UDC 622.268.6:622.838:331.45:519.2
DOI: 10.15587/1729-4061.2023.272454

EVALUATION OF THE EFFECTIVENESS OF SECONDARY SUPPORT OF HAULAGE DRIFTS BASED ON A COMPARATIVE ANALYSIS OF THE DEFORMATION CHARACTERISTICS OF PROTECTIVE STRUCTURES

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The object of this study is the processes of managing the state of lateral rocks in the coal rock array with preparatory workings. The influence of deformation characteristics of the protective structures of the preparatory workings on the stability of lateral rocks in the coal rock array has been established. The stable state of the above-the-drift pillars of coal is provided within the deformation resource, which corresponds to the critical level of the specific potential energy of the deformation. The limits of the deformation resource are the range of change in the relative deformation of coal pillars $0.1 \leq \lambda \leq 0.25$. When the critical level of the specific potential energy of deformation is passed, at $\lambda > 0.25$, there is a relative change in the volume of pillars $\delta\lambda > 0.1$, as a result of which their durability decreases and the state changes.

Under such conditions, the residual strength of coal pillars is not enough to limit the movement of lateral rocks, which provokes their collapse.

For protective structures made of crushed rock, within the established deformation resource of $0.4 \leq \lambda \leq 0.7$, with an increase in static load and cross-sectional area, the specific potential energy of deformation decreases, simultaneously with the relative change in the volume of the embedded material. This is due to the compaction of the crushed rock and an increase in its strength.

Regularities of change in the specific potential energy of deformation of protective structures have been established, which, under conditions of uniaxial compression, make it possible to assess, within the deformation resource, their stability.

To ensure the stability of lateral rocks in the coal rock array and to preserve the operational condition of the preparatory workings, it is advisable to use protective structures made of crushed rock. This method will limit the movement of the roof and sole in the produced space and avoid collapses

Keywords: coal rock array, protective structures, compression, deformation characteristics, potential energy, compaction, stability

Received date 10.10.2022
Accepted date 15.03.2023
Published date 28.04.2023

***How to Cite:** Tkachuk, O., Chepiga, D., Pakhomov, S., Volkov, S., Liashok, Y., Bachurina, Y., Podkopaev, S. (2023). Evaluation of the effectiveness of secondary support of haulage drifts based on a comparative analysis of the deformation characteristics of protective structures. Eastern-European Journal of Enterprise Technologies, 2 (1 (122)), 73–81. doi: https://doi.org/10.15587/1729-4061.2023.272454*

1. Introduction

Increasing the depth of development and intensifying mining operations in mines require the implementation of a set of measures aimed at improving the reliability and safety of miners. The level of safety of schemes for the preparation and development of excavation sites of coal mines is one of the main indicators determining the scope of their application.

Under conditions of gas-bearing and self-ignition coal seams prone to spontaneous combustion, pillar-free technological schemes for seam mining are rational. For the pillar-free technological schemes for working out steep layers and managing the roof against a complete collapse, various options for protecting site preparatory workings with artificial structures are used. At the same time, in the mines, the method of protecting the sliding drifts with coal pillars is widespread. The main requirements for pillars are to ensure the stability of the preparatory workings in the zone of influence of the cleaning work and the length of the excavation site.

To ensure the operational condition of the preparatory workings when using coal pillars, it is necessary to carry out repair work, which includes the re-attachment of individual sections or the entire workings. The complexity of repair work remains high and reaches 80–90 people-shifts per 1000 tons of average daily coal production. The length of the re-attached workings is about 50 % in relation to those traversed. Despite the large volume of repair work and its high labor intensity, the length of the workings with an unsatisfactory condition remains significant.

Under the difficult operating conditions of steep layers, the safety of work and the efficiency of coal mining depend on the correct choice of the technique for protecting workings and the parameters of protective structures. Therefore, the preservation of the preparatory workings in operational condition is an urgent task. This problem can be solved by studying the deformation properties of protective structures of the sliding drifts, which predetermine the stability of the lateral rocks in the coal rock array.

2. Literature review and problem statement

The safety and efficiency of the coal mine depends on the state of the preparatory workings. Being transport and ventilation lines, they provide access to coal reserves, continuity and reliability of the underground complex of the mine.

An increase in the depth of mining operations (up to 1200–1400 m) leads, among other things, to an increase in the displacement of rocks on the contour of the preparatory workings. Under such conditions, to limit or reduce the intensity of rock displacements, they began to use an arched pliable mount and increase the density of installation of fasteners along the length of the workings [1, 2]. This expectedly led to an increase in the cost and complexity of carrying out and maintaining the workings.

It is proposed to protect the preparatory workings of steep seams to use coal pillars 8 m high behind the reservoir uprising [3]. However, the use of pillars of this size under the existing procedure for working out floors in mines, especially under the conditions of development of close layers, is ineffective due to the creation of zones of increased mining pressure on neighboring layers.

