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Substantiating Parameters of Reinforced Rock Supports

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Abstract

In this work, we focus on the technology of stabilizing roof rocks by constructing separate rock supports reinforced with metal grids. Their parameters are specified using the results of physical structural modeling. The reinforced and non-reinforced rock supports with different fractional compositions are arranged and tested. Their initial shapes are similar to rectangular parallelepipeds with the base width-to-length ratios of 1:1, 1:1.5, and 1:2. Their shrinkage is determined by loading the supports regarding the rock particle size and the reinforcement density. Increasing the reinforcement density leads to reducing the linear dimensions without losing load-bearing capacity. It is proved that using the grids conduces the self-wedging of the rock particles. They are most effective at the initial stage of the formation of the load-bearing core. The exponential power dependence of the relative support shrinkage on the grid partitions number is obtained. The bearing core sizes in different supports are determined. For the non-reinforced supports, the core width is about 60% of the initial support width, and for the reinforced ones, it is about 90%. The exponential dependence of the core width-to-height ratio on the number of grid partitions is established. The expression for determining the reinforced support width is obtained. The support stability depends on the smallest initial base size. The size of the rock material has a little effect on the shrinkage. Reinforcement by three metal grids leads to reducing the pliability by 21% and 24% for the supports with the side ratios of 1:1 and 2:1, respectively.

1. Introduction

The problem of ensuring the operational condition of preparatory roadways is becoming more and more complicated because the underground mining and geological conditions of coal seams are worsening. In order to reduce the cost of workings and increase the production of coal from longwalls, roadways are reused, and efficient ventilation schemes are applied [1-3]. Therefore, developing and improving the protection methods for the preparatory roadways behind the longwall is a relevant issue.

The preparatory roadways behind the longwall face are often protected in coal massif by coal pillars [4-7]. However, there are conditions that when using coal pillars to protect the roadway is unacceptable due to significant mineral losses [8] or the coal property to self-ignite [1, 9, 10]. In some cases, coal pillars crash into the roof and floor or they are destroyed [11]. In such cases, special technologies are used. They pre-suppose constructing artificial structures [12] made of wood [13, 14], concrete [15-19], ordinary rock [8, 20, 21], etc. as pillars.

The use of limited-sized artificial structures is relevant for the protection of mine roadways and maintenance of the roof in the mined-out space [22-24]. In the underground extraction of zinc, lead, and salt [13, 25, 26], separate wooden cribs that can be filled with rock are used instead of pillars. In the extraction of gold [27], gypsum, and

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bauxite [28], concrete pillars are built. The main parameters of artificial structures are their load-bearing capacity and linear dimensions, on which the stability of roof rocks and the safety of miners depend. The financial costs of their construction are equally important.

Wood is commonly used for the construction of supports but its low strength, scarcity, and increased cost require the search for alternative roof support systems [24]. Concrete supports have the highest level of mechanization and a high load-bearing capacity but they cannot be considered low-cost [27]. Artificial structures must be technological, low-cost, and provide effective protection of roadways.

Ordinary rock is the cheapest material for artificial structures. The cost is reduced because the rock does not rise to the surface but is used as a backfill material. Additional costs for the rock loading and transportation and its storage in dumps are excluded. Besides, spreading of the dumps area leads to a decrease of fertile land, clogging of water bodies, increasing the concentration of dust in the air, releasing combustion products during self-ignition of coal residues, and oxidation products of chemicals.

As a rule, the rock comes from the faces and places of the roadway repair. The available volumes of rock are not enough for a full back-filling in the mined-out spaces behind the clearing faces. It is economically impractical to accumulate rock for protective structures from the most remote areas of the minefield. That is, the question of creating structures with limited rock volumes is interesting to investigate. Limiting the size of these structures will reduce the complexity of work by using a non-mechanized method of laying the rock. Therefore, the general principles for the creation of stable rock structures limited in dimensions and able to bear the roof rocks load should be considered.

2. Literature review and relevance of article

Using rubble strips as a means of protection has become a popular method because it allows leaving the rock in the mine. Rubble strips are cheaper than the other means for protection because the initial costs are offset by reducing the costs of maintaining the roadways with the use of rock. However, significant amounts of rock are required for rubble strips, and they have a shrinkage of up to 60%, which is accompanied by the loss of operational cross-section of the protected roadway.

In order to reduce the pliability of rubble strips and increase their load-bearing capacity, specific engineering solutions are suggested, namely limiting surfaces, which can be wooden racks, fabric, rubber or paper coatings, metal sheets or rods, etc.

The method is proposed for increasing the bearing capacity of the rubble strip using anchors that tighten the rock and create a preliminary force between the uprights [29]. Fences and support racks in the structure are made pliable in horizontal and vertical directions. Fences converge when anchors are tightened and the rock moves in the horizontal direction. Thus its density and the support bearing capacity increase. When the rock moves in the vertical direction, the rock wedging between the roof and the floor increases [29]. The scope of this method is limited by the seam thickness of 1.2 m. The authors do not indicate how the anchors between the fences will be tightened after the space between them is filled with stones. This is technically challenging to implement. However, this method can be used to reinforce the rubble strip. A similar technology was used at the Huayuan mine (China), where a strip of more than 2.5 m wide was secured on both sides with anchors [20].

The method of protection by rigid structures, i.e. supporting pillars of ordinary rock in a special shell, has been proposed [30]. The rock comes from wells drilled into the roof to make it collapse. There is also a similar method but more difficult to implement. It involves protecting by cribs inside of which there is ordinary rock in bulk and in bags [31]. It has also been proposed to use the walls made of car tires, and fill the voids inside them with stone [32, 33].

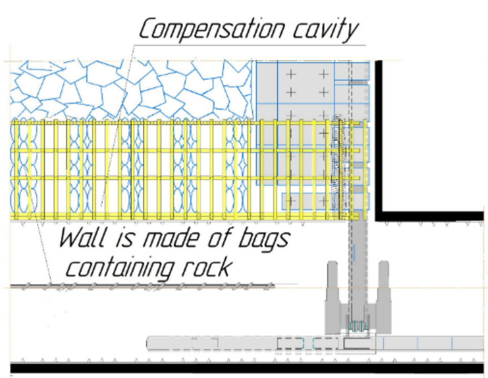
There is a method of protecting preparatory roadways by supports from bags of fabric 1.2 m long and 0.2-0.6 m in diameter filled with rock [34, 35]. The load-bearing capacity of such supports is 1.1-1.2 MN. The method has passed the experimental and industrial testing but has not been implemented because the bags are very heavy, which complicates their moving and does not meet the requirements in order to ensure safe working conditions. This method has been improved [36]. The bags are small and weigh up to 40 kg. They are laid in layers in the form of a solid wall. The application of the method has allowed isolating the preparatory roadways from the mined-out space, reducing the protected roadways displacement, as well as creating safe working conditions. However, the tests have revealed a number of shortcomings and omissions, namely: a large number of rock bags is required, and this wall has a significant shrinkage (up to 34%). This technology has also been used in China [37-39]. In the mines of Great Britain, the walls were laid out of paper bags filled with ordinary rock and reinforced with wire [40]. This technology was improved to a combined design [21]. Two walls were erected from bags with fine rock, and then the space between the walls was filled with the rock of any fraction.

