the relative vertical deformation is equal to the relative volume change ΔV (m^3). Obviously, when compressed, there is a decrease in the volume of the backfill material, and then a relative change in its void factor ΔM (%) also occurs, that is, the ratio is valid:

$$\frac{\Delta h}{h} = \frac{\Delta V}{V} = \frac{\Delta M}{M}, \tag{8}$$

where:

V – initial volume of the crushed rock sample, m^3.

Given the above, the change in void factor ΔM (%) of the backfill material is possible to determine using the expression:

$$\Delta M = \frac{\Delta h}{h} \cdot M, \tag{9}$$

when, as a result of its compressibility, there is a repacking of crushed rock fractions [20]-[25], [34], [35] within a system of backfilling the mass.

Backfill mass have a similar rigidity coefficient C (N/m) as in the spring. However, unlike a spring, the rigi-dity coefficient of the backfill mass is not constant and increases in proportion to the pressure increase [36].

Laboratory studies data on determining the rigidity C (N/m) of the backfill mass are presented in Table 3.

Figure 6 shows the graphs reflecting the change in the relative linear deformation λ_z and constrained modulus E_{constr} (MPa) of the backfill mass deformation at different crushed rock bulk density ρ_b (kg/m^3).

Table 3. Laboratory studies data of the compression characteristics of the backfill mass from crushed rock with different fractions

Fraction size, mm	Maximum compression force, F, kN	σ, MPa	ρ_b, kg/m^3	h, m	Δh, m	λ_z	E_{constr}, MPa	C, N/m
0.1-5	150	34.8	1820	0.063	0.023	0.36	95.3	$6.5 \cdot 10^6$
4-5	130	30.6	1680	0.062	0.021	0.33	90.2	$6.2 \cdot 10^6$
3-4	120	27.9	1720	0.063	0.02	0.31	87.8	$6.0 \cdot 10^6$
2-3	110	25.5	1860	0.064	0.017	0.26	96.1	$6.4 \cdot 10^6$
1-2	90	21	1880	0.062	0.011	0.17	118.3	$8.1 \cdot 10^6$
0.1-1	70	16.2	1940	0.062	0.007	0.11	142.5	$10 \cdot 10^6$

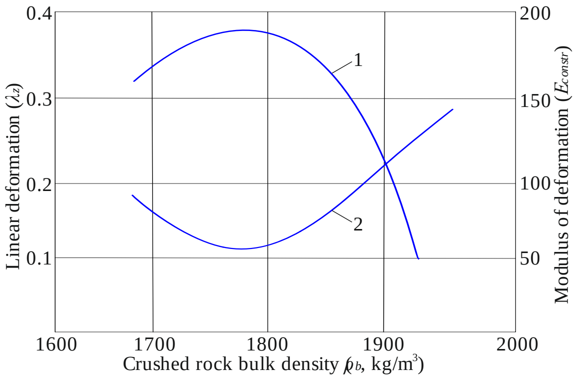

Figure 6. Graphs of the change in the relative linear deformation λ_z and constrained modulus E_{constr} (MPa) of the backfill mass deformation at different crushed rock bulk density ρ_b (kg/m^3): 1 – λ_z; 2 – E_{constr} (MPa)

It has been determined that with an increase in the crushed rock bulk density ρ_b from ρ_b = 1680 kg/m^3 to ρ_b = 1800 kg/m^3, the relative linear deformation λ_z of the backfill mass increases, and with ρ_b > 1800 kg/m^3, it sharply decreases (Fig. 6, dependence 1).

With an increase in the crushed rock bulk density from ρ_b = 1800 kg/m^3 to ρ_b = 1940 kg/m^3, the values of E_{constr} (MPa) increase from E_{const} = 60 MPa to E_{const} = 147 MPa. In the interval ρ_b = 1680-1800 kg/m^3, the values of the constrained modulus of backfill mass deformation decrease from E_{const} = 95 MPa to E_{const} = 60 MPa (Fig. 6, dependence 2).