To reduce the effect of stress concentration on the preparatory workings, it is proposed to increase the height of the pillars to 15–20 m [4]. It is important to note that pillars of this size somewhat limit the displacement of the thickness in the coal massif but significantly increase the loss of coal.

To ensure the stability of the preparatory workings, in studies [5, 6] the schemes of loading of pillars were considered and their durability was determined. By analyzing the stability of the pillars under different conditions when measuring the loads on them, the actual loads were determined, and a conclusion was made about their durability. This makes it possible to predict the state of coal pillars but does not assess the stability of lateral rocks in a coal rock array with workings.

To ensure the safety of site preparatory workings with pillar-free technological schemes for working out steep layers, it is proposed to use bushes made of wooden risers, which are installed intermittently above the sliding drift [7]. Being a mount of increasing support, riser bushes either break or are pressed into the lateral rocks, destroying them, as a result of which the arched mount in the drift is deformed.

The use of wooden risers to maintain lateral rocks above the drift allows one to limit the displacement of the roof and sole on the contour of the preparatory workings [7]. Meanwhile, in order to achieve the maximum effect of using this technique, it is necessary to increase the density of installation of risers, which is associated with additional costs of wood material.

It is known [8] that the most favorable effect on the state of lateral rocks in the coal rock array containing workings is introduced by the laying of the produced space. When using this technique, collapses of rocks of the immediate roof and sudden collapses of the main roof are excluded.

A number of experts believe that leaving rock in the mine is the most effective way to manage geomechanical processes in the development of cleaning and preparatory work [9, 10]. The efficiency of roof management in this case is significantly influenced by the level of shrinkage of the embedded array, which, in turn, depends on the deformation properties of the embedded material.

The practice of using pillar-free techniques of working out excavation sites on a steep fall has shown that if the deformation characteristics of protective structures do not correspond to the strength properties of lateral rocks in a coal rock array, it is impossible to ensure the operational condition of the preparatory workings. Therefore, it is advisable to study the influence of the deformation characteristics of protective structures on the stability of lateral rocks and the preservation of sliding drifts in the excavation section.

3. The aim and objectives of the study

The purpose of this study is to establish the influence of the deformation characteristics of protective structures on the stability of lateral rocks, which makes it possible to assess the effectiveness of the technique for protecting the preparatory workings and preventing the collapse of the coal rock array in the produced space.

To accomplish the aim, the following tasks have been set:

– to investigate the deformation properties of coal pillars and establish their deformation resource, within which the stability of lateral rocks is ensured;

– to investigate the deformation properties of structures made of crushed rock within their deformation resource, when the embedded material is compacted and there is an increase in the resistance of protective structures and the stability of the roof;

– to perform a comparative analysis of the deformation characteristics of protective structures to substantiate the stability of lateral rocks and the choice of technique for protecting preparatory workings.

4. The study materials and methods

The object of the study is the processes of managing the state of lateral rocks in the coal rock array with preparatory workings. Therefore, to investigate the influence of the deformation characteristics of the protective structures of the sliding drifts on the stability of lateral rocks, studies were conducted on models. Experimental models were represented by coal pillars and protective structures made of crushed rock. The models had the shape of a rectangular parallelepiped. The dimensions of experimental samples of protective structures are given in Table 1. Modeling scale M1:25.

Table 1

Dimensions of experimental samples of protective structures

No. of entry	Dimension				Cross-sectional area S, m^2	Volume V, m^3
	Length a, m	Width b, m	Height h_o, m	a/b		
1	0.08	0.04	0.04	2	0.0032	0.000128
2	0.08	0.08	0.04	1	0.0064	0.000256
3	0.12	0.08	0.04	1.5	0.0096	0.000384
4	0.1	0.1	0.04	1	0.01	0.0004
5	0.16	0.08	0.04	2	0.0128	0.000512
6	0.16	0.1	0.04	1.6	0.016	0.00064

In these studies, the identity of the equations of equilibrium of nature and model was ensured [11, 12]. The tensile strength of models at compression was determined from the following expression [12]:

$$\sigma_{com}^{m}=\frac{l_m}{l_n}\cdot\frac{\gamma_m}{\gamma_n}\cdot\sigma_{com}^{n},$$

where σ_{com}^{m}, σ_{com}^{n} is the compressive strength of the model and nature, respectively, N/m^2; l_m, l_n – linear dimensions of the model and nature, m; γ_m, γ_n – the density of the material of the model and nature, kg/m^3.

Characteristics of materials for research are given in Table 2.

Table 2

Characteristics of materials

Object	Material	γ, kg/m^3	σ_{com}, MPa
Lateral rocks			
model	sand and cement mixture	1,600	1.16
nature	aleurites	2,300	42
Coal pillar			
model	sand-cement mixture with rosin	1,100	0.4
nature	coal	1,300	12

In the selection of crushed rock we used the following ratio [12]:

$$\mathrm{tg}\rho_m=\mathrm{tg}\rho_n,$$

where $\rho_m=\rho_n=23°$ are the angles of internal friction of the material of the model and nature, deg.