A series of scientific research works [41] have been devoted to the use of flexible partitions. Flat and curved intercalated layers made of fabric or metal grid between the rock layers have been considered.

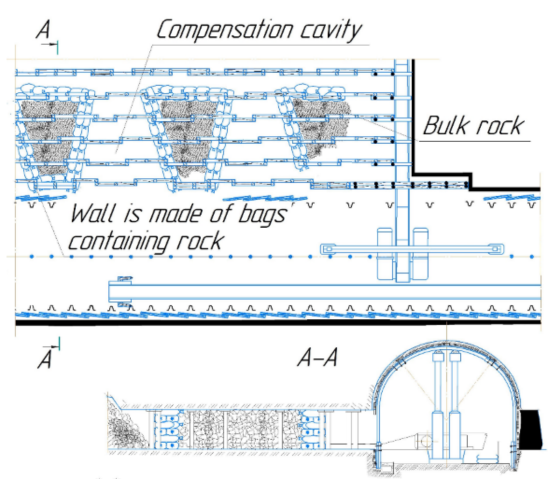
The bearing capacity of the rock strip increases due to the clutch between the rock particles and the partition resistance to the horizontal movement of the particles. The efficiency of reinforcing the rubble strips by grid partitions has been proved, and a method of calculating the parameters of such structures has been proposed [41].

The above-mentioned technologies involve the belt-type structure layout along the roadway. However, in certain conditions, a separate arrangement of supports is more suitable than the belt-type one, for example, to maintain technological processes or to redirect the stresses from the roadways. In order to redirect the stresses, supports are constructed, and compensation cavities are left between them.

The design of rock supports in the form of rectangular parallelepipeds (Figure 1a) and trapezoidal prisms (Figure 1b) has been proposed in the studies [42]. In these supports, using the rock bags are used. It is supposed to position a narrower face of the supports towards the roadway. The compensation cavities are left between the supports. The operational state of the roadway is maintained by redirection of stresses from the roadway into the cavities and the mined-out space. This technology has a certain disadvantage, namely the implementation challenge, especially when the supports are placed in the mined-out space. The bags are filled near the face or at the surface. The rock of a given fraction is sifted, and then the bags are filled and delivered to the place of laying. In order to construct the support of 1 m^3 volume, at least 50 bags of rock are required, and the weight of one bag should not exceed 40 kg (by sanitary standards).



(a)



(b)

Figure 1. Technological schemes of roadway protection by separately located supports with compensating cavities (a- in the form of rectangular parallelepipeds, b- in the form of trapezoidal prisms).

It has been proposed to use metal sheets in separate rock supports [43]. The sheets are laid between the rock layers parallel to the base. In this case, the bearing capacity of the supports increases. These supports are erected behind the longwall in the goaf in order to control the roof. The roof descends smoothly onto these supports. The stability of each support layer is ensured if its width is 5…7 times over its height. Therefore, when the number of layers increases, the width of the support decreases. This solution proves to be effective but it is difficult to create such a structure since the metal sheets are heavy and bulky. They cannot be moved in a tight working space where the height is low and wooden racks are installed between the roof and the soil.

Grid partitions are an alternative to metal sheets. They are similar to those used in the reinforcement of rubble strips [41]. Reinforced rock supports can form structures of any shape. According to the results of laboratory tests [42, 44], such supports allow shrinkage of 16-20%. They can be effective for keeping the roof in the mined-out space and for the roadway protection (Figure 2). The process of transporting rock from the place of extraction to the place of construction can be mechanized. The partitions are assembled near the place where the support is erected. They are made of steel or composite reinforcement. These can be prefabricated structures from small interconnected grids. The fittings and grids are lightweight and compact. However, the available amount of research works is insufficient for the industrial application of this technology, as there are no specific recommendations for the linear dimensions of such supports, number of grid partitions, and fractional composition of the rock. That is, there is a need for additional research works to clarify the parameters of the reinforced rock supports.

