This study addresses issues related to deformation processes in crushed rock backfills, which are used to control the condition of surrounding rocks in the extraction areas of coal mines.

The task under consideration is to maintain mine roadway stability by preventing roof collapses in the gob area by ensuring the bearing capacity of backfills.

Deformation processes were studied on model materials made of crushed rock of various grain-size distributions and bulk densities. The material was subjected to compression testing, which simulated the complete backfilling of the gob area. It was shown that the energy characteristics of deformation and compaction of crushed rock determine the bearing capacity of backfills. The deformation energy density was determined by the grain-size distribution of the crushed rock with a polyfractional composition. The maximum values of the specific potential deformation energy were recorded during compression of crushed rock with a coefficient of uniformity $C_u = 5.99$, which has a stiffness 7–13% higher than that of polyfractional materials with $C_u < 4$, which ensures the bearing capacity of the backfill mass. It was established that with an increase in the compaction coefficient of the backfill material, the relative volume change per unit of convergence, ΔV_K (m^{-1}), occurs according to a hyperbolic relationship, allowing the prediction of the ultimate compaction of the backfill material.

The stability of gob-side retained entries can be ensured by complete gob backfilling. The expected settlement of the backfill material determines the nature of the limitation of lateral rock movements in the gob area, the bearing capacity of the artificial massif, and depends on the grain-size distribution of the crushed rock

Keywords: grain-size distribution, crushed rock, compressive compaction, complete backfilling of the gob area

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EVALUATION OF DEFORMATION CHARACTERISTICS AND BEARING CAPACITY ASSESSMENT OF CRUSHED-ROCK BACKFILL WITH VARIOUS GRAIN SIZE DISTRIBUTIONS

Daria Chepiga
Corresponding author
PhD, Associate Professor*
E-mail: daria.chepiha@donntu.edu.ua

Oleksandr Tkachuk
Chief Engineer
Structural Unit "Elektroremont" of PJSC "Donbasenergo"
Sichovykh Striltsiv str., 9, Mykolaivka, Ukraine, 84180

Leonid Bachurin
PhD, Associate Professor*

Yaroslava Bachurina
Senior Lecturer*

Yevgen Podkopayev
Doctor of Philosophy (PhD)
LLC MC ELTEKO
O. Tyhoho str., 2, Kostyantynivka, Ukraine, 85105

Anatolii Bielikov
Doctor of Technical Sciences, Professor
Department of Labor Protection, Civil and Technogenic Safety
SEI "Prydniprovska State Academy of Civil Engineering and Architecture"
Arkhitektora Oleha Petrova str., 24-A, Dnipro, Ukraine, 49600

Olena Visyn
PhD, Associate Professor**

Serhii Podkopaiev
Doctor of Technical Sciences, Professor**

Larysa Bondarchuk
PhD, Associate Professor**

Igor Androshchuk
PhD, Associate Professor**

*Department of Mining Management and Labour Protection
Donetsk National Technical University
Shevchenka str., 9, Drohobych, Ukraine, 82100

**Department of Civil Security
Lutsk National Technical University
Lvivska str., 75, Lutsk, Ukraine, 43018

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1. Introduction

The extraction of a coal seam stimulates the processes of stratification and collapse of lateral rocks in the coal-rock mass, which leads to a decrease in the safety of operations in gob-side retained entries of coal mines. One of the effective methods of roof control during longwall mining operations is backfilling the gob area with crushed rock. This method helps to reduce manifestations of rock pressure and ensures the stability of mine roadways in the extraction panels. Mining operations with gob backfilling using waste rock generated during mining, or with coal preparation tailings, are one of the approaches to reducing environmental impact [1–3].

After backfilling the gob area, the waste rock forms a backfill mass that performs supporting functions and prevents unregulated subsidence of the ground surface, engineering structures, and facilities.

When using the backfilling of the gob area with waste rock, conditions are created in the coal-rock mass under which uncontrolled movement of the surrounding rocks is eliminated, and the stability of the mine roadways is maintained. However, such a geomechanical situation occurs with a certain grain-size distribution of the backfill material.

Based on this, a relevant scientific task arises to study the influence of the grain-size distribution of crushed rock on deformation processes in backfill masses. This will allow us to assess their bearing capacity and to develop measures to prevent collapses of lateral rocks, ensure the stability of the gob-side retained entries, and create safe working conditions in the extraction panels of coal mines.

2. Literature review and problem statement

In Donbas, over 2.6 billion tons of rock removed from mines are stored in 1,500 waste dumps covering about 30,000 hectares of agricultural land [2]. Therefore, it is possible to reduce the environmental impact of coal mining operations by applying technologies for coal mining with the waste rock left in the mines. Despite the experience gained in Ukrainian mines in gob backfilling, the scale of application of this technology remains extremely small. With an annual coal production in Ukraine of about 80 million tons in the early 2000s, about 8–10 million tons of waste rock accumulated annually in mine dumps [3]. It can be assumed that the main reasons for the insufficient application of coal mining technologies with waste rock left underground were the lack of special mechanized equipment. Moreover, transporting the waste rock to the backfilling site was complicated by the fact that, in 50% of cases, the condition of the mine roadways was unsatisfactory.

The essence of gob backfilling with waste rock is that the gob area of the longwall extraction panel is filled with backfill material. The backfill mass, when compacted, facilitates the smooth lowering of the roof [4, 5]. The use of gob backfilling in combination with powered roof support ensures rhythmic operation of the longwall face, reduces the intensity of rock pressure manifestations at the face [6], and increases the stability of the surrounding rocks and mine roadways.

When using complete gob backfilling, the collapse of lateral rocks and blockage of gob-side retained entries are eliminated. Possessing certain physical and mechanical properties, rock-based backfilling materials perform the functions of supporting structures and limit the displacement of surrounding rocks in the coal-rock mass [4, 7]. In work [4], it is demonstrated that complete backfilling of the gob area (with a filling ratio of at least 82.5%) can prevent the evolution of intensive fracturing around the mine workings and create a stable rock zone. At the same time, the mechanisms of backfill material compaction, which depend on the backfilling method and grain-size distribution, remain outside the scope of consideration. In [7], a theoretical and model-based justification of the influence of the deformability of the backfill mass on the state of the undermined rock strata behind the longwall face is provided, but the behavior of the backfill mass under ultimate pressure levels is not demonstrated, which is a consequence of the limitations of the model used.