Experimental samples in the form of coal pillars had a Poisson coefficient $\nu=0.3$. In protective structures made of crushed rock, particles of various sizes were used. Sieve analysis of crushed rock was performed in accordance with [13]; its results are given in Table 3. Bulk density of crushed rock $\rho_{n.r.}=1790$ kg/m^3 with hollowness $M=15$ %. Poisson coefficient $\nu=0.25$ [14].

Table 3

Sieve analysis data of crushed rock for experimental samples

Fraction size, mm	% in total volume
>5	4
4–5	16
3–4	19
2–3	24
1–2	18
0.1–1	14
<0.1	5

Roofing and sole rocks were modeled as a slab $l_s=0.3$ m long, $b_s=0.1$ m wide and $h_s=0.03$ m thick. To ensure the mechanical similarity of the model and nature, equality of weight parameters was rejected, which is quite permissible [11].

Experimental samples of protective structures were subjected to uniaxial compression on the P-50 press at the mining pressure laboratory of Donetsk National Technical University (Ukraine). During the research, the models were installed between the roof, sole, and metal plates of the press. The samples were subjected to continuous gradual deformation until the moment of loss of stability for coal pillars and complete compression of the embedded material for protective structures made of crushed rock. During the experiments, the relationship between the compressive force F (kN) and the decrease in the height of the sample h (m) was recorded.

Under uniaxial compression conditions, the relative deformation of experimental samples was determined using the following expression [15]:

$$\lambda=\frac{\Delta h}{h_0},\tag{1}$$

where Δh is the amount of deformation of the sample; h_0 – initial sample height, m.

The rigidity of the experimental samples was determined as in [16]:

$$C=\frac{F}{\Delta h}.\tag{2}$$

The relative change in the volume $\delta\lambda$ of experimental samples under uniaxial compression conditions was determined using the following expression [17]:

$$\delta V=(1-2\nu)\cdot\lambda.\tag{3}$$

The deformation module E_g of protective structures was determined on the basis of Hooke's law from expression [18]:

$$E_g=\frac{F}{S}\cdot\frac{h_0}{\Delta h},\tag{4}$$

where F/S is the mechanical stress, which under uniaxial compression conditions is considered pressure, N/m^2; S – cross-sectional area of the experimental sample, which is in contact with the roof and sole, m^2.

The work of the external force, which is spent on the deformation of samples, can be determined by the formula:

$$A=\frac{E_g\cdot S}{h}\cdot\frac{\Delta h^2}{2}=\frac{E_g\cdot V}{2}\cdot\lambda^2.\tag{5}$$

The amount of energy U (J) that is stored by the sample can be determined from the following expression [16]:

$$U=\frac{\sigma^2}{2E_g}\cdot V, \qquad (6)$$

where $\sigma^2/2E_g$ is the energy density or specific potential energy, J/m^3.

When deforming experimental samples, the work of external forces is spent on changing the volume and shape. The potential energy of protective structures can be divided by the energy of change in volume U_v (J/m^3) when, under conditions of uniaxial compression, the following expression [18] holds:

$$U_v=\frac{(1-2\nu)}{6E_g}\cdot\sigma^2, \qquad (7)$$

and the energy of change in shape [18]:

$$U_{sh}=\frac{(1+\nu)}{3E_g}\cdot\sigma^2. \qquad (8)$$

It should be noted that the deformation modulus E_g (Pa) should not be identified with the modulus of elasticity E (Pa) since it characterizes not only elastic but also residual deformations of experimental samples.

When performing research, the provision was taken into account that for coal pillars with specified geometric dimensions and characteristics of the material, there are certain levels of critical values of potential energy. Exceeding these levels with uniaxial compression changes the behavior of the deformed body. For protective structures made of crushed rock, the nature of the deformation is determined by the simultaneous change in the deformation module, shape, and volume.

5. Results of studying the deformation properties of protective structures to assess the effectiveness of techniques for the protection of workings

5. 1. Results of investigating the influence of the deformation properties of coal pillars on the stability of lateral rocks

Experimental samples in the form of coal pillars were considered. Table 4 gives the limiting values of the external force F (kN) and the deformation of samples Δh (m), which are registered under uniaxial compression conditions. Using these values, the values of the relative deformation λ and hardness C (N/m) of experimental samples were established.

Fig. 1 shows the general view of experimental samples in the form of coal pillars (moment of loss of stability).

Table 4

Deformation characteristics of coal pillars under uniaxial compression conditions

No. of entry	Coal pillars			
	F, kN	Δh, m	λ	$C\cdot10^6$, (N/m)
1	20.1	0.0056	0.14	3.59
2	41	0.0088	0.22	4.6
3	62	0.0092	0.23	6.74
4	66.1	0.01	0.25	6.6
5	86	0.0094	0.24	9.1
6	110	0.01	0.25	11.0

a *b* *c*

Fig. 1. General view of experimental samples in the form of coal pillars with uniaxial compression: *a* – λ=0.14, sample No. 1; *b* – λ=0.22, sample No. 2; *c* – λ=0.24, sample No. 5

In order to determine the deformation resource of coal pillars, the determination coefficient (R^2) was calculated in relation to different types of dependences between parameters S (m^2) and λ (Tables 1, 4).