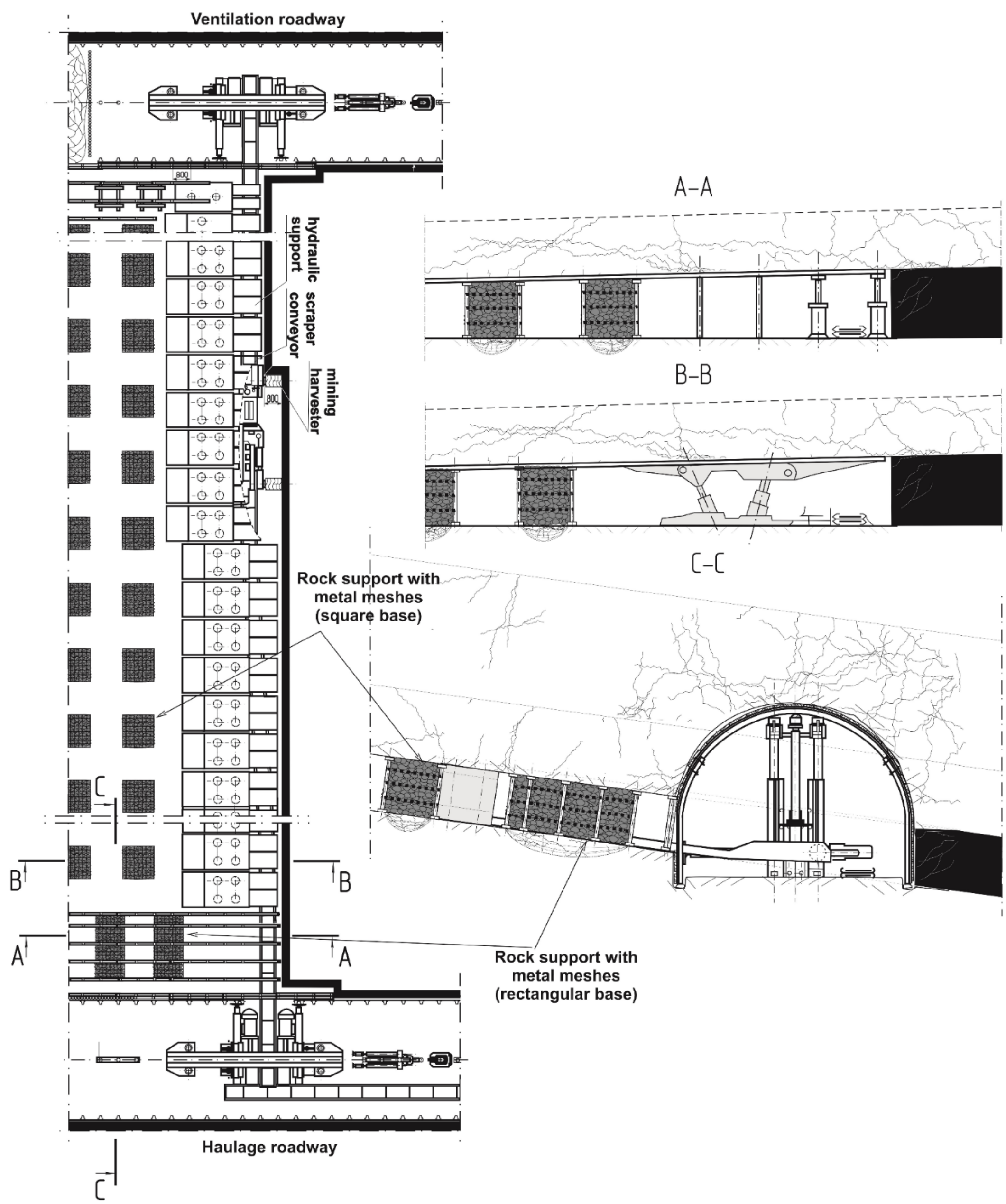


Figure 2. Technological scheme of using reinforced rock supports behind a longwall in goaf and at the roadway.

3. Materials and research methods

The research on refining the parameters of the reinforced rock supports can be based on the results of physical structural modeling [41]. Separately located rock supports with metal grid differ from the reinforced rubble strips since they are limited only in one direction (from the side of the roof and floor). The stability of such supports depends on the sizes of the bearing core (C), peripheral zones (P), and zones of free slopes (K). Peripheral zones and zones of free slopes create lateral resistance, and stabilize the bearing core. When the grids are used, the size of the peripheral zones can be reduced (Figure 3) because the clutch between rock particles and the grid compensates for the share of lateral resistance from these zones. Insufficient strength of the grid rods and their possible destruction can lead to uncontrolled subsidence of the support and loss of bearing capacity.

Each rock particle behaves like a wedge under vertical forces. Therefore, the horizontal forces lead to the mobility of particles. In order to prevent this movement, metal grids are used in the support, in the cells of which the rock particles get stuck. This allows limiting the horizontal movements and displacements of rock particles in the support (Figure 4), thereby, increasing the bearing capacity of the support.

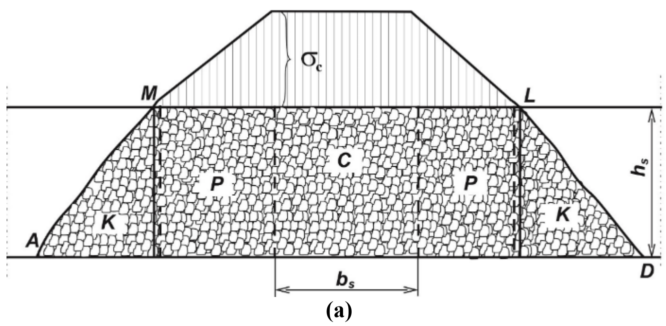


Figure 3. Diagram of characteristic zones of free rock fill (a) and reinforced with metal grid (b): *C*: central zone (bearing core); *P*– peripheral zones; *K*– zones of free slopes; b_s– width of fill in contact with the roof; h_s– height of fill; σ_c and σ_p– stress in the central and peripheral zones, respectively.

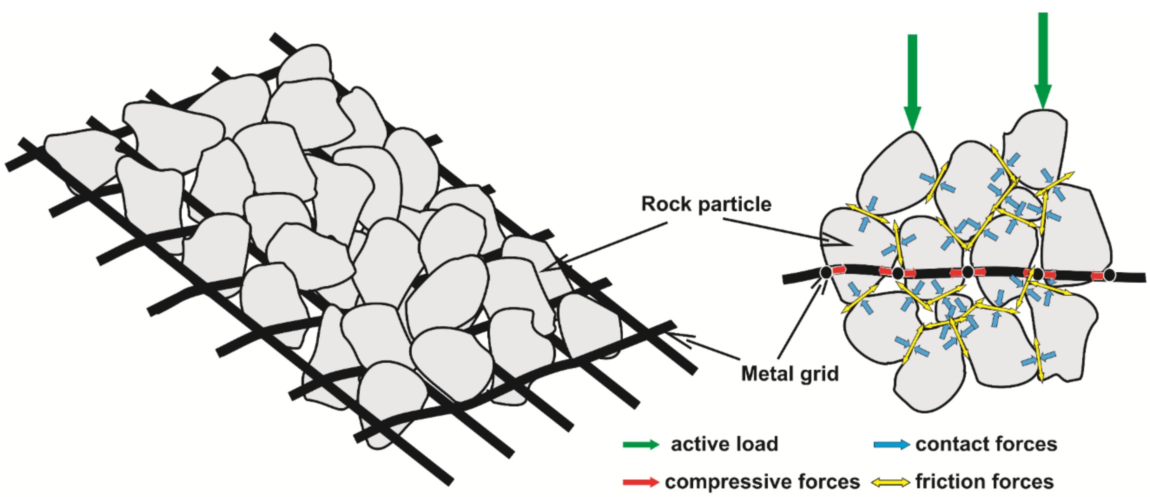


Figure 4. Scheme of interaction between rock particles and a metal grid.

The parameters of grid partitions should be determined taking into account the size of the cells, class, and diameter of the reinforcement in the grids, as well as the diameter of the maximum piece of rock in the support [41]. In particular, the size of the grid cells should be from 2.2 to 5 diameters of the maximum pieces of rock in the structure, and not more than 8 diameters of the reinforcement.

