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Method for controlling the floor heave in mine roadways of underground coal mines

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Abstract

Purpose. The method development and research on controlling the floor heave of mine roadways located in the zone of increased stresses by local strengthening the rocks with mixtures expanding in the solid phase.

Methods. The work uses the following research methods: analysis and generalization of previously performed research on the process of heaving the floor in mine roadways; full-scale mining studies, which include instrumental measurements at benchmark stations, rapid measurements, photo-fixation of floor rock cuts in the areas of dinting.

Findings. It has been determined that the problem of heaving the floor is relevant for most of the temporary roadways located in the zones of increased stresses, for example, in the zone of longwall face impact, both Ukrainian and foreign coal mines. The conducted full-scale mining studies have revealed that the floor rocks in the zone of increased stresses are in a destroyed state and can be represented as a block-discrete medium. A method for controlling the floor heave in mine roadways has been developed, which is based on the formation of locally strengthened zones of a special shape in the mine roadway floor. The strengthening effect is achieved by consolidating the rocks due to their compression by mixtures expanding in the boreholes drilled into the floor of the mine roadway. The method parameters have been calculated which make it possible to set the necessary expansion pressures for the formation in the mine roadway floor of a stable strengthened zone of a specified shape. Studies on the formation of local strengthening of floor rocks with mixtures expanding in mine conditions substantiate the fundamental possibility of rock consolidation.

Originality. The ideas about the consolidation of a block-discrete medium by compression and the formation of stable strengthened zones with mixtures expanding in the solid phase have been developed.

Practical implications. A method for controlling the heaving of floor rocks and a methodology for determining the method parameters have been developed. The results obtained can be used to ensure the stability of mine roadways in zones of increased stresses.

Keywords: *mine, floor heave, mine roadway, zone of increased stresses, longwall face, rocks*

1. Introduction

Over the last 20 years, great progress has been made in the means of fastening the coal mine roadways and ensuring their stability. Active implementation of two-level rock-bolting systems, improvement of the shotcrete process, design, geometry of the arch support and headboard contribute to a significant increase in the stability of the roof and sides of mine roadways at great depths. However, the mine roadway floor in most cases still remains unfastened. Therefore, the floor rocks experience significant destruction, especially in mine roadways maintained in the zone of longwall face impact at great depths. This phenomenon is typical for different coal basins, which is noted in the works of scientists from different countries [1]-[6].

As a result of the destruction of the mine roadway floor rocks, their heaving into the cavity of the drifts is observed. The presence of water in the rocks leads to the activation of deformation processes. This causes problems that arise when transporting rock mass, delivery of materials and equipment, ventilation of mine roadways and movement of miners. Restoration of the operational state of such mine roadways is becoming an important task of underground mining.

The heaving of the floor rocks is observed at all stages of the mine roadway existence and occurs with different intensity. The peculiarity of this complex process is that its nature depends on the mining-geological conditions in which it occurs. That is why there is still no single theory that describes and fully explains the heaving process.

The results of monitoring for the temporary roadways in Ukraine show that 19-23% of them are in unsatisfactory condition. The share of site roadways with a service life of up to 3 years, in which repair work is conducted, exceeds 75% of the total volume of roadways being repaired. These data have been obtained for mines with one or two longwall faces. For roadways serving the stope face, 90% of the deformations are associated with being in the zone of longwall face impact, while about 86% of the repair work is accompanied by dinting of the floor rocks [7].

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Despite more than a hundred years of scientific and industrial experience in maintaining mine roadways, in fact, almost the only way to control the floor heave today is dinting. The use of rock-digging machines, although it is the most progressive solution for mechanizing the rock dinting, unfortunately, is not always convenient in roadways in which belt conveyors and haulers are located, operating almost around the clock. In addition, dinting, conceptually, is not a means of controlling the floor heave, but only a way to eliminate the consequences of pressing out the rocks into the mine roadway cavity.

The reasons that form the floor heave, mainly include: swelling of rocks, pressing out of rocks from under the stamp, transition of rocks into a plastic (and viscous-plastic) state, creeping of rocks, destruction and pressing out of destroyed rocks, as well as a combination of these factors. Different mechanisms of heaving the floor rocks have led to different methods for controlling this phenomenon.

World experience in underground mining has made it possible to accumulate a large number of theoretical and practical solutions underlying the methods and means of ensuring the floor rock stability. It is expedient to reduce the main conceptual directions to the following:

– use of closed support structures (frame, prefabricated, monolithic);

– destressing the mass from increased stresses;

– strengthening of floor rocks in a mine roadway (mechanical, physical-chemical);

– combined methods.