After making the necessary calculations in accordance with [17, 18], the regression equation $\lambda=0.0677\cdot\ln(s)+0.5439$ was derived. The dimensionless characteristic of model accuracy and bond closeness (R^2) for this ratio is 0.8683. The deformation resource of coal pillars is within $0.14\leq\lambda\leq0.25$, after which there is a loss of stability of protective structures.

Table 5 gives the values of the specific potential energy of deformation of coal pillars $\sigma^2/2E_g$ and the relative change in their volume δV at pressure F/S (under uniaxial compression conditions).

Table 5

The value of the specific potential energy $\sigma^2/2E_g$ and the relative change in the volume δV of coal pillars under pressure F/S

No. of entry	Coal pillars		
	F/S, MPa	$\sigma^2/2E_g$, MJ/m^3	δV
1	6.28	0.44	0.056
2	6.4	0.7	0.088
3	6.45	0.74	0.092
4	6.61	0.77	0.1
5	6.67	0.78	0.096
6	6.87	0.86	0.1

From the above table, it is clear that with the growing pressure F/S the potential energy $\sigma^2/2E_g$ grows with the relative change in the volume of pillars (Table 5).

Table 6 gives the values of the relative deformation λ and the specific potential energy U_1 (MJ/m^3) of coal pillars.

Table 6

Value of the relative deformation λ and the specific potential energy U (MJ/m^3) of coal pillars

No. of entry	Coal pillars	
	Relative deformation during compression, λ_1	Specific potential energy, U_1 (MJ/m^3)
1	0.14	0.44
2	0.22	0.7
3	0.23	0.74
4	0.25	0.77
5	0.24	0.78
6	0.25	0.86

Table 6 shows that within the established deformation resource of coal pillars $0.14 \le \lambda \le 0.25$, the specific potential energy increases during deformation.

The relationship between specific potential energy and relative deformation is described by an exponential function in the form:

$$U_1 = e^{-0.5069+2.851\lambda_1} = 0.6023 \cdot e^{2.851\lambda_1},$$

with correlation coefficient $R_1^2 = 0.9828$ [19, 20].

5. 2. Results of the study of the influence of the deformation properties of structures made of crushed rock on the stability of lateral rocks

Experimental samples from crushed rock were considered. Table 7 gives the values of the external force F (kN) and the deformation of samples Δh (m) upon reaching which the final compression of the crushed rock occurred.

Table 7

Deformation characteristics of crushed rock structures under uniaxial compression conditions

No. of entry	Protective facilities made of crushed rock			
	F, MPa	Δh, m	λ	$C \cdot 10^6$ (N/m)
1	40	0.028	0.7	1.42
2	74	0.023	0.59	3.21
3	92	0.0208	0.52	4.42
4	105	0.0192	0.48	5.46
5	128	0.017	0.44	7.5
6	149	0.016	0.4	9.31

Fig. 2 shows the general view of experimental samples from crushed rock after uniaxial compression.

The values of the relative deformation λ and hardness C (N/m) of the experimental samples are given in Table 7.


a b c

Fig. 2. General view of experimental samples in the form of protective structures made of crushed rock after uniaxial compression: *a* – sample No. 1; *b* – sample No. 2; *c* – sample No. 5

Regression analysis between pairwise random variables (cross-sectional area and relative deformation) allows us to establish the relationship existing between these quantities and the corresponding measure of correlation of quantities [19, 20].

The regression equation is obtained for the logarithmic dependence:

$$\lambda = -0.19 \cdot \ln(s) - 0.38. \qquad (9)$$

The dimensionless characteristic of model accuracy and bonding closeness (R^2) for this ratio is 0.986. The average error with approximation is 2.03 %.

The deformation resource of crushed rock structures is within $0.4 \le \lambda \le 0.7$, which ensures the compaction of the rock.

Table 8 shows the values of the specific potential energy $\sigma^2/2E_g$ of deformation of structures from crushed rock and the relative change in their volume $\delta\lambda$ at pressure F/S (under uniaxial compression conditions).

Under conditions when the pressure on the structures of crushed rock decreases, the relative change in the volume of protective structures and the potential energy of deformation also decreases (Table 8).

Table 9 gives the values of the relative deformation λ and the specific potential energy U_2 (MJ/m^3) of structures made of crushed rock under uniaxial compression conditions.