It is necessary to take into account the condition (1) for determining the class of reinforcement in the partition [41].

$$\frac{d_f}{\sqrt{\varepsilon_{ub}\left(2+\varepsilon_{ub}\right)\pi d}}\sigma \le \left[\sigma_s\right], \tag{1}$$

where d– the rod diameter, m; $[\sigma_s]$– allowable rod stress during stretching, MPa (depending on the reinforcement grade); d_f– diameter of the largest piece of rock in the support, m (according to actual data from 0.1 to 0.25 m); σ– roof load stress, MPa; ε_{ub}– ultimate relative deformation of the reinforcement elongation (it measures from 0.014 to 0.02 corresponding to the reinforcement grade).

If condition (1) is fulfilled, the partition will not collapse. If condition (1) is not fulfilled, the partitions in the local sections will be destroyed because the operating stresses in the reinforcement will exceed its tensile strength.

The results of field and laboratory tests have been used to establish stable forms of rock supports [44]. It has been proved that the maximum stability of the floor rocks is provided by the square shape of the support (the ratio of the width of the support base to its length is 1:1). Such supports can be constructed in order to control the roof in the mined-out space and to protect the roadways in stable floor rocks. In conditions of the weak floor, the use of rigid structures is limited [45, 46], so for roadway protection; it is advisable to use supports in the form of rectangular parallelepipeds. Their narrower side should be faced towards the roadway. The construction of such supports will allow redirecting the squeezing forces from the roadway to achieve the arch effect (Figure 5) and ensure the stability of the roadway. Thus the ratio of the width of the support base to its length should be in the range of 1:2 to 1:3, the width of the support should not be less than the height, and the width of the cavities depends on the angle of internal friction of the underlying rocks and the width of supports [44]. The required width of the supports at which the stability of the entire structure will be ensured remains uncertain.

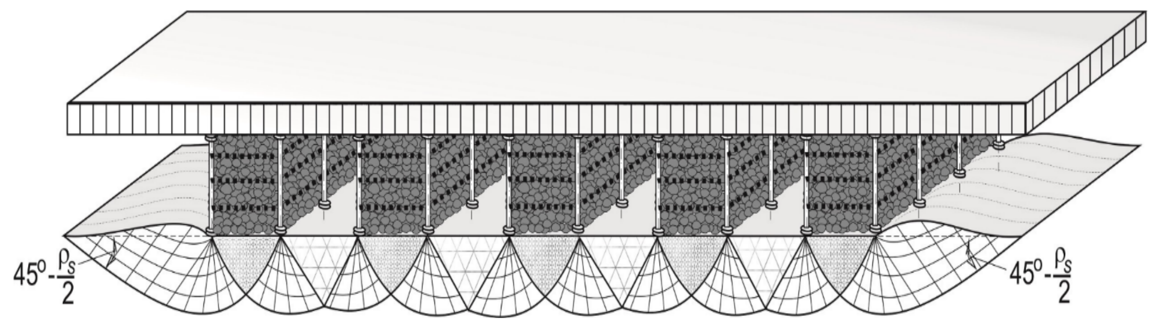


Figure 5. Scheme of rock displacements under compensating cavities and rock supports in the form of rectangular parallelepipeds under the condition of arch formation.

4. Physical structural modeling

4.1. Assembling and testing of structural models

In order to establish the parameters of the reinforced rock supports, the structural models of rock piles with metal grids are assembled. The modeling scale is 1:10. The models have different linear dimensions. The non-reinforced supports and the reinforced supports with one, two, and three metal grids are arranged (Figure 6). The models are compressed in one direction (top and bottom) by a hydraulic press to establish the dependence of the support shrinkage on the reinforcement density and the ratio of the initial linear dimensions. Sheets of white and copy paper have been placed under some models (Figure 7). Imprints from the bearing cores remain on the white sheets after testing the models, which determine the size and shape of the core in the plan. The shapes of the cores are also marked in the reinforced supports when the rock is removed from the metal grids. The core imprint of the grid rods deformation can be seen on the grids.

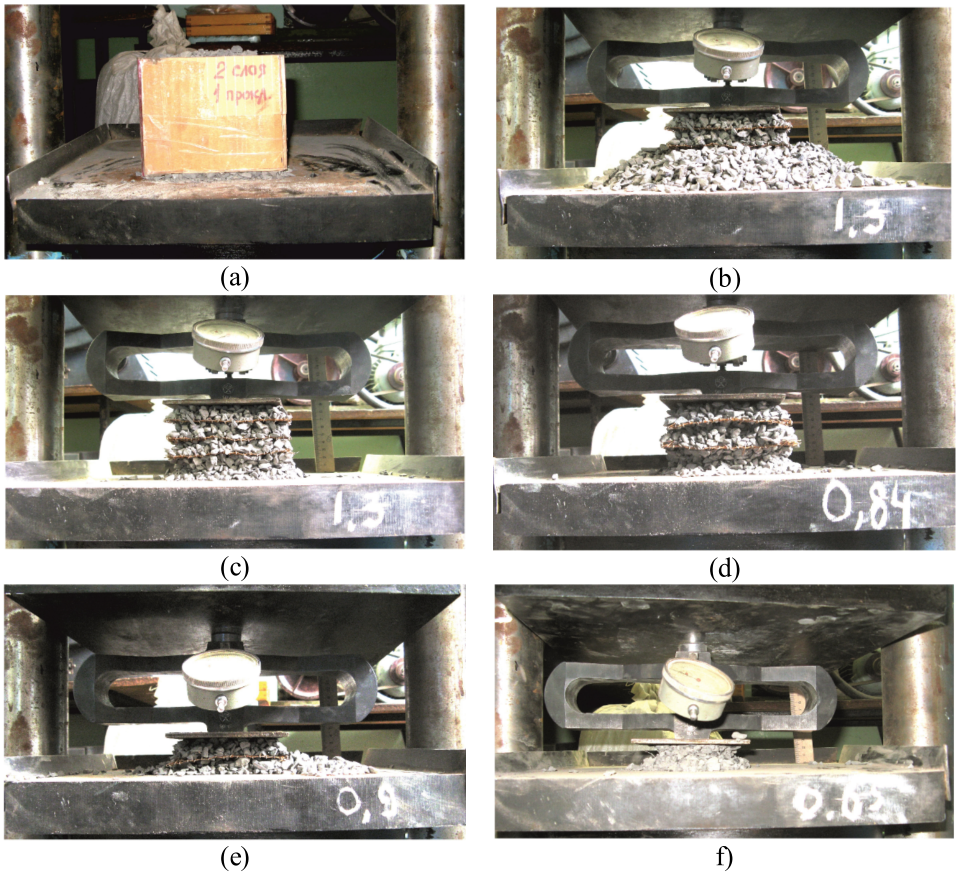


Figure 6. General view of rock support models with a different number of reinforcing metal grids (a- support in paper formwork, b- three grids and rock pile around it, c- three grids with removed rock, d- two grids with removed rock, e- one grid with removed rock, f- without grids with removed rock).