Operational experience from extraction panels with gob backfilling indicates an improvement in the geomechanical conditions around the gob-side retained entries. To achieve this goal, it is necessary to consider the deformation processes in the backfill masses of crushed rock that occur during unloading of the coal-rock mass [8].

Studies on the behavior of backfill masses from various materials demonstrate the importance of analyzing the influence of the grain-size distribution and component composition of the backfill material, as well as its preparation, on its deformation characteristics [5, 8–12].

In [5], in particular, the optimal ratio of the main components of the backfill mixture and the optimization of the technology of backfilling and preliminary compaction of the material are determined. The results are analyzed in the context of crack formation in the layers of the main roof and the effect of the degree of backfilling of the gob area on the amount of surface subsidence. However, since the study was focused on finding the optimal ratio in a backfill material composed of coal-fired power plant ash and coal beneficiation waste, the analysis of the influence of the grain-size distribution on the degree of settlement was left out of consideration.

In [8], attention is drawn to the need to avoid the use of materials with plastic properties when it comes to controlling the displacements of the undermined rock masses. This is one of the critical parameters when using hydraulic backfilling. Also, the cited work formulates the general recommended parameters for the grain-size distribution of the material used for backfilling and analyzes the influence of the grain-size distribution on the main physico-mechanical characteristics of the material. At the same time, a pre-compacted model material was used in the experiment. Although that does not prevent comparing the characteristics of different materials, it should be noted that pre-compaction under mine conditions is usually either impossible or ineffective, and the compaction coefficient is one of the most important parameters of the backfill material and should be determined by the deformation conditions. In [9], it is shown that pre-compaction at the level corresponding to the first, rapid stage of compaction significantly affects the material settlement; therefore, it is impossible to extrapolate the behavior of pre-compacted material to uncompacted material. The authors of [9] also emphasize the need for careful selection of solid materials for backfilling and control over their volumetric ratio.

In [10], attention is drawn to the importance of using well-graded materials for backfilling, and the experiments focus on studying the deformation behavior of materials with a rock size of up to 50 mm. However, since the methodology of this work is similar to that in [8, 9], the influence of pre-compaction and the corresponding caveats should be taken into account.

In contrast, in [11], the relationship between the grain-size distribution and the loosening coefficient of the backfill material obtained during selective extraction of coal and rock with a rock size of up to 140 mm was investigated. The dependences established by the authors make it possible to control the granulometric characteristics of the backfill material to achieve the maximum density of the backfill mass. The compaction reserve of the backfill material in the cited work is determined by assessing its void ratio, which is based on the assumption of the possibility of complete filling of the cavities as the material is compacted and further crushed under pressure. However, this assumption has not been verified by testing the material under pressure.

When modeling the behavior of backfill materials, methods are used similar to those used to study the behavior of gob material in the gob area [13, 14]. The key characteristics of backfill material include the possible degree of compaction, determined by the ratio of the volume of the backfill material to the volume of extracted coal [5, 15], void ratio [11], ultimate deformation under pressure [13, 14], material density and mass ratio of the backfill material to extracted coal [16], as well as the deformation modulus [17]. In [17], variations of partial backfilling are also considered, including the protection of gob-side retained entries with rubble backfill strips, and the deformation modulus is used to assess their bearing capacity. Accordingly, the authors provide various recommendations regarding the optimal parameters of backfilling and the characteristics of backfill materials. Most of the above-mentioned studies, namely [1, 5, 8–11, 15, 16], are aimed at determining the characteristics of the backfill mass that are optimal for preventing the effects of undermining the rock mass and the surface. This requires achieving minimal settlement of the backfill material, but the magnitude of the ultimate settlement of the backfill material is not directly estimated, despite the use of a methodology that defines it as one of the key parameters [13, 14].

In the case of using complete backfilling as a method of controlling the state of the rock mass, attention should be paid to the importance of the unloading effect of the rock mass on the stability of mine roadways. From this perspective, it is necessary to consider the backfill mass as an element of the mine roadways' secondary support and maintenance system, the deformation mechanism of which has a direct impact on the stability of mine roadways. For this purpose, the bearing capacity of the secondary support structure is important. Its value is proportional to the work required to deform the material of the structure. Accordingly, the material capable of accumulating the maximum potential deformation energy would have the greatest bearing capacity.

Our review of the literature reveals insufficient attention to the compaction mechanisms of the backfill material, in particular, the dependence of bearing capacity and ultimate settlement on the grain-size distribution and backfilling method. The cited studies are focused on optimizing the characteristics of backfill masses to prevent the undermining of the rock mass and the surface, but do not analyze the influence of the grain size distribution on the degree of settlement and bearing capacity at ultimate pressure levels. Experiments often use pre-compacted material, which does not reflect actual mine conditions, where compaction is limited or unavailable. Although ultimate settlement is one of the key deformation properties of backfill material, its direct assessment is absent or carried out by indirect methods, indicating a gap in the understanding of the deformation behavior of backfill masses.

Therefore, a study determining the deformation characteristics and assessing the bearing capacity of backfill masses made of crushed rock is appropriate. The application of results will make it possible to improve measures to increase the efficiency of coal mine extraction panels.

3. The aim and objectives of the study

The purpose of the study is to determine the specific effects of the grain-size distribution of crushed rock on deformation processes in backfill masses. This will make it possible to predict the stability of gob-side retained entries, taking into account the bearing capacity of backfill masses.

To achieve this aim, the following objectives were accomplished:

– to assess the deformation properties of crushed rock with various grain-size distributions;

– to assess the bearing capacity of filling mass made of crushed rock of heterogeneous grain-size distribution.