Table 8

The value of the specific potential energy $\sigma^2/2E_g$ and the relative change in the volume δV of structures from crushed rock under pressure F/S

No. of entry	Protective structures from crushed rock		
	F/S, MPa	$\sigma^2/2E_g$, MJ/m^3	δV
1	12.5	4.41	0.35
2	11.5	3.34	0.29
3	9.5	2.45	0.26
4	10.5	2.52	0.24
5	10.0	2.12	0.22
6	9.3	1.86	0.2

Table 9

Value of relative deformation λ and specific potential energy U (MJ/m^3) of experimental samples

No. of entry	Protective structures from crushed rock	
	Relative deformation during compression, λ_2	Specific potential energy, U_2 (MJ/m^3)
1	0.7	4.44
2	0.59	3.34
3	0.52	2.45
4	0.48	2.52
5	0.44	2.12
6	0.4	1.86

Table 9 shows that within the deformation resource of structures made of crushed rock, the potential energy of the deformed body is reduced.

The relationship between specific potential energy and relative deformation is described by a function in the following form:

$$U_2 = e^{-1.6048+5.6313\lambda_2} = 0.2009 \cdot e^{5.6313\lambda_2}. \qquad (10)$$

The correlation coefficient for these ratios is equal to $R_2^2 = 0.9597$, which indicates the presence of an actual exponential functional relationship between the specified parameters [19, 20].

5. 3. Evaluation of the deformation properties of protective structures to substantiate the stability of lateral rocks and the choice of technique for protecting workings

Fig. 3 shows plots of changes in the relative deformation of experimental samples under uniaxial compression dependent on the cross-sectional area. The plots (Fig. 3, curve 1) demonstrate that for the model of coal pillars, with an increase in the cross-sectional area from S=0.0032 m^2 to S=0.016 m^2, the value of the relative deformation λ varies from λ=0.14 to λ=0.25 as a function of logarithmic dependence.

For protective structures made of crushed rock, with an increase in the cross-sectional area S, m^2, the value of the corresponding deformation λ decreases. Between the studied parameters there is a logarithmic relationship (Fig. 3, curve 2).

Fig. 4 shows plots of changes in the amount of deformation dependent on the work of compression of experimental samples. For experimental samples in the form of coal pillars, with an increase in the parameter Δh, (m), from Δh=0.0056 m to Δh=0.01 m, the compression work also increases from A=55.4 (J) to A=549.6 (J) (Fig. 4, curve 1). Under conditions of uniaxial compression of protective structures from crushed rock, with an increase in the parameter Δh, (m) from Δh=0.016 m to Δh=0.028 m, the compression work decreases from A=1187 J to A=555.1 J (Fig. 4, curve 2). Fig. 5 shows plots that reflect the relationship between the specific potential energy and the relative change in the volume of experimental samples.

The plots demonstrate that with an increase in the specific potential energy of the deformation of experimental samples, the relative change in volume δV increases (Fig. 5).

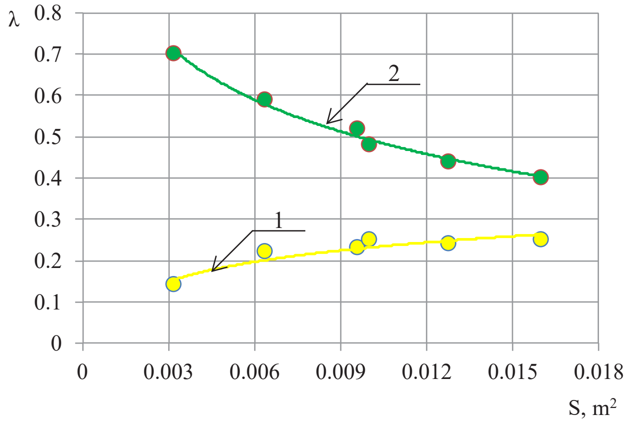


Fig. 3. Plots of changes in the relative deformation λ of experimental samples under uniaxial compression dependent on the cross-sectional area S, m^2: 1 – coal pillars; 2 – protective structures made of crushed rock

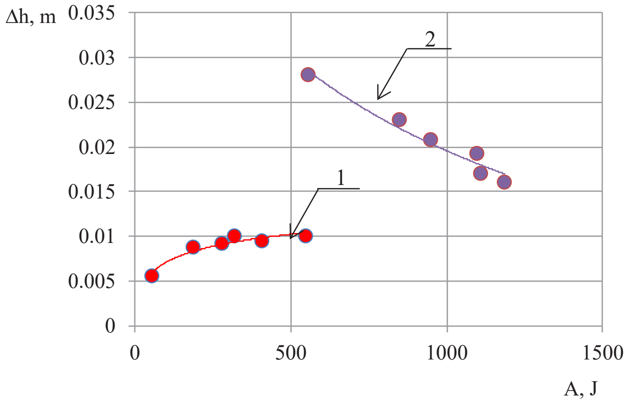


Fig. 4. Plots of changes in the amount of deformation Δh (m) dependent on the work of compression A (J) of experimental samples: 1 – coal pillars; 2 – protective structures made of crushed rock