The simplest solution to the problem of heaving the floor is to use closed types of supports, such as a ring or a back arch support [8]-[10].

Closed supports are widely used in capital roadways with a long service life. Rigid and yielding concrete, reinforced concrete, block, tubing supports are also widely used. Fastening of site roadways, located in the zone of longwall face impact, with metal supports, circular closed supports, ovoid and arched with a back arching cannot withstand the pressure from the floor and, therefore, are not practically used in domestic mines. The main reason for this is considered to be too large deformations of the site roadway floor.

During destressing of the border rocks, the increased stresses are removed from them. To achieve this effect, destress cavities are artificially formed in the floor or sides of the mine roadway, such as grooves, wells or holes. Pressure relief grooves are built in the floor from one or both sides of the mine roadway [11], [12]. The destressing effect depends on the shape, size and method of their implementation. With the drilling and blasting method of forming the grooves, side rocks are additionally destroyed, which helps to reduce the level of stresses not only in the floor, but also in the sides of the mine roadway.

In addition to drilling and blasting method, the drilling and cutting method is also used to built depressurization holes in the mine roadway floor. The last two methods are technically quite complex. The hole is usually located in the center of the mine roadway floor, and its depth is much greater than that of the grooves and reaches several meters. To create a hole without using the drilling and blasting method of rock destruction, it is necessary to drill boreholes with a small spacing, which is technically difficult. Sometimes, instead of holes, wells drilled at a small spacing are used as destress cavities. At mechanical cutting a hole in the floor with hard rocks, technical difficulties also arise [11]. Destress cavities, usually wells, are created in the sides of the mine roadway, which also reduces the floor heave.

In modern conditions, when mining the coal deposits, destressing of the mass with holes is almost never used. This is conditioned by the high technical complexity of the method implementation and the disappearance over time of the destressing effect when closing holes as a result of the rock mass deformation.

In recent years, methods involving the strengthening of floor rocks have become most widespread.

Strengthening can be conducted with the use of chemical mixtures with or without preliminary dinting, as well as rock-bolting systems. When using chemical strengthening, an artificial beam [13], [14] or arch [15], [16] is formed in the floor. The quality of strengthening in this case depends on the water saturation of rocks and can be improved by dehydrating them [17], [18].

Chemical strengthening is effective at different stages of mine roadway operation, but its disadvantages include the relatively high cost of materials and equipment for performing work, as well as the bearing structure rigidity. Due to the fundamental infeasibility of deformations, the destruction of the formed bearing structure in the zones of high rock pressure occurs. Such cases are typical for mine roadways located in the zone of stope operations influence.

The necessary yielding property is provided by methods of strengthening the floor rocks in the mine roadway using rock bolts [13], [19], [20]. With all the positive characteristics of rock-bolting, strengthening the floor with the rock bolts in the zones of increased rock pressure is quite complex. First of all, the floor rocks are not monolithic, therefore, fastening of the destroyed rocks with rock bolts is ineffective. In zones of longwall face impact, the degree of destruction of the floor rocks can be such that individual rock fragments have sizes ranging from a few centimeters to tens of centimeters. In addition, clay rocks and argillites, especially in the presence of water, are characterized by plastic deformations that are not restrained by either rigid steel bolts or flexible glass-polymer and rope bolts.

The combination of rock-bolting and strengthening technologies is by far the most effective method for reducing the floor heave in coal mine roadways [21].

In recent years, combined fastening technologies have been widely used, which are based on joint use of back arching made of metal frames and concrete layer with rock-bolting of floor rocks with resin-grouted roof bolts [22], [23] or flexible rope bolts [24], [25].

Such technological solutions minimize the floor heave, but they require large capital expenditures and significantly increase the labor intensity of mining operations.

It follows from the above analysis that the most promising direction for ensuring the stability of the floor rocks in mine roadways in the zones of increased stresses is the strengthening of rocks. The main reserve for ensuring the stability of the floor is in the advanced technologies of rock-bolting and injection of binding substances of a new level. Thus, the development of new conceptual solutions and ways to control the floor heave is an urgent scientific task.

The purpose of this work is to develop and study a method for controlling the floor heave in mine roadways, located in the zone of increased stresses, by local strengthening of rocks with mixtures expanding in the solid phase.