4. Materials and methods

The object of the study is deformation processes in crushed rock backfills, which are used to roof control in the coal mine extraction panels. This experiment is part of a comprehensive study on the behavior of backfill material in models made from crushed rock under various loading conditions and with different grain-size distributions [12, 18].

The research hypothesis is that the potential deformation energy of crushed rock backfills determines their bearing capacity and stress-strain state. The maximum amount of potential strain energy per unit volume can be accumulated by a material that has a compaction reserve associated with the rearrangement (repacking) of grains and additional crushing of fractions.

The study assumes that the backfill material is under conditions of confined compression. Confined compression creates a specific stress-strain state in which the material cannot expand in the horizontal direction but undergoes vertical deformation under load. This method is conventionally used to model backfill masses and the behavior of gob material [13].

Backfill masses made from crushed rock with various grain-size distributions were modeled. Deformation processes in backfill masses made from crushed rock were studied under laboratory conditions and evaluated based on the condition of experimental models. The model parameters were determined based on the principles of geometric and force similarity, ensuring identical dimensionless characteristics [19]. As one of the characteristics of the material that depends on the grain-size distribution, bulk density ρ_b (kg/m^3 or t/m^3) was used.

During modeling, the identity of the equilibrium equations of the *in-situ* conditions and the model, as well as the reproduction of the corresponding deformation conditions, was ensured. At the same time, to achieve mechanical similarity between the model and *in-situ* conditions, equality of weight parameters was not maintained, since the action of gravity does not affect the deformation processes in the experiment.

The modeled loading conditions corresponded to a depth of 1000 m, which, given an average density of rocks in the mass of 2400 kg/m^3, corresponds to a pressure of 24 MPa. When testing the models, the aim was to reach the same load level.

Deformational similarity under such conditions is achieved automatically, since dimensionless indicators – relative deformation and compaction coefficient – are studied.

Geometric similarity is ensured by a single scaling ratio between the dimensions of model samples and the grains of the model material, and the dimensions of the mined coal seam and the rock fragments used for mechanical backfilling. The geometric modeling scale of 1:25 was adopted. This scale reflects the grain-size distribution of the crushed rock and the height of the model samples. The height of the samples is 0.04 m, thus corresponding to the mined coal seam thickness of 1.0 m.

When selecting crushed rock for the experimental models, the following ratio [19] was used

$$\mathrm{tg}\varphi_{mm} = \mathrm{tg}\varphi_{bm}, \quad (1)$$

where φ_{mm}, φ_{bm} are the internal friction angles of the model material and the backfill material, respectively, in degrees. The internal friction angle of the model material and the actual backfill material are identical and equal to 23°, and the Poisson's ratio of the model material and the actual backfill material are also the same and equal to 0.25.

As the source material, sandy-clay shale with an *in-situ* density of 2438 kg/m^3 and a bulk density of 1350 kg/m^3 was used. The grain size range of the rock in the backfill mass under mine conditions was taken as 0.1–150 mm, with D_{90} = 120 mm (90% of the pieces and grains of the material have a size less than or equal to 120 mm). As the model material, the same rock was used, crushed to a grain size range of 0.1–5 mm, which also corresponds to the 1:25 scale.

Sieve analysis data for the crushed rock model material batches are given in the Table 1. The uniformity and curvature coefficients were calculated using the grain-size distribution characteristics: 10% of particles have a size less than or equal to the D_{10} value, and 60% of grains have a size less than or equal to D_{60}. The cumulative grain-size distribution curves of the model materials with a polyfractional composition are shown in Fig. 1.

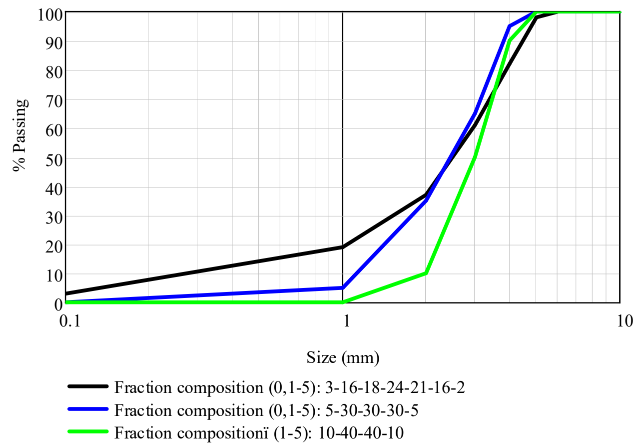
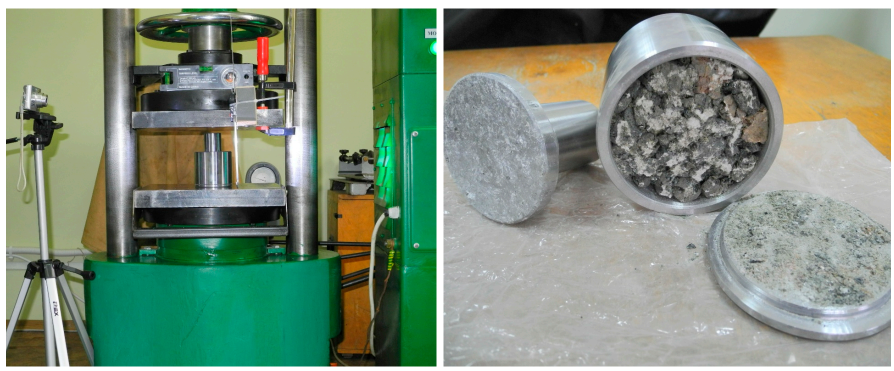


Fig. 1. Cumulative grain-size distribution curves of crushed rock

The optimal parameters for use as backfill material ($C_u > 4$, $1 \le C_c \le 3$ [8]) from the given batches correspond to model material No. 1, which is well-graded. For comparison, two additional samples with a grain size range of 1–5 and 2–5 mm (model materials Nos. 7, 8) were also prepared; these do not meet the optimal parameters given in [8].



a *b*

Fig. 2. Equipment for confined compression testing: *a* — GP-50 press with installed compression device; *b* — compression device

For the confined compression tests, a thick-walled metal cylinder with a diameter of 0.075 m and a height of 0.075 m was used. It was filled with crushed rock of the appropriate grain-size distribution to a height of 0.063 m. Thus, the cross-sectional area was 0.00442 m^2, and the material volume was 0.000278 m^3. The appearance of the experimental equipment is shown in Fig. 2.