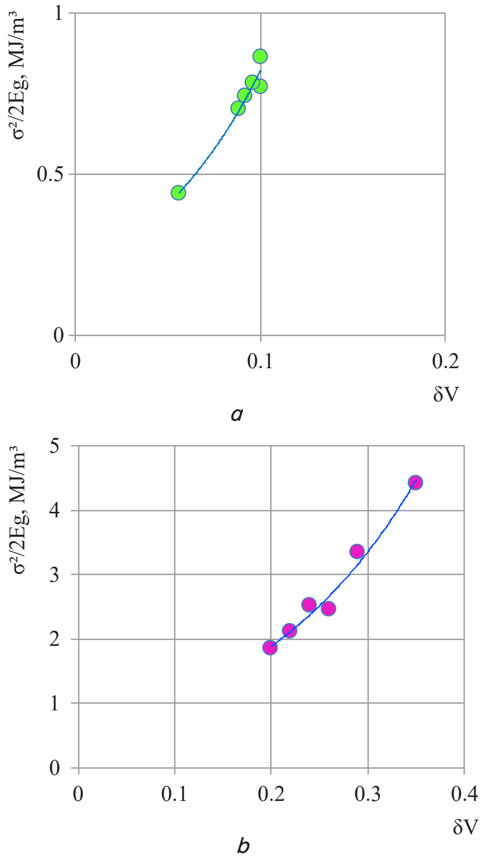


Fig. 5. Plots showing the relationship between the specific potential energy $\sigma^2/2E_g$ and the relative change in the volume δλ of experimental samples: *a* – coal pillars; *b* – protective structures made of crushed rock

Using expressions (7) and (8), the amount of energy of the form change U_{sh} (J/m^3) and the change in volume U_v (J/m^3) was determined. As the calculations show, for coal pillars at the transverse deformation coefficient ν=0.3:

$$U_v = 0.066\frac{\sigma^2}{E_g}, \tag{11}$$

and

$$U_{sh} = 0.43\frac{\sigma^2}{2E_g}. \tag{12}$$

For protective structures made of crushed rock, with a coefficient of transverse deformation ν=0.25:

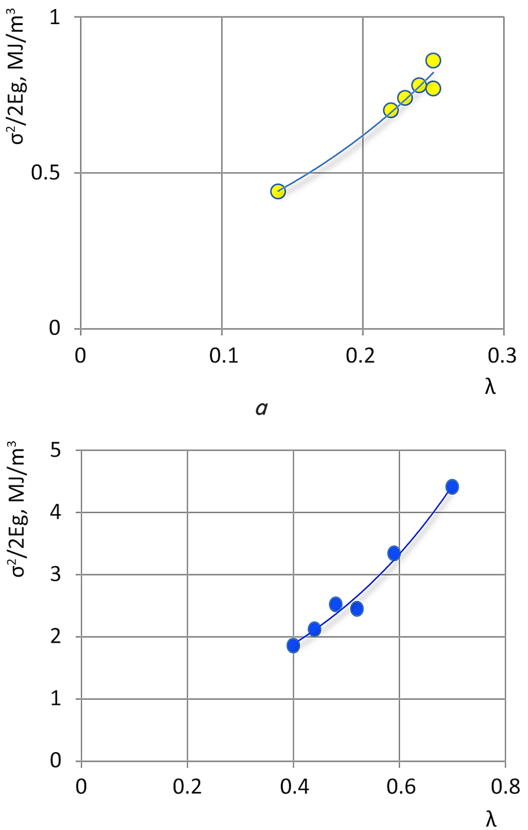
$$U_v = 0.088\frac{\sigma^2}{E_g}, \tag{13}$$

and

$$U_{sh} = 0.41\frac{\sigma^2}{E_g}. \tag{14}$$

As the cross-sectional area of the experimental samples increases, the values of U_v and U_{sh} increase while the ratio U_{sh}/U_v remains constant. For coal pillars, this ratio U_{sh}/U_v is 6.5, and for protective structures made of crushed rock U_{sh}/U_v=4.9. The value of this ratio depends on the coefficient of transverse deformation of the material of protective structures. It is obvious that for coal pillars the potential energy of form change takes 86 %, and for protective structures made of crushed rock – 82 %, of the total potential energy of deformation under uniaxial compression conditions. The volume change consumes 14 % and 18 % of the potential deformation energy, respectively.

Fig. 6 shows the plots of changes in the potential energy of deformation of uniaxial compression dependent on the relative deformation of experimental samples.