2. The research methods

The development of effective measures to control the floor heave is possible only in the conditions of a clear understanding of the mechanism for the development of this process. Full-scale mining studies conducted in the Donbass mines indicate that the border zone rocks during dinting are predominantly in a discrete state. In order to determine the dynamics of deformation processes around the mine roadway, as well as the physical state of the floor rocks, the authors have conducted full-scale mining studies.

The place of research is the site of the 12th western longwall face of c_{18} seam, DP Shakhtoupravlinnia Pivdennodonbaske No. 1. The longwall face was mined to the seam dip using a combined mining system, the conveyor passage of the 12th western longwall face was used repeatedly, and the conveyor passage of the 11th western longwall face was mined out behind the longwall face (Fig. 1).

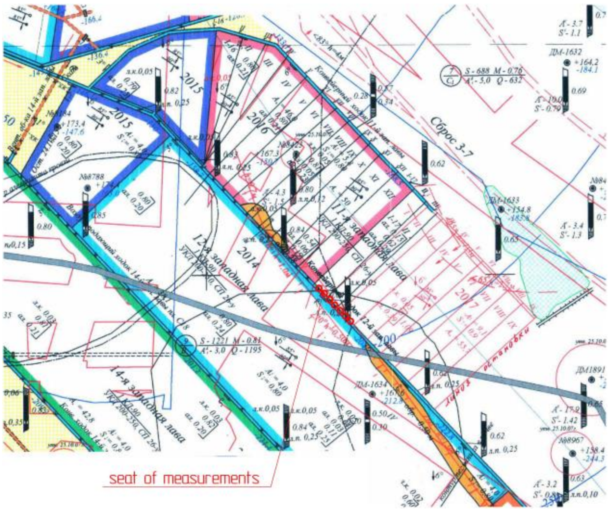


Figure 1. Copying from the plan of mine roadways indicating the place of experiments

Coal seam c_{18} has a simple and complex two-band structure with parting in the lower part of the seam. The thickness of the upper band of the seam is 0.60-0.80 m, the average thickness of the seam is 0.75 m, the lower band is 0.30-0.40 m, the thickness of the rock interlayer is from 0 to 1 m and more. The occurrence of the seam is gently undulating, the dip angle is 6-8°.

In the immediate roof of the seam, there is mainly gray siltstone, weakly micaceous with horizontal stratification. Fractured siltstone B_3. Dry. Layer thickness is 2.5-5.0 m. The hardness coefficient by M. M. Protodyakonov scale is 3.0. The main roof is presented by gray fine-grained quartz sandstone. At the beginning of the layer it is dense, at the end of the layer it changes into a laminal carbonized detritus. The contact is clear. According to lithological properties – A_2. In the immediate floor of the seam, in local areas, there is a dark gray sandstone in the upper part –"underclay" with a thickness of 0.7 and hardness coefficient of 3-4 by M.M. Protodyakonov scale. In most of the area, sandstone is replaced by siltstone, in which the upper part of the layer up to 0.35 m thick is able to soak. It is prone to heaving – P_2.

The measurements are carried out at special measuring points, built in mine roadways. Each measurement is repeated three times, results are recorded in the observation log. The average value is taken for calculations and analysis.

In the conditions of the conveyor passage of the 12th western longwall face of c_{18} seam, a control site 30 m long (52 PK + 6 m – 53PK +16 m) is planned, where 4 measuring stations are set with a spacing of 10 m. Each station consists of 4 reference benchmarks set in the roof (reference benchmark 1), floor (reference benchmark 2) and sides (reference benchmarks 3, 4) of the drift. The reference benchmarks are markers on the support frame, in the form of a kerve in the frame, into which a piece of steel wire is rolled. Observations at the stations have been conducted for three months.

Each time of taking the measurements, the state of the mine roadways is photographed using a digital camera. In addition, along the entire length of the mine roadways in which the research is conducted, the height is rapidly measured, which makes it possible to obtain and analyze the general nature of convergence.

3. Results and discussion

3.1. Results of full-scale mining studies

After processing the research results, it has been revealed that in the mine roadway, maintained before the longwall face, the period of intensive floor heave correlates with the time it enters the bearing pressure zone. For the conditions of conveyor passage of the 12th western longwall face of C_{18} seam, the general characteristic of deformations can be traced by analyzing the profile of the mine roadway height (Fig. 2a). Convergence intensification is observed in the area of 80-60 m before the face. It can be seen from the sketches of mine roadway cross section (Fig. 2b, c) and general dynamics of deformations, the vertical convergence is more than 1.0 m. In this case, the heaving of the floor predominates.