The compression device with a batch of model material was placed between the metal plates of the GP-50 press and subjected to gradual loading. During the tests, at each stage of gradual loading, the deformation of the model Δh (m) and the corresponding load F (kN) were recorded.

For simplicity, the deformation of the testing equipment (the press and the components of the compression device) and friction forces were neglected.

The relative deformation λ of the material was determined by the expression

$$\lambda = \frac{\Delta h}{h_0}. \quad (2)$$

Under confined compression conditions, the relative change in the material volume ΔV is equal to the relative deformation λ, i.e.

Table 1

Sieve analysis data of crushed rock for experimental models

No.	Grain size, mm	% of total volume							Bulk density, ρ_b, kg/m^3	Uniformity coefficient $C_u = D_{60}/D_{10}$	Curvature coefficient $C_c = D_{30}^2 / D_{10}D_{60}$
		> 5	4–5	3–4	2–3	1–2	0.1–1	< 0.1			
1	0.1–5	2	16	21	24	18	16	3	1810	5.99	1.78
2	4–5	–	100	–	–	–	–	–	1680	–*	–*
3	3–4	–	–	100	–	–	–	–	1720	–*	–*
4	2–3	–	–	–	100	–	–	–	1860	–*	–*
5	1–2	–	–	–	–	100	–	–	1880	–*	–*
6	0.1–1	–	–	–	–	–	100	–	1920	–*	–*
7	1–5	–	10	40	40	10	–	–	1870	1.63	0.96
8	2–5	–	20	40	40	–	–	–	1840	1.56	0.96

*Note: * – for homogeneous fractions, the coefficients of uniformity and curvature are not calculated.*

$$\delta V = \frac{\Delta V}{V} = \frac{\Delta h}{h_0} = \lambda. \quad (3)$$

where ΔV is the change in the volume of the backfill material, m^3; V is the initial volume of the material, m^3; h_0 is the initial height, m.

The compaction coefficient k_c of the crushed rock was calculated by the ratio of the volume occupied by the crushed rock before compaction to the volume of this rock after compaction

$$k_A = \frac{V}{V - \Delta V} = \frac{1}{1 - \delta V}. \quad (4)$$

The specific potential deformation energy or strain energy density U (MJ/m^3) of the material was determined according to [20]

$$U = \frac{\sigma^2}{2E_d}, \quad (5)$$

where σ is the mechanical stress, Pa; E_d is the deformation modulus, Pa.

Mechanical stress is equal to pressure and is determined as

$$\sigma = \frac{F}{S}. \quad (6)$$

The stiffness of the model material C (N/m) was determined as

$$C = \frac{F}{\Delta h}. \quad (7)$$

The specific change in the volume of the model material per unit of convergence of lateral rocks ΔV_K (m^{-1}), during gradual loading, was determined according to [21]

$$\Delta V_K = \frac{\delta V}{\Delta U_{avg}}, \quad (8)$$

where ΔU_{avg} is the average increment of displacements, mm.

The average increment of displacements was determined as

$$\Delta U_{avg} = \frac{\Delta U_i + \Delta U_{i-1}}{2}, \quad (9)$$

where ΔU_i is the deformation increment, mm.

The deformation increment ΔU (mm) with increasing load was determined as

$$\Delta U_i = \Delta h_i - \Delta h_{i-1}, \quad (10)$$

where i is the number of measurement intervals.

The ΔV_K indicator is an informative parameter for tracking changes in the intensity and nature of material deformation and makes it possible to clearly identify intervals of stabilization or, conversely, an increase in the intensity of displacements. This approach is aimed at identifying the limit of deformation of the backfill material, which can be predicted based on experimental data.

Regression analysis of data was carried out using the "Regression" tool of the "Data Analysis" package in Microsoft Excel and in Mathcad.

5. Results of the study of deformation processes in backfill masses

5. 1. Results of the study of the deformation properties of crushed rock with various grain-size distribution

Under confined compression conditions, crushed rock with various grain-size distributions changes the height of the compression models due to the settlement of the backfill material.

Fig. 3 shows plots of changes in mechanical stress depending on the relative deformation of the experimental models. In all experiments, an increase in the relative deformation of experimental models from mechanical stress was recorded (Fig. 3).

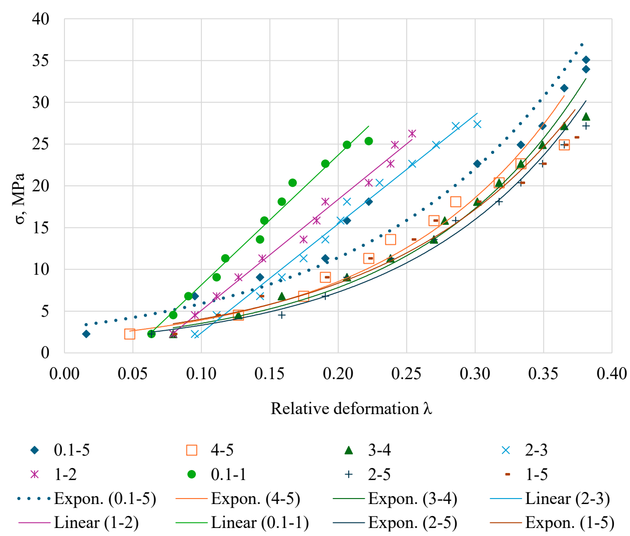


Fig. 3. Relationship between mechanical stress σ (MPa) and relative deformation λ of experimental models

Fine-grained materials in models 4–6 demonstrate linear-elastic behavior (the coefficients of determination for approximation lines are in the range of 0.985–0.99). For model materials 1–3 and 7–8, a characteristic exponential dependence [13, 22] of the following form is observed

$$\sigma = ae^{b\lambda}, \quad (11)$$

where $a = p_{st}$ is the structural strength of crushed rock under confined compression conditions, MPa; b – exponential rate parameter.