Figure 7. General view of white and copy paper before placing it under the model.

The models have been assembled and tested in accordance with the similarity criteria:

1. Geometric similarity

$$\left(\frac{l_{\mathrm{m}}}{l_{\mathrm{n}}}\right) = \text{const}, \qquad (2)$$

where l_{m} та l_{n}– linear dimensions in the model and life-size, respectively, m.

2. Equality of internal friction angle of model material (ρ_{m}) and destroyed rocks (ρ_{n})

$$\rho_{\mathrm{m}} = \rho_{\mathrm{n}}. \qquad (3)$$

3. Force similarity

$$P_{\mathrm{m}} = P_{\mathrm{n}} \left(l_{\mathrm{m}} / l_{\mathrm{n}} \right)^3 \cdot \left(\gamma_{\mathrm{m}} / \gamma_{\mathrm{n}} \right), \qquad (4)$$

where P_{m} i P_{n} – force magnitude in the models and life-size, respectively, kN; γ_{m} and γ_{n} – specific density of the model material and rocks, respectively, N/m^3.

4. Similarity of mechanical characteristics

$$N_{\mathrm{m}} = \left(l_{\mathrm{m}} / l_{\mathrm{n}} \right) \cdot \left(\gamma_{\mathrm{m}} / \gamma_{\mathrm{n}} \right) \cdot N_{\mathrm{n}}, \qquad (5)$$

where N_{m} and N_{n}– mechanical characteristics in the model and life-size, respectively, kPa.

The maximum load of the model is calculated by the formula [21].

$$g_m = \left(l_m / l_n \right) \cdot \left(\gamma_m / \gamma_n \right) \cdot g_n, \qquad (6)$$

where g_m– the magnitude of stress between the roof rocks and life-sized supports when $\gamma_m/\gamma_n = 1$ and $l_m/l_n = 0.01 – g_m = 0.01g_n$. Taking into account the area of supports, the load in the model should be equal to 14 kN.

The reinforced and non-reinforced rock volumes are prepared. All volumes have the same rock particle size of $0.08h_s$ to $0.27h_s$. A metal grid with a wire diameter of 0.5 mm and a cell size of 6 mm×6 mm is used for reinforcement.

During back-filling, the rock volumes are placed in a special paper formwork (Figure 6a). They are rectangular parallelepipeds with linear dimensions of 0.1 × 0.1 × 0.1, 0.1 × 0.1 × 0.15, and 0.1 × 0.1 × 0.2 m. Thus the supports had initial ratios of base width to length of 1: 1, 1:1.5, and 1:2.

The structural models of rock supports are arranged, and the initial and final heights of the supports are recorded before and after loading each support. After the formwork is removed, the rock volumes take the shape of truncated cones, and their initial dimensions are measured before loading. Then a load of 14 kN is applied to the pile, while the final dimensions of the supports are recorded. The difference between the initial and final height of the support is equal to the absolute value of its shrinkage, which can be used to calculate the relative shrinkage at different initial sizes of supports, taking into account the size of rock particles and the reinforcement density.

4.2. Analysis of results of physical modeling

When testing the reinforced models with partitions, the rock volume deformation differs from the non-reinforced ones. After removing the formwork, the initial height of the reinforced supports is well over the non-reinforced ones. Moreover, the structure with three partitions practically does not crumble, and its natural shrinkage before loading does not exceed 2%. In the non-reinforced supports, natural shrinkage before loading reaches 49% (Figure 8). Vertical force in the rock volumes causes a further shrinkage of about 20%, regardless of the reinforcement density (Figure 8). Thus after the cores are formed, the supports are compressed equally regardless of the reinforcement density. As a result, the shrinkage is 21% and 75%, respectively, for the supports with three partitions and the non-reinforced ones. This indicates that the grids are more effective at the initial stage for the formation of the bearing core. The function of the grid partitions is to lead to the self-wedging of rock particles in order to prevent the expansion of the rock volume when the bearing core is formed. The rock becomes jammed in the support due to the forces that are perpendicular to the roof, floor, and partitions. These forces are caused by friction and clutch of the rock particles with these surfaces.

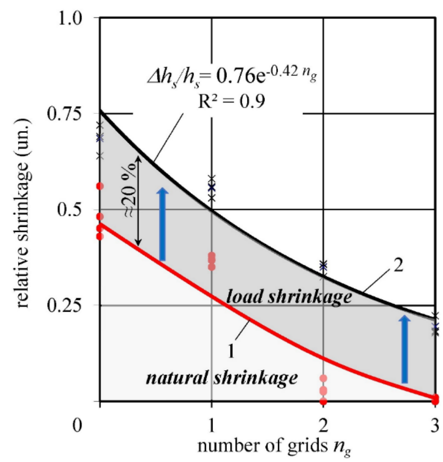


Figure 8. Graphs showing dependence of relative shrinkage value of rock supports $\Delta h_s/h_s$ on the number of partitions along the support n_g at different stages of their testing (1 and 2- before and after loading of supports, respectively).

After measuring the support shrinkage, the following exponential power dependence of the relative shrinkage $\Delta h_s/h_s$ on the number of partitions in the support n_g is deduced:

$$\frac{\Delta h_s}{h_s} = 0.76e^{-0.42\,n_g} \qquad (7)$$

($R^2 = 0.96$; $t > t_{critical\ value}$ (122.3 > 2.16)

$F > F_{critical\ value}$ (156.0 > 3.81))

Also the dimensions of the support are measured after full loading. Then the piled rock outside the core is removed (Figure 6). This allowed us to study the load-bearing cores in different supports, and determine their size depending on the density of the structure reinforcement.

For the non-reinforced supports, the rock removal leads to their imbalance and subsequent shrinkage, and for the reinforced ones, it has a lesser effect on the overall shrinkage. The dimensions of the bearing cores are significantly smaller than the dimensions of the supports themselves. For the non-reinforced supports, the core width is about 60% of the initial width of the support, and for the reinforced ones, it is about 90%. After processing the results of measurements of the bearing core sizes of rock supports with a different number of partitions n_g, the ratio of their width b_c to height h_c is established, and the exponential dependence of this ratio on n_g is determined:

$$\frac{b_c}{h_c} = 2.29e^{-0.28n_g} \tag{8}$$

($R^2 = 0.96$; $t > t_{critical\ value}$ (122.3 > 2.26)

$F > F_{critical\ value}$ (108.0 > 4.26))

After comparing the core width b_c with the initial width of the rock pile in contact with the roof b_r before the removal of rock, the exponential dependence of the ratio b_r/b_c on n_g is established.

$$\frac{b_r}{b_c} = 2.25e^{-0.28n_g} \tag{9}$$

($R^2 = 0.96$; $t > t_{critical\ value}$ (61.9 > 2.26);

$F > F_{critical\ value}$ (27.6 > 4.26))

Graphically, the dependences (8) and (9) are shown in Figure 9.