From the data in Table 3 follows that the maximum compression Δh = 0.023 m of crushed rock in a steel cylinder occurs at ρ_b = 1820 kg/m^3, and the minimum compression value Δh = 0.007 m is recorded when ρ_b = 1940 kg/m^3. It is evident that with an increase in the value of the constrained modulus of deformation E_{constr} (MPa), the compressibility of the backfill material decreases. The constrained modulus of deformation E_{constr} (MPa) characterizes the compression degree of the crushed rock system, namely, the backfill mass shrinkage.

Figure 7 shows the graphs of changes in void factor ΔM (%) of the backfill material from crushed rock with different bulk density ρ_b (kg/m^3) under uniaxial compression in a steel cylinder.

It is seen from Figure 7 that with an increase in ρ_b (kg/m^3), the value of ΔM (%) decreases from of ΔM = 6.6% at ρ_b = 1680 kg/m^3 to ΔM = 0.88% at ρ_b = 1940 kg/m^3 which testifies a variable compaction coefficient of the backfill material having different granulometric composition of the crushed rock. With an increase in the rigidity of the backfill mass material $c \cdot 10^6$ (N/m), the values of the compaction coefficient k_{compa} and the backfill mass shrinkage ΔZ (%) decrease ΔZ (%) (Fig. 8). It can be noted that at the maximum rigidity of the backfill mass, when $c = 10 \cdot 10^6$ N/m, the minimum compression value is Δh = 0.007 m.

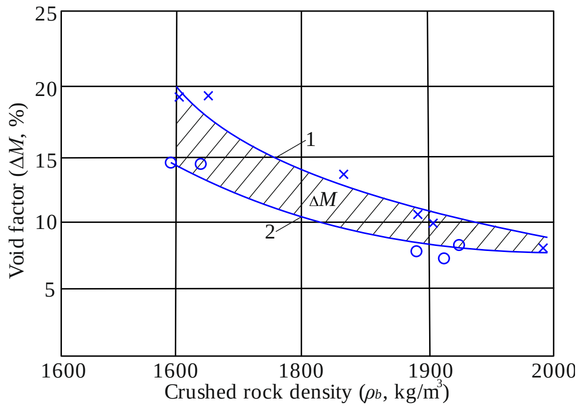

Figure 7. Change in the void factor ΔM (%) of the backfill material from crushed rock with different granulometric composition at a certain bulk density ρ_b (kg/m^3) as a result of uniaxial compression in a steel cylinder: 1 – void factor M (%) before compression; 2 – void factor M (%) after compression

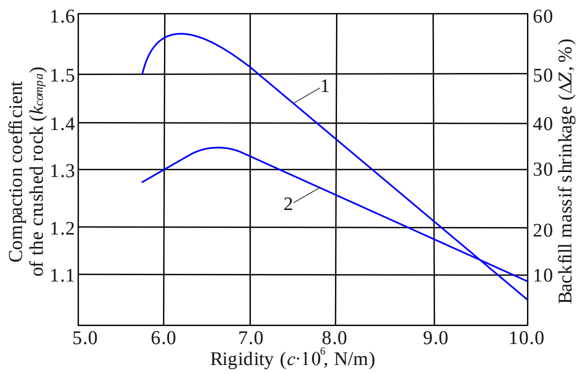

Figure 8. Graphs of the change in the crushed rock compaction coefficient k_{compa} and the backfill mass shrinkage ΔZ (%) at a variable rigidity $c \cdot 10^6$ (N/m): 1 – k_{compa}; 2 - ΔZ (%)

Hence, the minimum compaction coefficient is k_{compa} = 1.1 with the backfill mass shrinkage Δz = 10% (Fig. 9).

It is also obvious that with an increase in the compressive force F (kN), the rigidity of the backfill mass material increases. Thus, for the crushed rock, the size of the fraction of which is 0.1-1 mm, with an increase in the compressive force from F = 20 kN to F = 60 kN, the rigidity of the backfill mass material increases from $C = 7.4 \cdot 10^6$ N/m to $C = 9.5 \cdot 10^6$ N/m. As a result of this interaction, the maximum compression of the homogeneous crushed rock of the fine fraction occurs, and Δh = 0.007 m (Fig. 10).