This dependence, by extrapolating experimental data [22], makes it possible to estimate the structural strength of backfill material made from crushed rock with various grain-size distributions (Table 2).

High values of the coefficients of determination, in the range of 0.95...0.98 for the "stress-strain" relationships, indicate the correctness of the tests and a minimum number of deviations, which are part of the natural variability of material properties, as well as the shape and size of the grains.

After processing the experimental data on the confined compression for crushed rock with various bulk densities, a table of deformation properties of the model materials was compiled (Table 3).

According to the experimental data given in Table 3, a regression analysis of the deformation properties of model materials made from crushed rock was performed to qualitatively analyze the relationships between the studied parameters, in order to assess the influence of grain-size distribution on deformation processes and the bearing capacity of backfill masses.

Table 2
Confined compression parameters

No.	Structural strength p_{st}, MPa	Exponential rate parameter (b)	R^2
1	3.05	6.5963	0.96
2	1.8112	7.7602	0.95
3	1.6059	7.9229	0.98
7	1.9696	7.2208	0.97
8	1.5144	7.8547	0.98

Table 3

Deformation properties of crushed rock with various bulk densities after confined compression

No.	σ, MPa	U, MJ/m^3	λ	C, MN/m	k_c	ΔV_K, m^{-1}
1	35.09	6.68	0.38	6.25	1.62	761.9
2	24.9	4.55	0.36	5.45	1.58	243.3
3	28.3	5.39	0.38	6.26	1.62	380.9
4	27.39	4.13	0.3	9.15	1.43	317.4
5	26.26	3.33	0.25	9.32	1.34	507.9
6	27.16	2.81	0.22	10.9	1.29	222.2
7	25.8	4.81	0.37	5.5	1.62	497.3
8	27.6	5.17	0.38	5.83	1.59	380.9

Fig. 4 shows the plots of change in relative deformation λ of the experimental models and the potential deformation energy of model materials made from crushed rock as a function of bulk density.

The maximum value of relative deformation of the model material $\lambda = 0.38$ (compaction to 62% of the initial volume) is observed in the range of bulk density values for crushed rock from 1680 to 1840 kg/m^3 (Fig. 4, curve 1).

As the rock density approaches its original *in-situ* value, the relative deformation decreases as expected: the minimum relative deformation of the model material $\lambda = 0.22$ was recorded during confined compression of crushed rock with a grain size of 0.1–1 mm and a bulk density of 1920 kg/m^3 (Fig. 4, curve 1).

The relationship between the studied parameters λ and ρ_b (t/m^3) can be fitted with a quadratic curve according to the regression equation of the form

$$\lambda = -7.397\rho_b^2 + 26.05\rho_b - 22.532, \quad (12)$$

with a coefficient of determination $R^2 = 0.76$.

The maximum values of the potential deformation energy of the backfill material of 6.68 MJ/m^3 were recorded during gradual loading of crushed rock with a heterogeneous grain-size distribution and a bulk density of 1810 kg/m^3 (Fig. 4, curve 2).

The relationship between the studied parameters U (MJ/m^3) and ρ_b (t/m^3) can also be fitted with a quadratic curve according to the regression equation of the form

$$U = -172\rho_b^2 + 610\rho_b - 534.8, \quad (13)$$

with a coefficient of determination $R^2 = 0.80$.

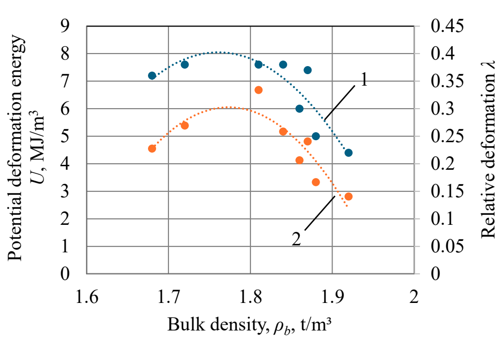


Fig. 4. Plots of the change in relative deformation λ of the experimental models and the potential deformation energy U (MJ/m^3) of the crushed rock backfill mass depending on the bulk density ρ_b (t/m^3) of the original material: 1 — λ; 2 — U

Fig. 5 shows the plots of change in the average displacement increment during confined compression depending on the potential deformation energy of the backfill material made from crushed rock with various grain-size distributions. To track the change dynamics, individual points on the plots are connected by guide lines.

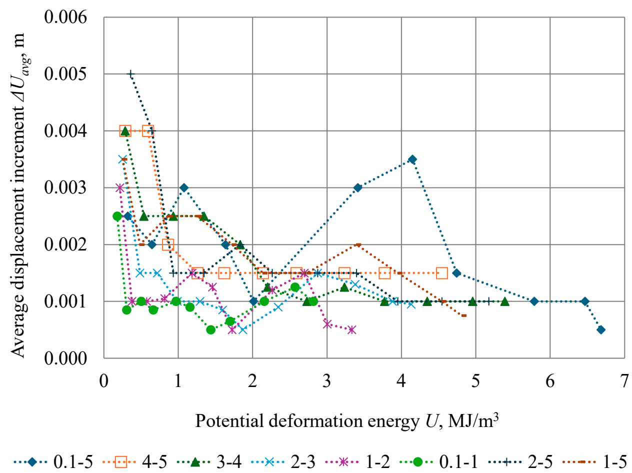


Fig. 5. Plots of change in average displacement increment ΔU_{avg} (mm) depending on the potential deformation energy U (MJ/m^3) of material

The presented plots reflect the work of compressing the backfill material, which is accompanied by deformation processes in the crushed rock and a periodically varying average displacement increase. The maximum values of the specific potential deformation energy of the backfill material, 4.54–6.68 MJ/m^3, are recorded during deformation of crushed rock with a grain size of 3–4 mm and with polyfractional composition (0.1–5 mm). The minimum values of the potential deformation energy of the backfill material, up to 2.81–3.33 MJ/m^3, are recorded during deformation of crushed rock with a grain size of 0.1–1 mm and 1–2 mm.