The dependences show that as the number of grid partitions increases, the amount of support shrinkage decreases due to the formation of bearing cores. Their width averages 1.0 h_c, 1.2 h_c, and 1.6 h_c if the number of partitions is 3, 2 and 1, respectively, and 2.4 h_c - for the non-reinforced supports. The core height h_c is equal to the final support height after loading. As the reinforcement density of the supports reduces and the rock particles mobility increases, the supports expand to 1.0 h_c (three grids), 1.1 h_c (two grids), 2.0 h_c (one grid), and 2.0 h_c (no grids). That is, increasing the density of the rock support reinforcement leads to reducing their linear dimensions. According to these results and the calculation scheme (Figure 10), the expressions are deduced in order to determine the width of the reinforced supports.

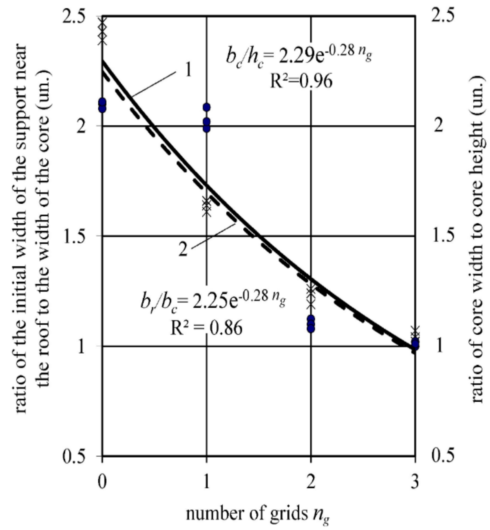


Figure 9. Graph showing dependences of width-to-height ratio of bearing cores (1) on support width (under the roof) to core width (2) on the quantity of partitions n_g in the support (× and ■ - markers to trend lines 1 and 2, respectively).

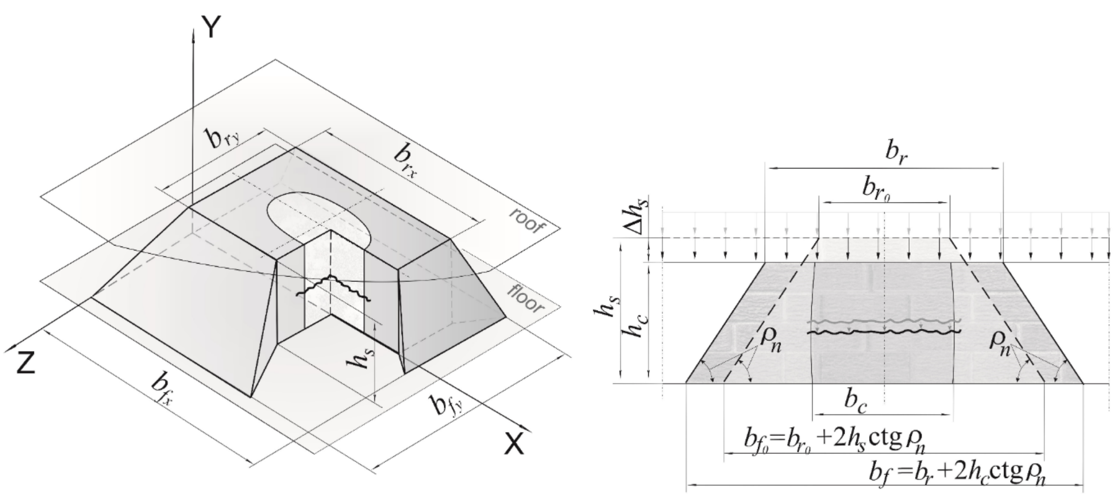


Figure 10. Calculation scheme for determining width of reinforced rock support.

Since $\Delta h_s = h_s - h_c$ (Figure 10), and according to (7), (8), and (9) after transformations, the width of the reinforced rubble support in contact with the roof will be defined by the expression:

$$b_r = 5.15 h_s \left(\frac{e^{0.42 n_g} - 0.76}{e^{0.98 n_g}} \right) \quad (10)$$

where h_s– initial height of the support at the time of its construction, m; n_g–number of partitions along the support.

Thus according to Figure 10, the support width in contact with the floor will be determined by the expression:

$$b_f = h_s \left(1 - \frac{0.76}{e^{0.42 n_g}} \right) \left(\frac{5.15}{e^{0.56 n_g}} + 2\text{ctg}\rho_n \right) \quad (11)$$

where ρ_n– angle of the natural slope of rocks in the pile, degrees.

The stability of the support is determined by its width in contact with the roof so when determining the linear dimensions of the rock supports with metal grids, it is advisable to use expression (10).

The ratio of the parallelepiped sides during back-filling is not changed significantly in the values of the support pliability. Comparison of the results of the support modeling with the ratios of the side of 1:1, 2:1, and 2:3 during back-filling at maximum loads reveals that the supports behave identically, and the values of relative shrinkage of the supports with the same number of partitions differ only by 6.1...9.5% (Figure 11). This indicates that the stability of the reinforced and non-reinforced supports with a rectangle base depends on the initial length of the smaller axis of the base in the plan, in which the bearing cores have the shape of an ellipse (Figure 12). For the reinforced supports with a square base, the shape of the cores is similar to a circle (Figure 12), and its diameter depends on the density of reinforcement and the smallest initial size of the base in the plan.

As for small fractions, the ratio of the larger to smaller axes of the bases (ellipses) ranges from 1.11 to 1.92, depending on the density of reinforcement (the smallest in the non-reinforced supports, and the biggest in the supports with three partitions). The length of the smaller axis averages 80% of the initial width of the support during back-filling. As for the large fraction, the ratio of the axes is 1.13 (for the non-reinforced supports) and 1.54 (for the support with three partitions), and the length of the smaller axis averages 88% of the initial width of the support. The figures indicate that by changing the size of the back-filling material and the density of reinforcement, it is possible to preserve the initial dimensions of such supports, and to provide sufficient resistance to overhanging rocks.