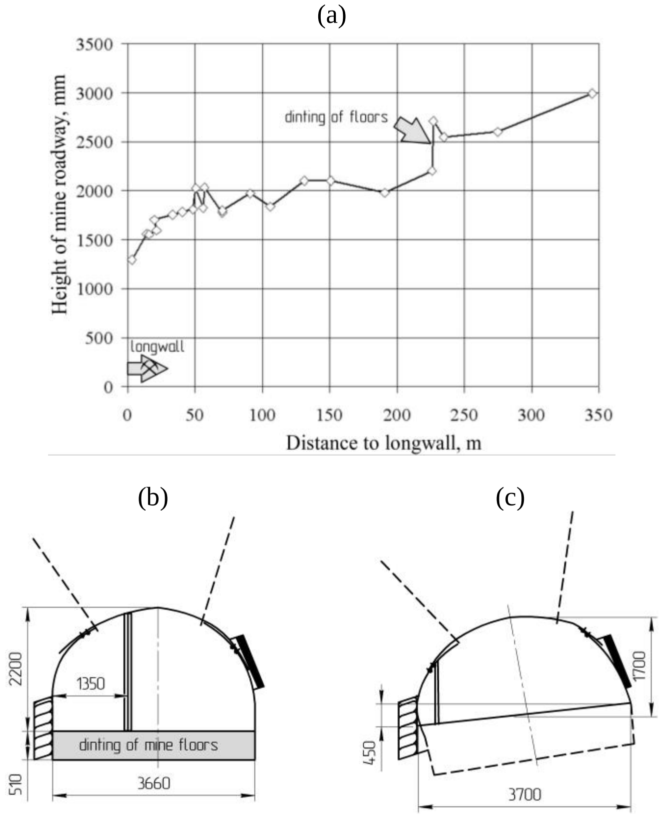


Figure 2. Conveyor passage height of the 12th western longwall face of c18 seam before the longwall face (a) and sketches of the mine roadway state 229 m before the longwall face (b) and 20 m before the longwall face (c)

The floor heave dynamics in the zone of intensive displacements, determined from measuring stations, is given in Figure 3.

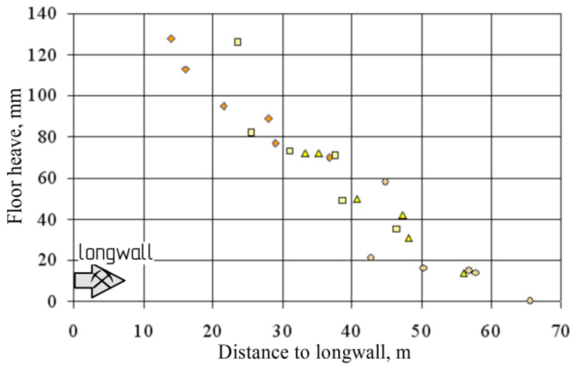


Figure 3. Vertical displacements of the conveyor passage floor of the 12th western longwall face of c_{18} seam obtained from measuring stations (65-14 m from the longwall face)

The floor heave at the passage site of 65-14 m before the longwall face is about 130 mm. That is, only during this period, the zone of destroyed rocks increases by at least 1.3 m, and judging by the total value of heaving the floor for the entire period of mine roadway existence, the size of this zone, when the mine roadway is located in line with the longwall face, exceeds 7.0 m. Analyzing the dynamics of heaving, it can be concluded that the rate of heaving the floor at the control site is on average 2.9-3.1 mm/day. At the same time, it is obvious that the rocks around the mine roadway are already destroyed, even before they enter the zone of intense deformations. The floor in the face of dinting, 229 m before the longwall face approach, is already represented by a small-block medium (Fig. 4), the place of dinting corresponds to the sketch in (Fig. 2a, b). In the zone of intense deformations before the longwall face, the zone of destroyed rocks develops deep into the mass in proportion to the deformation of the mine roadway contour, and within the zone, the rocks are additionally stratified and destroyed.

The floor rocks have higher fracturing than the rocks in the sides and roof, even in places with low water inflow.

The floor rocks in the face of dinting have a marked discrete state. The linear size of the rock partings to be dinted is in the range of 0.15-0.4 m. About 80-85% of heaving occurs during the period of intense deformations.

In addition to the above results of observations at measuring stations, the physical state of the floor rocks is studied during the survey of mine roadways and the photographs are shown in Figure 5.

Analysis of photographs and measurement results indicates that the floor rocks within dinting have a small-block structure. This allows, in the first approximation, to represent the rock mass in the mine roadway floor, at least to a depth equal to half the depth of destruction zone, as a discrete or block-discrete mass relative to the drift width.