It should be noted that the backfill mass of crushed rock are complex research objects, the physical characteristics of which depend on a large number of factors.

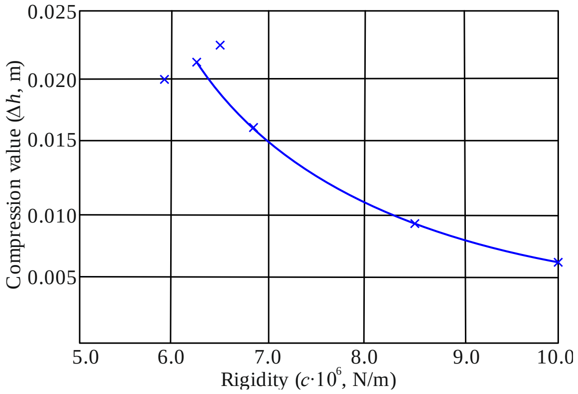

Figure 9. Graphs of the change in the compression value Δh (m) of the backfill mass depending on the rigidity c·10⁶ (N/m)

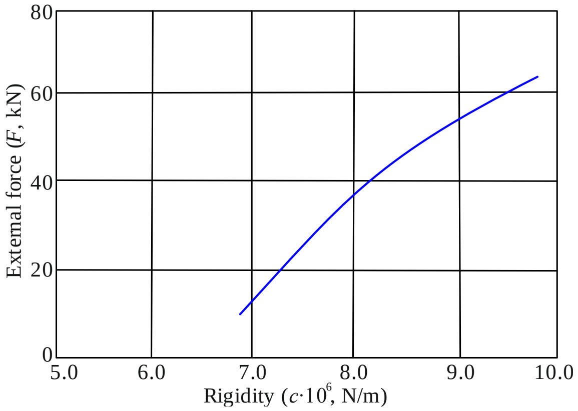

Figure 10. Graph of the change in the external force value F (kN) applied to a plunger in a steel cylinder with crushed rock under uniaxial compression depending on the backfill material rigidity c·10⁶ (N/m): crushed rock fraction 0.1-1 mm

Each specific type of backfill mass as a physical body was assessed using a number of physical characteristics. The physical parameters determined from the experiments give an estimate of the backfill mass real properties with a certain error (up to 13%).

4. Discussion of experimental research results

To assess the deformation properties of the backfill mass, compression pressure on the crushed rock with various granulometric composition is used in this study. Compression tests (Fig. 1) are a convenient tool for modelling the backfill mass behaviour under load for determining their physical and mechanical characteristics.

As a research result, it has been revealed that the granulometric composition of the crushed rock and its inhomogeneity are the main characteristics for determining the physical properties of backfill mass (Table1, Fig. 2), used to support side rocks in the coal-rock mass enclosing mine workings.

The void factor of the backfill mass depends on the granulometric composition of the crushed rock, taking into account the geometric shape, size and arrangement of particles in space (Table 2, expr. 7, Fig. 7). As a result of compression, the backfill mass shrinkage occurs, that is, repacking of crushed rock particles, and hence a decrease in the volume and void factor of the backfill material (Figs. 3, 4, 8). In the case when the backfill mass is represented by a homogeneous fraction of a large size, its deformation occurs due to the elastic compression of the crushed rock. With an inhomogeneous granulometric composition of the crushed rock, as a result of compression, a mutual displacement of fractions occurs relative to each other, with a maximum backfill mass shrinkage and a maximum compaction coefficient (Fig. 5).

The deformation characteristics of the backfill mass, as a system, determine their ability to respond to the impact of various external factors, which are manifested in the coal-rock mass enclosing mine workings. One of the main requirements for backfill mass, intended to ensure the side rocks stability and the safety of mine workings is their rigidity. The value of the backfill mass rigidity, under constant load, is regulated by the granulometric composition of the crushed rock (Table 3). The greater the rigidity of the backfill mass system, the higher the deformation modulus (Fig. 6).