When the size of the rock material in the supports increases, the shrinkage of the latter decreases insignificantly but the increase in the number of partitions has a significant effect on the pliability and stability of the supports. Therefore, it has been concluded that the size of the rock fractions can be ignored in the construction of supports. Reinforcing the rock supports with three metal grids leads to reducing their shrinkage to 21-32% depending on the ratio of the linear dimensions of the supports in the plan. The best result (21% of shrinkage) is obtained if the initial ratio of the base sides is 1:1 so such supports can be recommended in order to control the roof in the mined-out space. When protecting the roadways in the weak floor rocks, it is advisable to construct rock supports with three metal grids, and the ratio of the base sides should be 2:1, which will ensure a shrinkage of 24%.

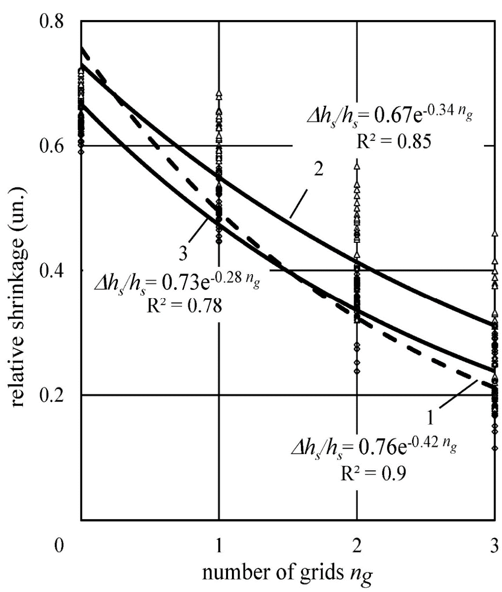
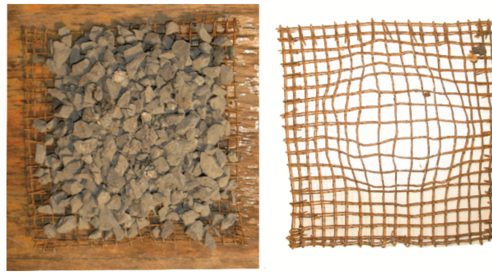
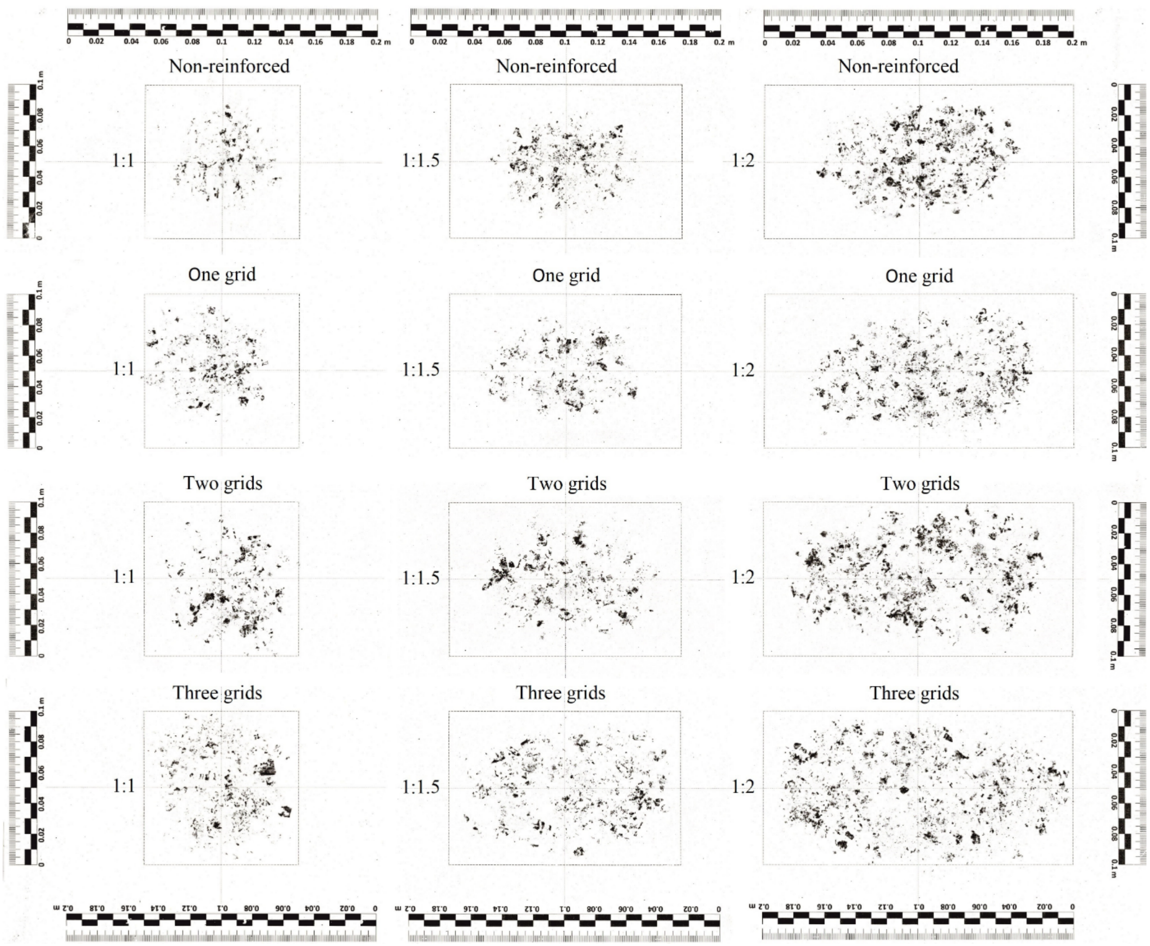


Figure 11. Graphs showing dependence of relative shrinkage of rock supports $\Delta h_s/h_s$ on the number of partitions along the height of support n_g at different ratios of the base sides during backfilling: 1:1 (1), 2:3 (2), i 2:1 (3).



(a)



(b)

Figure 12. General view of metal grid after model disassembly, the base side ratio of 1:1 (a), and the imprints of the support cores of different reinforcement densities and sizes of supports (b).

5. Feasibility study on time and cost of new proposed supports

In order to construct the reinforced rock supports, a smaller volume of rock is required compared to a rubble strip and a reinforced strip, which are erected in a belt along the roadway. Therefore, the costs of implementing the technology can be lower.

The cost of erecting supports is determined by the labor costs and the cost of reinforcement. Thus the cost of erecting the support is determined by the expression:

$$C = W + M, \qquad (12)$$

where *C*– total costs for the construction of the support; *M*– cost of reinforcement (grids); *W*– wages.