3.2. The idea formation of a method for controlling the floor heave

Laboratory studies, the results of which are presented in [7], prove that the formation of locally strengthened zones of a special shape in a mass, represented by a discrete medium, makes it possible to reduce the compaction of rocks under the mine roadway by 20% and the heaving of floor rocks by at least 40%.

(a)

(b)

Figure 4. Floor rock sections when dinting in the conveyor passage of the 12th western longwall face of C_{18} seam, DP Shakhtoupravlinnia Pivdennodonbaske No. 1

(a)

(b)

Figure 5. Floor rock sections during dinting: (a) drainage drift on C_{18} seam, DP Shakhtoupravlinnia Pivdennodonbaske No. 1; (b) conveyor passage of the 11th western longwall face of c_{18} seam, DP Shakhtoupravlinnia Pivdennodonbaske No. 1

Based on the results obtained during the research, a working hypothesis has been formulated to ensure the stability of the floor by creating locally strengthened zones, which is given below. It is expedient to implement the proposed approach under conditions of intensive floor heave in cases where the border rocks are in the zone of inelastic deformations and represent a block-discrete medium. Under such conditions, the floor heave can be reduced by forming a locally strengthened zone in the form of a straight prism with the apex of its base triangle facing the mine roadway floor and a height that approximates the vector of maximum stresses in the floor. In this case, the angle at the apex of the prism base triangle should be 55-95 degrees.

After the method implementation within the zone of destroyed rocks (DRZ) (1) (Fig. 6a) with a radius R_1, a strengthened zone is formed in the floor (2). A change in the equilibrium state around the mine roadway, which is caused, for example, by the longwall face approach and the transition of surrounding mass into the zone of bearing pressure, leads to an increase in DRZ by the value of dR, to radius R_2 (Fig. 6b). The destruction of rocks within the zone dR (3) is accompanied by an increase in their volume, which creates an external pressure on the rocks within DRZ until the beginning of its growth and contributes to their displacement towards the mine roadway (4). This leads to a floor heave in the mine roadway by a value of U_{fl} (Fig. 6c).

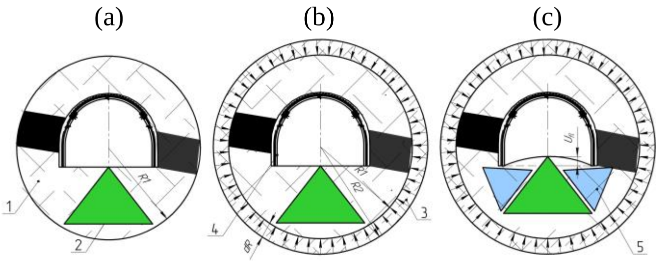


Figure 6. The mechanism for implementing the method of ensuring the floor stability in the mine roadways by creating locally strengthened zones: R_1 – the initial radius of the zone of destroyed rocks; R_2 – the radius of the zone of destroyed rocks after its growth; U_{fl} – floor heave 1 – the zone of destroyed rocks; 2 – the strengthened zone; 3 – the area of an increase in DRZ in case of the stress-strain state disturbance; 4 – mine roadway; 5 – wedge "seat"

The displacement of the strengthened zone (2) in the direction of the mine roadway floor leads to the initial propping of rocks in the floor and sides of the mine roadway. This makes it possible to form a mechanical system in the border rocks, which props when the rocks displace towards the mine roadway floor and provides increasing resistance to the floor heave. The greater the load acting on the system, the greater the effect of propping, compaction of border rocks and, accordingly, resistance to heaving.

The triangle base of the strengthened zone foot (2) acts as a wedge in the floor. The wedge "seat" (5) is formed in the sides of the mine roadway (5), which ensures reliable propping of the floor rocks and prevents the displacement of the strengthened zone towards the mine roadway floor.

Since the vector of maximum deformations can differ from the vertical, orientation of the locally strengthened rock zone in the form of a triangular prism is chosen so that its height approximates the vector of maximum stresses in the floor. This makes it possible to maximize the use of wedge effect in the "strengthened zone – floor rocks" system.