a

b

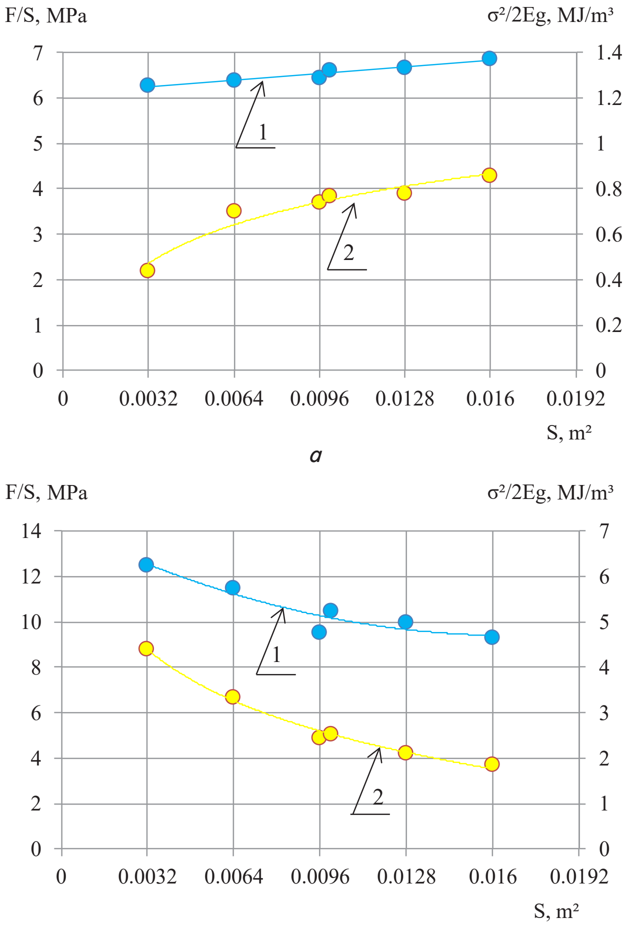
Fig. 6. Plots of changes in the specific potential energy of deformation of uniaxial compression $\sigma^2/2E_g$, MJ/m^3, dependent on the relative deformation λ of experimental samples in the form of a model: *a* – coal pillars; *b* – protective structures made of crushed rock

For coal pillars, with an increase in relative deformation from $\lambda=0.14$ to $\lambda=0.25$, the specific potential energy increases exponentially from $\sigma^2/2E_g=0.44$ MJ/m^3 to $\sigma^2/2E_g=0.86$ MJ/m^3 (Fig. 6, *a*).

For protective structures made of crushed rock, with an increase in relative deformation from $\lambda=0.4$ to $\lambda=0.7$, the specific potential energy also increases exponentially from $\sigma^2/2E_g=1.86$ MJ/m^3 to $\sigma^2/2E_g=4.41$ MJ/m^3 (Fig. 6, *b*).

Fig. 7 shows the plots of changes in the magnitude of pressure and specific potential energy under conditions of uniaxial compression of experimental samples of different cross-sectional areas.

It was recorded that with an increase in the external force and cross-sectional area of experimental samples from S=0.0032 m^2 to 0.016 m^2, for coal pillars, the pressure increases in linear dependence (R^2=0.94) (Fig. 7, *a*, curve 1), and for protective structures made of crushed rock, it decreases by logarithmic dependence (R^2=0.87) (Fig. 7, *b*, curve 2).



a

b

Fig. 7. Plots of changes in the value of pressure F/S (MPa) and specific potential energy under uniaxial compression of experimental samples of different cross-sectional areas S, (m^2): *a* – coal pillars; *b* – protective structures made of crushed rock; 1 – F/S; 2 – $\sigma^2/2E_g$

The change in the potential energy of deformation occurs according to the logarithmic dependence (for coal pillars, R^2=0.94; for protective structures made of crushed rock, R^2=0.99). For coal pillars, an increase from $\sigma^2/2E_g$=0.44 to 0.86 MJ/m^3 is recorded (Fig. 7, *a*, curve 1); for protective structures made of crushed rock, from $\sigma^2/2E_g=4.41$ to 1.86 MJ/m^3 (Fig. 7, *b*, curve 2).

6. Discussion of results of investigating the deformation characteristics of protective structures to assess the effectiveness of protection techniques

Given the results of our studies into the deformation characteristics of protective structures, their influence on the stability of lateral rocks and the preservation of preparatory workings was established. This makes it possible to assess the effectiveness of techniques for the protection of preparatory workings. Experimental samples were used to study the deformation characteristics (Table 1). Such samples, with an aspect ratio of length to width a/b=(1–2), were subjected to uniaxial compression.

For above-the-drift pillars of coal or structures made of crushed rock, between the change in their size λ and the specific potential energy during compression, there is an exponential relationship that makes it possible, within the deformation resource, to assess the condition of protective structures (Fig. 3).

With different cross-sectional areas of experimental samples, in the range of changes in relative deformation for coal pillars ($0.1 \leq \lambda \leq 0.25$) (Fig. 3, curve 1) and protective structures made of crushed rock ($0.4 \leq \lambda \leq 0.7$) (Fig. 3, curve 2), their stable state and increase in durability are ensured. At these intervals between the magnitude of the relative deformation and the change in the cross-sectional area of protective structures, there is a functional dependence that allows one to determine their deformation resource.