The constrained modulus of deformation E_{constr} (MPa) cannot be taken as a constant physical characteristic of the backfill mass, since is a variable value that depends on the system rigidity (Table 3). For efficient mining of coal seams at great depths, when providing the side rocks stability during unloading of the coal-rock mass and to maintain the mine workings in an operational state, it is necessary to focus on the method of controlling the roof in the stope face by backfilling of the mined-out space. To obtain the maximum effect from the use of backfilling of the mined-out space, it is necessary to provide the inhomogeneity of the source backfill material, as a system of fractions.

Having certain physical and mechanical peculiarities, backfill mass from crushed rock are protective structures for mine workings, which restrain the displacements of side rocks in the coal-rock mass.

The use of backfilling of the mined-out space helps to reduce the loss of minerals in the subsoil. Backfilling is used to leave rock in the mine after mining operations and mine workings repair. Moreover, when conducting stope works with the backfilling of the mined-out space, the problem of waste-free, environmentally friendly production is solved. For backfilling of the mined-out space, wastes from processing plants and rock waste dumps can be used with certain requirements for backfill materials substantiated in this research. In modern conditions, the backfilling of the mined-out space should be considered as a way to protect the environment from the technogenic impact of underground mining operations.

5. Conclusions

1. The physical and mechanical characteristics of the crushed rock determine the ability of the backfill mass, as a deformable system to respond to the impact of external factors, which are manifested during unloading the coal-rock mass. The change in the void factor and the backfill mass shrinkage under compression pressure influence depends on the load value, the size of the crushed rock fractions and their percentage content in the total volume.

2. The deformation properties of the backfill mass indicate that under a constant load, their rigidity variance is possible as a result of a change in the crushed rock granulometric composition. The maximum shrinkage of the backfill mass occurs at the maximum value of the crushed rock compaction coefficient, when k_{compa} = 1.56. With this compaction coefficient value, the optimal characteristics of the backfill mass are ensured. When solving the problem of mine work-

ings stability, it is necessary to predetermine the issues of the backfill mass rigidity, which will restrain the side rocks displacements with a certain permissible value of shrinkage and ensure the unloading of the coal-rock mass from stresses.

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References

[1] Zhang, D., Miao, X., Ma, L., & Feng, G. (2004). Technique of gob-side entry retaining with entry-in packing in fully-mechanized coalface with top-coal caving. *Mining Science and Technology, 36*(10), 49-54. https://doi.org/10.1201/9780203022528-9

[2] Yang, S.-L., Ding, X.-P., Wang, X., Li, X.-M., & Lin, L. (2013). Analysis of floor failure depth by using electric profiling method in longwall gangue backfill mining. *Journal of Coal Science and Engineering (China), 19*(3), 282–289. https://doi.org/10.1007/s12404-013-0303-4

[3] Wu, W., Bai, J., Yan, S., Wang, X., & Wu, B. (2020). Planning and design of underground space construction during longwall mining in coal mines. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 1-15. https://doi.org/10.1080/15567036.2020.1747574

[4] Vasil'yeva, I.V. (2015). Aktual'nyye voprosy monitoringa porodnykh otvalov ugol'nykh shakht i okhrany okruzhayushchey sredy. *Míneralní Resursy Ukrainy*, (3), 39-45.

[5] Piwniak, G.G., Bondarenko, V.I., Salli, V.I., Pavlenko, I.I., & Dychkovskiy, R.O. (2007). Limits to economic viability of extraction of thin coal seams in Ukraine. *Technical, Technological and Economic Aspects of Thin-Seams Coal Mining*, 129-132. https://doi.org/10.1201/noe0415436700.ch16

[6] Khayrutdinov, M.M., & Shaymyardyanov, I.K. (2009). Podzemnaya geotekhnologiya s zakladkoy vyrabotannogo prostranstva: nedostatki, vozmozhnosti sovershenstvovaniya. *Gornyy Informatsionno-Analiticheskiy Byulleten'*, (1), 240-250.