3.3. Method of forming the locally strengthened zones in the floor with the use of expanding mixtures

The developed method is based on forming the locally strengthened zones from consolidated destroyed rocks using self-expanding mixtures. Consolidation of rocks by compressing them with mixtures expanding in the solid phase makes it possible to ensure the stability of the floor rocks while maintaining the mine roadway, including in conditions of high fragmentation and in the zones of high rock pressure, with a minimum amount of drilling operations. As these mixtures, it is proposed to use compounds, the increase in the volume of which is based on the hydration process of converting calcium oxide into hydroxide. An example is non-explosive destructive mixtures, the pressure and deformation characteristics of which have been studied in detail in the works [26], [27].

A method for controlling the floor heave includes drilling the boreholes in the floor rocks of the mine roadway, filling the boreholes with a hardening solution, which is used as a self-expanding mixture in the hydration process, thereby sealing the boreholes. The boreholes are drilled in two rows, so that the expansion of the hardening solution in them creates in the floor between the boreholes locally strengthened zone of compressed rocks in the form of a triangular prism with the apex of its base triangle facing the mine roadway floor. The length of the boreholes is calculated in such a way that the widest part of the formed strengthened zone extends beyond the vertical projections of the mine roadway sides by 0.08-0.15 half-span of the mine roadway. The essence of the method is explained in Figure 7.

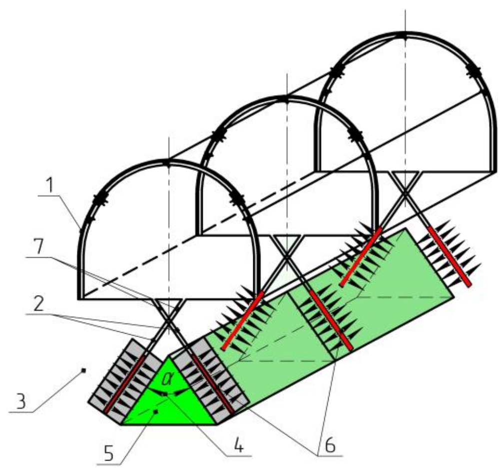


Figure 7. Method for controlling the floor heave: 1 – mine roadway; 2 – borehole; 3 – floor rocks; 4 – the angle at the prism base triangle apex of strengthened rocks; 5 – strengthened zone; 6 – self-expanding hardening solution; 7 – sealing material

A differential peculiarity of the proposed method is that, with a minimum consumption of a fast-hardening composition, a consolidated rock zone with specified parameters is created in the mine roadway floor. At the same time, not the entire rock volume within the formed zone is strengthened, but only a certain area. The strengthening effect is achieved by compressing the rocks and increasing the friction between the rock fragments during self-expansion of the mixture filled in the boreholes.

To implement the method, it is necessary to set the required pressure of the expanding mixture to form a stable strengthened zone. The limit equilibrium method is used to solve these problems.

It can be argued that a consolidated strengthened zone in the form of a triangular prism is stable, provided that it is stable in the most dangerous section. This section for our problem is the area of rocks at the triangle base of the prism foot, where there is a maximum distance between boreholes with expanding material. The calculation scheme for the described case is given in Figure 8.

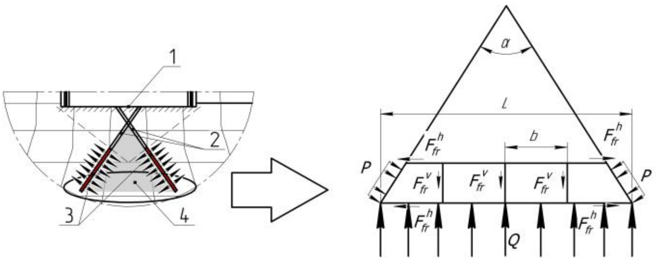


Figure 8. Calculation scheme for the formation of forces within the consolidated zone: 1 – mine roadway floor; 2 – boreholes; 3 – expanding mixture; 4 – locally strengthened zone; P – the pressure creating an expanding mixture, MPa; F_{fr}^h – friction force along the horizontal boundaries of the blocks, kN; F_{fr}^v – friction force along the vertical boundaries of the blocks, kN; Q – pressure from the rock expansion with an increase in size of the destruction zone, MPa; b – the rock block length, m; α – the angle between the boreholes, degree

Let us consider the problem for a single thickness d.

The equilibrium state of the rock mass area along the width L is ensured by applying a distributed load P (expanding mixture pressure) along its edges in the area of length y. In this case, the total friction forces along the vertical boundaries of rock blocks F_{fr}^v are balanced by their weight, taking into account the additional load created by pressure from the growth of the destruction zone Q.