For coal pillars, within the established deformation resource, simultaneously with an increase in stability, the potential energy reaches a critical level at which the short-term stability of protective structures is realized. In these intervals, a relative change in the volume of $0.05 \leq \delta\lambda \leq 0.1$ of protective structures was recorded (Table 5). With an increase in static operating load and during the transition of the critical level, when $\lambda > 0.25$ and $\delta V > 0.1$, the shape of the experimental samples changes and after the loss of stability there is a decrease in the resistance of the pillars. Under the conditions of uniaxial compression of coal pillars, the reserve of elastic energy increases and the deformation modulus decreases (Fig. 5, 7, *a*). The main element in the mechanism of destruction of coal pillars is the critical density of the potential energy of deformation, the amount of which is determined by their (pillars) size.

For protective structures made of crushed rock of different particle size distribution, within the established deformation resource, the crushed rock is compacted as a system of fractions of the embedded material, after which an increase in their durability is observed. Within the deformation resource, a relative change in the volume of embedded material of $0.2 \leq \delta V \leq 0.35$ (Table 8) was recorded. With an increase in the size of such protective structures, under the action of a static load, the value of δV decreases, and the work of uniaxial compression increases, which is associated with the compaction of the rock and the creation of a stable structure (Fig. 5, 7, *b*). For protective structures made of crushed rock with their uniaxial compression, a change in the behavior of a deformed body occurs when the primary material is compacted. At the same time, simultaneously with the growth of the deformation module, a change in the shape and volume of the pliable support occurs, due to which their holding increases, and the movement of lateral rocks is limited (Fig. 2).

The rigidity of coal pillars or structures made of crushed rock, as a deformation characteristic of protective structures, is sensitive to the behavior of lateral rocks (Fig. 1, 2; Tables 4, 7). Depending on the combination of rigidity of protective structures, the conditions for the formation of external load on them and contact interaction with the roof and sole, the stability of side rocks in the coal rock array should be ensured.

For protective structures, with an increase in static load and relative deformation λ, with an increase in the area S, m^2, the change in the specific potential energy $\sigma^2/2E_g$, MJ/m^3, occurs according to the logarithmic dependence. Under such conditions, for coal pillars, the deformation modulus decreases, and for structures made of crushed rock, it grows. This process, within the deformation resource of the applied protective structures, allows one to establish their durability (Fig. 6, 7).

Thus, it can be summed up that the deformation resource of the protective structures of the preparatory workings determines the effectiveness of the protection technique used. For coal pillars, the deformation resource is limited, which allows for a short-term preservation of the stable state of the lateral rocks in the coal rock array, which means that this technique has a limited scope. The use of crushed rock for protective structures, allows one to ensure the stability of the lateral rocks around the preparatory workings, and this effect increases with increasing size of protective structures. Therefore, in order to preserve the stability of lateral rocks in the coal rock array and the operational condition of the preparatory workings, it is advisable to use structures made of crushed rock.

The results of our research could be used in coal mines for a reasonable choice of techniques of protection and parameters of protective structures. This would ensure the operational condition of the recoil drifts and reduce the volume of repair work to restore the workings. For further development of research, in order to clarify the parameters of protective structures, it is necessary to conduct full-scale experiments in the mine.

7. Conclusions

1. For coal pillars, with an increase in the area S (m^2) and static operating load in the range of change in relative deformation of $0.1 \leq \lambda \leq 0.25$, simultaneously with an increase in specific potential energy, a relative change in volume occurs in the range of $\delta V = 0.05–0.1$. This makes it possible to ensure their stability. Under conditions where $\lambda > 0.25$, with an increase in $\delta V > 0.1$, there is a decrease in the resistance of pillars and their destruction. As a result, the residual strength of protective structures does not make it possible to limit the movement of lateral rocks and leads to their collapse in the produced space of the excavation section.

2. For protective structures made of crushed rock, with an increase in the area S (m^2) and static operational load in the range of change in relative deformation of $0.4 \leq \lambda \leq 0.7$, a decrease in specific potential energy is observed. At the same time, there is an increase in the deformation modulus and a relative change in the volume of protective structures. The minimum value of $\delta V = 0.2$ corresponds to the maximum area, and the maximum value $\delta V = 0.35$ – minimum area. This is due to the process of compaction of crushed rock in the total volume of embedded material and an increase in the resistance of pliable supports and makes it possible to ensure the integrity of the lateral rocks in the produced space of the excavation site.

3. Based on a comparative analysis of the deformation characteristics of protective structures, the effectiveness of the use of structures made of crushed rock has been established. This will ensure a stable condition of the lateral rocks and workings due to the compaction of the crushed rock within the deformation resource ($0.4 \leq \lambda \leq 0.7$). When using coal pillars that have a limited deformation resource ($0.1 \leq \lambda \leq 0.25$), it is impossible to ensure a stable condition of the lateral rocks and prevent collapse, which limits the use of the protection technique.

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 and the results reported in this paper.

Funding

The manuscript was prepared with the assistance of the Program «Ukraine Digital: Ensuring Academic Performance in a Crisis (2022)» of the German Academic Exchange Service (DAAD) and the Federal Ministry of Education and Science of Germany.

Data availability

All data are available in the main text of the manuscript.

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