[7] Dzyuba, S.V., Shmelev, N.A., & Koval', N.V. (2012). Analiz tekhnologiy podzemnoy razrabotki mestorozhdeniy poleznykh iskopayemykh pri vedenii gornykh rabot v slozhnykh gorno-geologicheskikh usloviyakh. *Geotekhnicheskaya Mekhanika*, (101), 284-291.

[8] Bulat, A.F., Skipochka, S.I., Palamarchuk, T.A., & Antsiferov, V.A. (2010). *Metanogeneratsiya v ugol'nykh plastakh*. Dnepropetrovsk, Ukraina: Lira.

[9] Seitmuratova, E., Arshamov, Y., Bekbotayeva, A., Baratov, R., & Dautbekov, D. (2016). Priority metallogenic aspects of late paleozioc volcanic-plutonic belts of Zhongar-Balkhash fold system. *International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management*, (1), 511-518. https://doi.org/10.5593/sgem2016/b11/s01.064

[10] Kolokolov, O.V. (1997). *Tekhnologiya zakladki vyrabotannogo prostranstva v shakhtakh i rudnikakh*. Dnepropetrovsk, Ukraina: Sich.

[11] Zhukov, V.E. (2001). On one strategic mistake in resolving the problem of developing steep formations. *Ugol of Ukraine*, (7), 6-10.

[12] Kuz'menko, O., Petlyovanyy, M., & Stupnik, M. (2013). The influence of fine particles of binding materials on the strength properties of hardening backfill. *Annual Scientific-Technical Colletion – Mining of Mineral Deposits*, 45-48. https://doi.org/10.1201/b16354-10

[13] Zhukov, V.Ye., Vystorop, V.V., & Kolchin, A.M. (1984). *Malootkhodnaya tekhnologiya dobychi uglya*. Kiev, Ukraina: Tekhnika.

[14] Zhukov, V.Ye. (2001). Ob odnoy strategicheskoy oshibke v razreshenii problemy razrabotki krutykh plastov. *Ugol' Ukrainy*, (7), 6-10.

[15] Zborshchik, M.P., & Podkopayev, S.V. (1992) Mekhanizm povysheniya ustoychivosti krovli v lavakh pri primenenii zakladki vyrabotannogo prostranstva. *Ugol' Ukrainy*, (5), 20-23.

[16] Iordanov, I., Simonova, Y., Kayun, O., Podkopayev, Y., Polozhii, A., & Boichenko, H. (2020). Substantiation of the stability of haulage drifts with protective structures of different rigidity. *Eastern-European Journal of Enterprise Technologies, 3*(7(105)), 87-96. https://doi.org/10.15587/1729-4061.2020.202483

[17] Kazikayev, D.M., Kozyrev, A.A., Kaspar'yan, E.V., & Iofis, M.A. (2016). *Upravleniye geomekhanicheskimi protsessami pri razrabotke mestorozhdeniy poleznykh iskopayemykh*. Moskva, Rossiya: Gornaya kniga.

[18] Podkopaiev, S., Iordanov, I., & Chepiha, D. (2017). Stability of the coal seam roof during the sudden collapse of lateral rocks. *Mining of Mineral Deposits*, 11(3), 101-110. https://doi.org/10.15407/mining11.03.101

[19] Sipidin, V.P., & Sidorov, N.N. (1963). *Issledovaniye gruntov v usloviyakh trekhosnogo szhatiya*. Moskva, Rossiya: Gosizdatel'stvo po stroitel'stvu, arkhitekture i stroitel'nym mterialam.

[20] Ter-Martirosyan, Z.G., Mirnyy, A.Yu., & Dzharo, M.N. (2012). Opredeleniye prochnykh kharakteristik nesvyazannykh gruntov pri kompressionnykh ispytaniyakh. *Internet-Vestnik VolgGASU*, (3), 1-6.