This condition is written in the form:

$$\frac{Q}{L\cdot d}=\sum F_{fr}^{v}+\frac{P\sin\frac{\alpha}{2}}{y\cdot d}. \tag{1}$$

Friction forces acting on the boundaries of rock blocks are equal to:

$$F_{fr}^{v}=\left(\frac{P\cos\frac{\alpha}{2}}{y\cdot d}-F_{fr}^{h}\right)\cdot k_{fr}\cdot\left(n+1\right), \tag{2}$$

where:

$P\cos\frac{\alpha}{2}$ – the pressure projection of the material that expands and compresses the rock blocks along the horizontal area, Pa;

F_{fr}^{h} – the horizontal friction forces along the boundaries of the compressible block, N;

k_{fr} – the rock-to-rock friction coefficient;

n – the number of blocks into which the rock layer is divided.

$$F_{fr}^{h}=\frac{P\sin\frac{\alpha}{2}}{y\cdot d}\cdot k_{fr}+y\cdot d\cdot\sin\frac{\alpha}{2}\cdot L\cdot\gamma\cdot k_{fr}. \tag{3}$$

Then the equilibrium condition (1), given (2) and (3), takes the form:

$$\frac{Q}{L\cdot d}=\left(\frac{P\cos\frac{\alpha}{2}}{y\cdot d}-\left(\frac{P\sin\frac{\alpha}{2}}{y\cdot d}\cdot k_{fr}+y\cdot d\cdot\sin\frac{\alpha}{2}\times\right.\right.$$
$$\left.\left.\times L\cdot\gamma\cdot k_{fr}\right)\right)\cdot k_{fr}\cdot\left(n+1\right)+\frac{P\sin\frac{\alpha}{2}}{y\cdot d}; \tag{4}$$

$$P=\left(\frac{Q}{L\cdot d}+y\cdot d\cdot\sin\frac{\alpha}{2}\cdot L\cdot\gamma\cdot k_{fr}^{2}\left(n+1\right)\right)\Big/$$
$$\Big/\left(\frac{\cos\frac{\alpha}{2}}{y\cdot d}-\frac{\sin\frac{\alpha}{2}}{y\cdot d}\cdot k_{fr}^{2}\left(n+1\right)+\frac{\sin\frac{\alpha}{2}}{y\cdot d}\right). \tag{5}$$

To determine the load Q from the growth of the destroyed rock zone, let us solve the following problem.

The mine roadway of a round shape (Fig. 9) with a radius r_r is driven at a depth of H and fastened by a support with a load-bearing capacity P_0, operating in a constant resistance mode. It is assumed that the rocks containing the mine roadway are homogeneous and isotropic, the stresses in the virgin mass are taken as hydrostatic – γH.

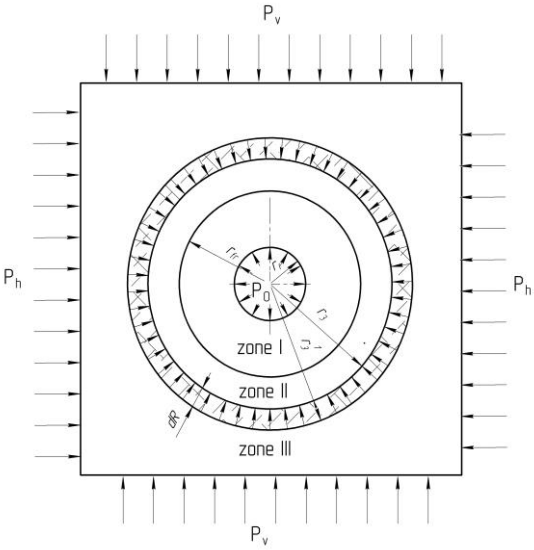


Figure 9. Scheme for calculating the stresses around the mine roadway: P_h – horizontal pressure, MPa; P_v – vertical pressure, MPa; P_0 – support resistance, MPa; r_{fr} – radius of fracture zone, m; r_r – radius of mine roadway, m; r_3, r_3^1 – plastic flow zone before and after growth, m; dR – increase in the size of the plastic flow zone

The possibility of replacing the mine roadway of any cross-sectional shape with a round one in analytical research has been substantiated in the works of prof. I.L. Chernyak. In this case, the possible error does not exceed 10%.

By the time the work began, a brittle fracture zone of size r_{fr} (DRZ – zone I) had formed around the mine roadway, and a plastic flow zone continues to form. Its size is r_3. As a result of rock deformation in the zones of brittle fracture and plastic flow by the value dR to r_3^1, the displacements occur in the mine roadway contour and its radius decreases to r^*_r.