Fig. 6 shows the distribution pattern of the experimental values of stiffness of the backfill masses and the relative change in the volume of the backfill material per unit of lateral rock convergence ΔV_K for various bulk densities of crushed rock.

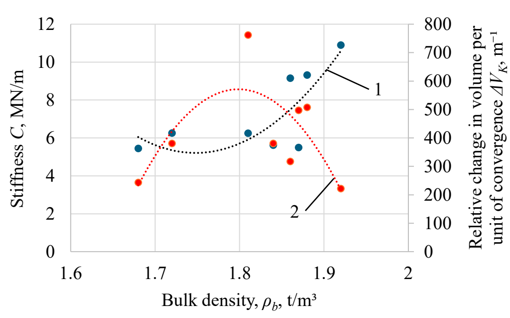


Fig. 6. Distribution pattern of the experimental values of stiffness C (MN/m) of backfill masses and the relative change in the volume of backfill material per unit of the lateral rocks convergence ΔV_K (m^{-1}) depending on the bulk density ρ_b (t/m^3) of crushed rock: 1 — C; 2 — ΔV_K

The presented data indicate an increase in the stiffness of backfill masses after confined compression with an increase in the bulk density of the original material. The maximum stiffness value of the model material (10.9 MN/m) was recorded for the densest fraction of 0.1–1 mm with a bulk density of 1920 kg/m^3. The minimum stiffness value (5.45 MN/m) was observed for the largest fraction of 4–5 mm, with a bulk density of 1680 kg/m^3 (Fig. 6, Table 4).

When comparing the relative change in the volume of backfill material per unit of lateral rock convergence ΔV_K, depending on the bulk density of crushed rock, it was found that the maximum ΔV_K values are achieved when using polyfractional, well-graded material (0.1–5 mm; bulk density of the original material 1810 kg/m^3).

The minimum values $\Delta V_K = 222.2–243.3$ m^{-1} are observed during compression of the densest (0.1–1 mm) and coarsest (4–5 mm) fractions of crushed rock with bulk densities of 1920 and 1680 kg/m^3, respectively (Fig. 6, Table 4). It should be noted that the maximum value of the parameter $\Delta V_K = 761.9$ m^{-1} corresponds to the maximum compaction of crushed rock with a compaction coefficient $k_c = 1.62$ (Table 4). This backfill material has a heterogeneous grain-size distribution (a mixture of fractions of 0.1–5 mm, uniformity coefficient of 5.99).

5.2. Results of assessing the bearing capacity of a backfill mass made from crushed rock with a heterogeneous grain-size distribution

Table 4 presents the deformation characteristics of crushed rock with heterogeneous grain-size distribution (0.1–5 mm) under confined compression conditions.

According to the experimental data in Table 4, the bearing capacity of the crushed rock backfill mass was assessed.

Fig. 7 shows the plot of the change in average displacement increment versus the compressive load.

A periodic variation in the average displacement increment with increasing compressive load from 10 to 155 kN was recorded (Fig. 7). During compression, the grains of crushed rock are gradually repacked simultaneously with a change in the volume of the backfill material.

The decrease in the average displacement increment from 35 to 5 mm in the range 110 kN < F < 155 kN occurs after the compaction reserve of the crushed rock is exhausted due to the rearrangement of grains (Fig. 7). Under such conditions, the specific potential deformation energy is spent on changing the volume of the backfill material.

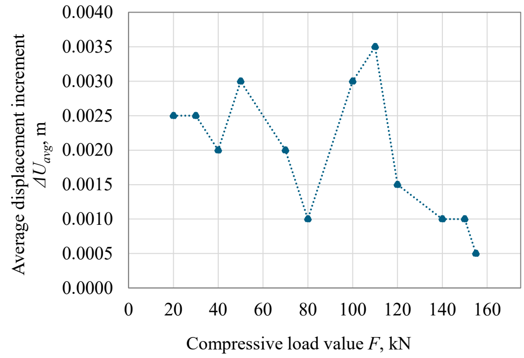


Fig. 7. Plot of the change in the average displacement increment ΔU_{avg} (m) depending on the compressive load F (kN)

Fig. 8 shows a plot of the change in the specific potential deformation energy of the backfill material with the relative change in the volume of crushed rock per unit of lateral rock convergence.

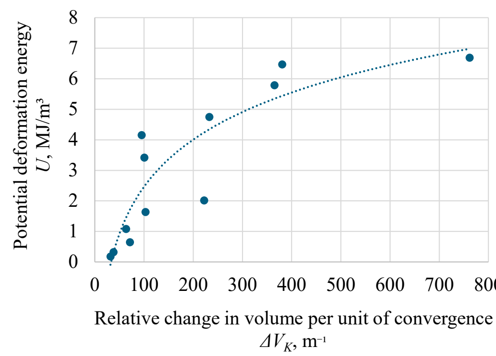


Fig. 8. Plot of the change in specific potential deformation energy U (MJ/m^3) of the backfill material versus the relative change in the volume of crushed rock per unit of lateral rock convergence ΔV_K (m^{-1})

A relationship has been established between the studied parameters that can be fitted with a logarithmic curve according to the regression equation

$$U = 2.2247 lnV_K - 7.78, \quad (14)$$

with a coefficient of determination $R^2 = 0.80$.

Fig. 9 shows the plot of the relative change in the volume of backfill material per unit of lateral rock convergence versus the change in the compaction coefficient of the backfill mass.

When approaching the maximum values of the relative deformation of the backfill material, the parameter ΔV_K increases progressively (Fig. 9). The relative deformation after compaction of the crushed rock has a limiting value. Based on this, the relationship should be hyperbolic, with the asymptote corresponding to the maximum value of relative deformation.