[21] Wesley, L.D. (2009). *Fundamentals of soil mechanics for sedimentary and residual soils*. Hoboken, New Jersey, United States: https://doi.org/10.1002/9780470549056

[22] Krupnik, L.A., Shaposhnik, Y.N., Shaposhnik, S.N., & Tursunbaeva, A.K. (2013). Backfilling technology in Kazakhstan mines. *Journal of Mining Science, 49*(1), 82-89. https://doi.org/10.1134/s1062739149010103

[23] Bondarenko, V., Symanovych, G., & Koval, O. (2012). The mechanism of over-coal thin-layered mass deformation of weak rocks in a longwall. *Geomechanical Processes During Underground Mining*, 41-44. https://doi.org/10.1201/b13157-8

[24] Abdiev, A., Mambetova, R., Abdiev, A., & Abdiev S. (2020). Development of methods for assessing the mine workings stability. *E3S Web of Conference*. Preprint.

[25] Tsytovich, N.A. (1983). *Mekhanika gruntov*. Moskva: Vysshaya shkola.

[26] Craing, R.F. (1997). *Soil mechanics*. London, United Kingdom: Spon Press.

[27] Robitalle, V., & Tremblay, D. (1997). *Mecanique des sols: Theorie et pratique*. Canada: Science.

[28] Borsch, N.I. (2009). *Soil mechanics*. Omsk, Rossiya: SibADI.

[29] Podkopayev, S.V., Gavrish, N.N., Deglin, B.M., & Kamenets, V.I. (2012). *Laboratornyy praktikum po kursu "Mekhanika gornykh porod"*. Donetsk, Ukraina: DonNTU.

[30] Tsirel', C.B., Gaponov, Yu.S., & Shokov, A.N. (2013). Otsenka vliyaniya granulometricheskogo sostava na szhimayemost' i pustotnost' zakladochnogo materiala. *Gornyy Informatsionno-Analiticheskiy Byulleten'*, (12), 80-83.

[31] Anikeyenko, A.V., & Medvedev, N.N. (2007). Strukturnyy analiz monodispersnykh upakovok tverdykh sfer pri raznoy plotnosti. *Struktura i Dinamika Molekulyarnykh Sistem*, (1), 700-705.

[32] Bertail, P., Soulier, P., & Doukhan, P. (2006). *Dependence in probability and statistics. Lecture Notes in Statistics*. Berlin, Germany: Springer. https://doi.org/10.1007/0-387-36062-x

[33] Mirnyy, A.Yu., & Ter-Martirosyan, A.Z. (2014) Podbor granulometricheskogo sostava peschano-graviynykh smesey dlya peschanykh podushek i nasypey. *Zhilishchnoye Stroitel'stvo*, (9), 43-49.

[34] Yakobi, O. (1981). *Praktika upravleniya gornym davleniyem*. Moskva, Rossiya: Nedra.

[35] Kobayashi, H., Mark, B.L., & Turin, W. (2009). *Probability, random processes, and statistical analysis*. Cambridge, United Kingdom: Cambridge University Press. https://doi.org/10.1017/cbo9780511977770

[36] Ishibashi, I., & Hazarika, H. (2015). *Soil mechanics fundamentals and applications*. London, United Kingdom: CRC Press. https://doi.org/10.1201/b18236

Експериментальні характеристики деформаційних властивостей закладних масивів

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Мета. Визначити деформаційні властивості закладних масивів, використовуваних для збереження цілісності вуглепородної товщі, що вміщає гірничі виробкит.

Методика. Для досягнення поставленої мети були виконані лабораторні дослідження на зразках з роздробленої породи різного гранулометричного складу, які піддавалися одноосьовому стиску в сталевому циліндрі. Експериментальні дані оброблялися методами математичної статистики.