The labor costs are determined by the tariff rate for a working shift and the labor intensity for moving rock and reinforcement (grids) and erecting support according to the formula:

$$W = R \cdot T, \quad (13)$$

where R– tariff rate per shift; T– labor intensity.

In order to determine the labor intensity for moving the rock, the current enterprise standards are used. To calculate the labor intensity for carrying reinforcement (grids) and assembling the partition, the time norms are determined.

In a coal mine, the time standard for the assembly of a grid partition is determined when erecting supports along the roadway with the ratios of the sides of 2:1. The partition consists of pre-fabricated interconnected metal grids. The size of a separate grid is 0.6 × 0.8 m, the grid size is 0.1 × 0.1 m, and the reinforcement diameter is 0.08 m. The time rate is determined using the time-keeping observations. The time for the following procedures is determined: accepting of the shift, inspecting the workplace according to safety rules, preparing the working tools, delivering the grids to a distance of 15 m and laying them, preparing the place for laying the grids, cleaning the working tools, and turning over the shift. The time standard for laying one partition is 0.1785 man-hours. Thus the complexity of work for assembling three partitions is equal to 0.476 man-shifts.

The labor intensity for moving 1 m^3 of rock to a distance of 5 m is 0.145 man-shifts. The total labor intensity for assembling support with a rock volume of 2.1 m^3 and three partitions is 0.7805 man-shifts.

At the time of the feasibility study, the underground worker's tariff rate was $18.33, and the cost of the partition grids was $25.35. The wage costs are determined according to expression (13) and the amount to $14.31. Therefore, according to expression (12), the cost of erecting the support was $39.66.

The total costs for the construction of the reinforced supports along the 1000 m long roadway amount to $19,830. This is 1.4 and 3.0 times less than the cost of the non-reinforced and reinforced rubble strip, respectively.

6. Conclusions

According to the research findings, the following conclusions can be drawn:

-For the non-reinforced rock supports, the width of the bearing cores is about 60% of the initial width of the support, and for the reinforced ones, it is about 90%.

-Metal grids in rock supports are the most effective for the formation of the bearing core at the initial stage. They conduce self-wedging of the rock particles, and prevent the rock from expanding at the time of formation of bearing cores.

-Increasing the reinforcement density of the rock supports leads to reducing their linear dimensions.

-The stability of the support is determined by the width of the contact point with the roof, taking into account the initial height of the support at the time of its construction and the number of partitions along the height of the support. An expression for determining the width of the support in contact with the roof was proposed.

-The stability of the reinforced and non-reinforced supports depends on the smallest initial size of the base in the plan.

-Reinforcing the rock supports with three metal grids leads to reducing their pliability to 21% and 24% for the supports with the base size ratio of 1:1 and 2:1, respectively.

-In order to control the roof in the mined-out space, it is advisable to build the reinforced rock supports with a square base with a base side ratio of 1:1.

-The stability of the roadway behind the longwall is achieved by re-directing the stresses from the roadway due to the construction of separately located reinforced rock supports in the form of rectangular parallelepipeds with compensatory cavities between them. The ratio of the base sides of parallelepipeds is 2:1.

Thus the efficiency of using the reinforced grid partitions in rock supports as limiting elements was confirmed. At the initial stage of their loading, they conduce self-wedging of rock particles, prevent the supports from expanding at the moment of bearing core formation, and significantly change the load and deformation characteristics of the structures. The principles for determining the parameters of the reinforced rock supports were proposed.

The conclusions are based on the results of the laboratory studies and calculations. The results obtained indicate that the use of the reinforced rock supports is promising, and further research works in this direction are required. Therefore, the next stage of the research involves the industrial testing of the new proposed supports in the mine conditions. After that, the simulation results can be used to develop recommendations on applying the reinforced rock supports in roadway protection and roof control.

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چکیده:

در این پژوهش، بر روی فناوری تثبیت سنگ‌های سقف بـا سـاخت سیسـتم‌های نگهـداری سـنگی جداگانـه تقویـت شـده بـا شـبکه‌های فلـزی تمرکـز شـده اسـت. پارامترهای آنها با استفاده از نتایج مدلسازی ساختاری فیزیکی مشخص شده است. سیستم نگهداری سنگی تقویت شـده و تقویـت نشـده بـا درزه‌هـای متفـاوت بـرای انجام این آزمایش گردآوری شدند. شکل اولیه آنها شبیه به مستطیل متوازی الاضلاع با نسبت عرض به طول پایه ۱:۱، ۱:۱/۵ و ۱:۲ اسـت. انقبـاض آنهـا بـا بارگـذاری تکیه گاه‌ها با توجه به اندازه ذرات سنگ و چگالی تحکیم سازی (آرماتور) تعیین می‌شود. افزایش چگالی آرماتور منجر بـه کـاهش ابعـاد بـدون از دسـت دادن ظرفیـت باربری می‌شود. ثابت شده است که استفاده از شبکه‌ها باعث ایجـاد گوه‌هـایی در ذرات سـنگ مـی‌شـود. آنهـا در مرحلـه اولیـه تشـکیل هسـته بـاربر مـؤثرتر هسـتند. وابستگی توان نمایی به انقباض نسبی سیستم نگهداری و تعداد پارتیشن‌های شبکه بستگی دارد. ابعـاد هسـته مرکـزی بـاربری بـرای سیسـتم‌های نگهـداری مختلـف تخمین زده شد. برای سیستم نگهداری‌های تقویت نشده، عرض هسته حدود ۶۰ درصد از عرض سیستم نگهداری اولیـه و بـرای پایـه هـای تقویـت شـده حـدود ۹۰ درصد است. وابستگی نمایی نسبت عرض به ارتفاع هسته، به تعداد پارتیشن‌های شبکه ایجاد شده بستگی دارد. تعریفی برای تعیین عـرض سیسـتم نگهـداری تقویـت شده به دست می‌آید. پایداری پشتیبانی به اندازه کوچکترین سیستم نگهداری اولیه بستگی دارد. اندازه مواد سـنگی تـاثیر کمـی در انقبـاض دارد. تقویـت توسـط سـه شبکه فلزی، منجر به کاهش انعطاف پذیری ۲۱٪ و ۲۴٪ برای سیستم‌های نگهداریً با نسبت جانبی ۱:۱ و ۲:۱ می‌شود.

کلمات کلیدی: محافظت از بزرگ راه‌ها، ساخت و ساز مصنوعی، سنگ معمولی ، سیستم نگهداری سنگ، تحکیم و بهسازی.