Table 4

Deformation characteristics of crushed rock with a heterogeneous grain-size distribution (0.1–5 mm) under confined compression conditions

F, kN	Δh, m	ΔU, m	ΔU_{avg}, m	λ	ΔV_K, m^{-1}	E_d, MPa	σ, MPa	U, MJ/m^3	k_c
10	0.001	0.001	–	0.016	–	142.6	2.26	0.018	1.02
20	0.005	0.004	0.0025	0.079	31.8	57.0	4.53	0.180	1.09
30	0.006	0.001	0.0025	0.095	38.1	71.3	6.79	0.323	1.11
40	0.009	0.003	0.002	0.143	71.4	63.4	9.05	0.647	1.17
50	0.012	0.003	0.003	0.190	63.5	59.4	11.32	1.078	1.24
70	0.013	0.001	0.002	0.206	103.2	76.8	15.85	1.635	1.26
80	0.014	0.001	0.001	0.222	222.2	81.5	18.11	2.012	1.29
100	0.019	0.005	0.003	0.302	100.5	75.1	22.64	3.413	1.43
110	0.021	0.002	0.0035	0.333	95.2	74.7	24.90	4.150	1.50
120	0.022	0.001	0.0015	0.349	232.8	77.8	27.16	4.743	1.54
140	0.023	0.001	0.001	0.365	365.1	86.8	31.69	5.785	1.58
150	0.024	0.001	0.001	0.381	381.0	89.1	33.95	6.467	1.62
155	0.024	0	0.0005	0.381	761.9	92.1	35.09	6.683	1.62

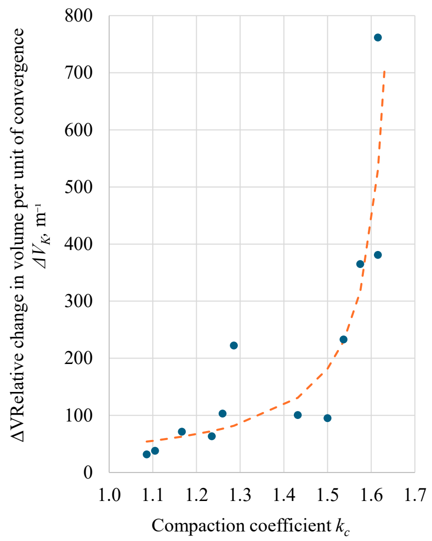


Fig. 9. Plot of the relative change in the volume of backfill material per unit of lateral rock convergence ΔV_k (m^{-1}) versus the change in the compaction coefficient k_c of the backfill mass

According to the data processing results, a regression relationship of the form

$$\Delta V_K = \frac{29.24}{1.538 - 0.918 k_c}, \qquad (15)$$

with a coefficient of determination $R^2 = 0.89$ between the studied parameters was established.

This relationship is similar to Salamon's formula [14], which establishes a correlation between stress and relative deformation of a granular material subjected to confined compression, but has a more apparent asymptotic behavior. This makes it possible to calculate the limiting value of the compaction coefficient of a backfill mass made from crushed rock with a heterogeneous grain-size distribution. In this case, $k_c = 1.538/0.918 = 1.676$. The increase in the parameter ΔV_K at maximum values of the compaction coefficient indicates an increase in the resistance of the backfill mass, due to which its bearing capacity is ensured.

6. Discussion of the results of studies on deformation processes in backfill masses

As a result of our studies, certain features of deformation processes in backfill masses made from crushed rock with various grain-size distributions and bulk density were established (Table 1, Fig. 1). The model materials were subjected to confined compression (Fig. 2), simulating complete backfilling of the gob area with crushed rock. The specific potential deformation energy (5) of the backfill masses was considered equivalent to the work spent on confined compression.

During the gradual loading of the models, the height (settlement) of the material batch decreased. This led to a reduction in the void ratio of the backfill material and a change in its volume (3). In this case, the settlement of the crushed rock and its degree of compaction are determined by its grain-size distribution. The degree of compaction of the crushed rock was estimated by the compaction coefficient (4). When the maximum values of the crushed rock compaction coefficient were reached (Table 4), the deformation parameters of the models also reached their limits. Under these conditions, the backfill material changes its properties and stress-strain state. Compaction of the backfill mass was estimated under loading that exceeded the structural strength (Fig. 3). The limitation of displacements was recorded as the relative change in the volume of crushed rock per unit of convergence ΔV_K (8).

The structural strength of the backfill mass is determined by the presence of rigid contact between the particles of crushed rock. Beyond the structural strength values (Table 2), elastic bonds are destroyed, and grains shift, allowing them to be positioned more compactly within the available volume of crushed rock. The structural strength of a backfill mass made from crushed rock with a heterogeneous grain-size distribution ($C_u = 5.99$, $p_{st} = 3.05$ MPa) best reflects its ability to resist loading.

Under confined compression of crushed rock, there is a relationship between the specific potential deformation energy of the backfill masses and the bulk density of the material, which can be fitted with a quadratic curve (Fig. 4). The deformation energy density is determined by the grain-size distribution of the crushed rock. It was established that at a relative deformation of the backfill mass $\lambda = 0.38$, the maximum limit value of the deformation energy density $U = 6.68$ MJ/m^3 is recorded. Under these conditions, the compaction coefficient of crushed rock with a heterogeneous grain-size distribution (0.1–5 mm, 1–5 mm, 2–5 mm) is 1.59–1.62, which ensures maximum compression of the backfill mass. A heterogeneous grain-size distribution of crushed rock promotes a compact arrangement of grains within the total volume of the backfill material. Accordingly, a homogeneous material with a high density has the lowest compaction coefficient, while a polyfractional material has the highest compaction coefficient (Table 3).

Under confined compression, in the initial stage, grain rearrangement occurs in the crushed rock, which is accompanied by a change in the volume of the backfill material (Tables 3, 4). For crushed rock with a heterogeneous grain-size distribution in the ranges of 0.1–5 mm, 1–5 mm, and 2–5 mm, the volume change (3) occurs due to rearrangement and more compact packing of grains ($k_c = 1.59$–1.62). For crushed rock with fractions of 4–5 mm and 3–4 mm with the same compaction coefficient, $k_c = 1.58$–1.62, the volume change occurs due to additional crushing of grains and subsequent repacking. As the size of uniform fractions decreases, the compaction coefficient is reduced, since further crushing of the material and its repacking becomes increasingly limited. Based on this, one of the main factors that determines the deformation characteristics of an artificially created mass of crushed rock should be considered its grain-size distribution.