Результати. В результаті виконаних лабораторних досліджень встановлено, що при компресійному стискуванні закладного матеріалу з роздробленої породи, модуль деформації є змінною величиною і залежить від значення прикладеного навантаження, а значить, не може застосовуватися як фізична характеристика закладного масиву. Доведено, що модуль деформації характеризує жорсткість закладного масиву, тобто його граничний напружений стан. Величину жорсткості, при постійному зовнішньому навантаженні, можна регулювати гранулометричним складом дробленої породи. Встановлено, що досягнення максимальної усадки закладного масиву, забезпечується при перепакування неоднакових за розмірами фракцій роздробленої породи при об'ємному стисненні закладного матеріалу. У разі, коли закладний матеріал представлений однорідної фракцією роздробленої породи, при збільшенні компресійного модуля, жорсткість закладного масиву збільшується, а усадка зменшується.

Наукова новизна. Доведено, що значення коефіцієнта ущільнення подрібненої породи, який характеризує усадку закладного масиву, корелюються параболою і залежать від гранулометричного складу вихідного матеріалу. При неоднорідному гранулометричному складі, значення коефіцієнта ущільнення приймають максимальні значення, а для закладного матеріалу з однаковою фракцією – зменшуються, у міру зміни насипної щільності роздробленої породи.

Практична значимість. Для забезпечення стійкості бічних порід і збереження гірничих виробок в експлуатаційному стані, необхідно забезпечити рівномірну за обсягом неоднорідність гранулометричного складу роздробленої породи, що визначає здатність покрівлі і ґрунту вугільного пласта ефективно реагувати на вплив зовнішніх факторів, що проявляються в масиві осадових гірських порід при веденні гірничих робіт.

Ключові слова: *стійкість, покрівля, вугільний пласт, очисний вибій, напружено-деформований стан, моделювання, еквівалентні матеріали*

Экспериментальные характеристики деформационных свойств закладочных массивов

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Цель. Определить деформационные свойства закладочных массивов, используемых для сохранения целостности углепородной толщи, вмещающей горные выработки.

Методика. Для достижения поставленной цели были выполнены лабораторные исследования на образцах из дробленой породы разного гранулометрического состава, которые подвергались одноосному сжатию в стальном цилиндре. Экспериментальные данные обрабатывались методами математической статистики.

Результаты. В результате выполненных лабораторных исследований установлено, что при компрессионном сжатии закладочного материала из дробленой породы, модуль деформации является переменной величиной и зависит от значения прикладываемой нагрузки, а значит, не может применяться как физическая характеристика закладочного массива. Доказано, что модуль деформации характеризует жесткость закладочного массива, т.е. его предельное напряженное состояние. Величину жесткости, при постоянной внешней нагрузке, можно регулировать гранулометрическим составом дробленной породы. Установлено, что достижение максимальной усадки закладочного массива, обеспечивается при переупаковке неодинаковых по размерам фракций дробленой породы при объемном сжатии закладочного материала. В случае, когда закладочный материал представлен однородной фракцией дробленой породы, при увеличении компрессионного модуля, жесткость закладочного массива увеличивается, а усадка уменьшается.

Научная новизна. Доказано, что значения коэффициента уплотнения дробленой породы, который характеризует усадку закладочного массива, коррелируются параболой и зависят от гранулометрического состава исходного материала. При неоднородном гранулометрическом составе, значения коэффициента уплотнения принимают максимальные значения, а для закладочного материала с одинаковой фракцией- уменьшаются, по мере изменения насыпной плотности дробленой породы.

Практическая значимость. Для обеспечения устойчивости боковых пород и сохранности горных выработок в эксплуатационном состоянии, необходимо обеспечить равномерную по объему неоднородность гранулометрического состава дробленой породы, что определяет способность кровли и почвы угольного пласта эффективно реагировать на воздействия внешних факторов, проявляющихся в массиве осадочных горных пород при ведении горных работ.

Ключевые слова: *устойчивость, кровля, угольный пласт, очистной забой, напряженно-деформированное состояние, моделирование, эквивалентные материалы*

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