Deformation processes in backfill masses composed of crushed rock are associated with the interaction of grains of various sizes, an increase in the number of contacts between them, and lead to qualitative changes in the properties of the source material. With an increase in compressive load, the vertical settlement of the backfill material also increases. An increase in displacements is observed, which is due to the mutual movement of crushed rock grains. The subsequent repacking of the backfill material is associated with additional crushing of particles, the proportion of which gradually increases. There is a decrease in the average displacement increment with an increase in the strain energy density (Fig. 5).

It was recorded that with the minimum stiffness of the backfill mass (Fig. 6, curve 1), the maximum value of the relative change in the volume of crushed rock per unit of lateral rock convergence is ensured (Fig. 6, curve 2). A comparison of the deformation characteristics of polyfractional model materials Nos. 7, 8 with material No. 1 confirms that the well-graded material of model No. 1, which meets the recommendations of [8], has 7–13% higher stiffness and is capable of withstanding greater loads, while maintaining similar compaction indicators.

Under confined compression of crushed rock with a heterogeneous grain-size distribution, the average displacement increment decreases (Fig. 7). During the gradual repacking of crushed rock grains, the strain energy density increases, indicating compaction of the crushed rock. This is confirmed by the established relationship between the specific potential deformation energy of the backfill material and the relative change in its volume per unit of lateral rock convergence ΔV_K, which is fitted with a logarithmic curve (Fig. 8). The determining factor in this relationship is the relative deformation of the backfill material. It was recorded that when the maximum compaction of the crushed rock is achieved, the relative deformation of the backfill material is $\lambda = 0.38$ (Table 4). Under these conditions, the parameter ΔV_K tends toward unlimited growth, which indicates an increase in the resistance of the backfill mass and a limitation of the displacement increments. Thus, as the relative deformation increases, the change in parameter ΔV_K allows, based on experimental data, determination of the expected ultimate compaction coefficient (for a heterogeneous, polyfractional material, in this case, it is 1.676). From this point, the maximum bearing capacity of the backfill mass can be expected, which will allow complete restriction of lateral rock movements.

The ultimate compaction coefficient of the backfill material can be determined in the laboratory by using the asymptotic nature of the established hyperbolic relationship between the relative change in the material volume per unit of lateral rock convergence and the compaction coefficient (Fig. 9). The compaction coefficient of crushed rock should be considered an indicator of the bearing capacity of the backfill material. Changes in the bearing capacity of the backfill material occur with a decrease in the volume of crushed rock under confined compression conditions (Table 3). The bearing capacity at maximum compaction of the crushed rock reflects the response of the backfill material to external influence.

The stability of gob-side retained entries is ensured when the gob area is completely backfilled with waste rock. Substantiating the method of maintenance of gob-side retained entries when extracting coal seams with longwall mining and roof control by complete backfilling of the gob area requires an assessment of the expected displacements of lateral rocks. Such an assessment depends on the amount of roof rock subsidence in the gob area and the intensity of displacements. The amount of roof rock subsidence is determined by the ultimate compaction coefficient of the backfill material, while the displacements intensity is determined by stiffness. To reduce the amount of settlement of the backfill mass, pre-compaction should be performed, as recommended in [4, 9, 10]. In this way, settlement can be reduced by nearly half [4]. In the study, pre-compaction was not used to allow determination of structural strength. At the same time, the structural strength value (Table 2) makes it possible to estimate the degree of compression required for pre-compaction.

The load-bearing effect of backfill masses develops gradually over time as the original material is compacted and leading to an increase in their resistance. Under such conditions, the movements of the lateral rocks in the gob area are limited, and at certain compaction coefficients, roof collapse may not occur at all. A heterogeneous grain-size distribution of the crushed rock ensures the maximum bearing capacity of the backfill mass. However, a qualitative assessment of the bearing capacity of backfill masses should take into account changes in their stiffness under load. Therefore, in further studies, it is advisable to determine the effect of this parameter on deformation processes in the backfill masses, considering the grain-size distribution of the crushed rock.

The research results can be used for a well-grounded selection of methods for rock pressure control and maintaining gob-side retained entries. It should be noted that the results of the present study are limited to the use of sandy-clay shales as backfill material. In further studies, it is necessary to assess the bearing capacity of backfill masses when using other types of rocks and their mixtures. To refine the assessment of the bearing capacity of backfill masses, it is advisable to conduct studies on materials with grain sizes corresponding to real crushed rock and under actual mine conditions.

7. Conclusions

1. It was experimentally established that, under confined compression of crushed rock, there is a relationship between the specific potential deformation energy of backfill masses and the bulk density of materials with various grain-size distributions, which can be fitted with a quadratic curve (correlation strength evaluated by the coefficient of determination of 0.80). The highest strain energy density values correspond to a well-graded model material with a coefficient of uniformity $C_u = 5.99$, which has a stiffness 7–13% higher than that of poorly graded materials with $C_u < 4$, which ensures the bearing capacity of the backfill mass.

2. Prevention of roof collapses in the extraction areas of coal mines occurs by limiting the movement of lateral rocks in the gob area by ensuring the bearing capacity of the backfill mass. It was experimentally established that, under confined compression of crushed rock with a heterogeneous grain-size distribution, there is a relationship between the specific potential deformation energy of the backfill material and its relative volume change per unit of lateral rocks convergence ΔV_K, which can be fitted with a logarithmic curve (correlation strength evaluated by the coefficient of determination of 0.80). The key factor in this relationship is the relative deformation of the backfill mass, which determines the strain energy density and influences the formation of its bearing capacity. The bearing capacity of the backfill mass is achieved when using a well-graded backfill material that provides a compaction coefficient of crushed rock of 1.62.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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