To solve the problem, limit equilibrium method is used.

The state of rocks in zone I is described by expression:

$$\sigma_{\Theta_1} - (2\lambda + 1)\cdot\sigma_{r_1} = \sigma_n^{res}, \tag{6}$$

where:

$\sigma_{\Theta 1}$ and σ_{r1} – tangential and radial acting stresses, respectively;

λ – side thrust coefficient;

σ_n^{res} – residual rock strength in the zone I.

The residual rock strength can be determined from the expression:

$$\sigma_n^{res} = (2\lambda + 1)\cdot\sigma_r + \sigma_0 - E^* \cdot \varepsilon'_p, \tag{7}$$

where:

E^* – deformation characteristic describing the inclination angle of the descending section of the complete deformation diagram. It is determined according to the data of experimental studies from the expression:

$$E^* = \frac{\sigma_0 - \sigma_n^{res}}{\varepsilon'_p}, \tag{8}$$

where:

$\varepsilon'_p = \varepsilon'_1$ – superlimiting longitudinal rock deformation in zone I.

The distribution of radial and tangential stresses in zone I is described by the expression:

$$\sigma_{r_1} = \left(P_0 + \frac{\sigma_n^{res}}{2\lambda}\right)\cdot r^{2\lambda} - \frac{\sigma_n^{res}}{2\lambda}; \tag{9}$$

$$\sigma_{\Theta_1} = (2\lambda + 1)\left(P_0 + \frac{\sigma_n^{res}}{2\lambda}\right)\cdot r^{2\lambda} - \frac{\sigma_n^{res}}{2\lambda}. \tag{10}$$

According to the accepted working scheme, loading of the strengthened zone occurs by radial stresses σ_{r1}. Therefore, as a first approximation, it can be taken:

$$Q = \sigma_{r_1} = \left(P_0 + \frac{\sigma_n^{res}}{2\lambda}\right)\cdot r^{2\lambda} - \frac{\sigma_n^{res}}{2\lambda}, \tag{11}$$

then the equilibrium condition takes the form:

$$P = \left(\frac{\left(P_0 + \frac{\sigma_n^{res}}{2\lambda}\right)\cdot r^{2\lambda} - \frac{\sigma_n^{res}}{2\lambda}}{L\cdot d} + y\cdot d\cdot\sin\frac{\alpha}{2}\cdot L\cdot\gamma\cdot k^2{}_{fr}(n+1)\right) \Big/ \frac{\cos\frac{\alpha}{2}}{y\cdot d} - \frac{\sin\frac{\alpha}{2}}{y\cdot d}\cdot k^2{}_{fr}(n+1) + \frac{\sin\frac{\alpha}{2}}{y\cdot d}. \tag{12}$$

As an example, Figure 10 shows the dependence of the required expansion pressure on the degree of the mass destruction in the strengthened zone in the form of a prism with triangle base of 4.8 m foot, angle at its apex 60 degrees, friction coefficient 0.45.

It can be seen from the graphs that the greatest required expansion pressure to maintain the strengthened zone shape in a stable state for the modeled situation reaches 43 MPa. But even with an imbalance in the widest part, the strengthened zone performs its function, since a more compacted consolidated zone is formed inside it, due to a decrease in the distance between the boreholes filled with expanding material.

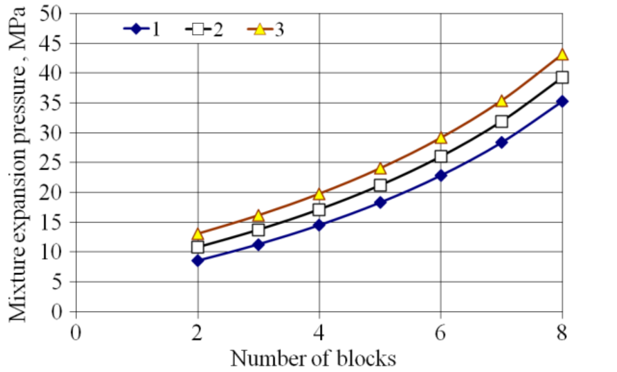


Figure 10. Dependency graphs of the required expansion pressure on the number of rock blocks in the lower part of the strengthened zone with the final strength of rocks within the DRZ: 1 – 10 MPa; 2 – 20 MPa; 3 – 30 MPa

3.4. Research on the creation of local strengthening with expanding mixtures in mine conditions

Before experimental testing of the proposed method for controlling the floor heave, it is necessary to study the process of forming the compacted zones around the boreholes with expanding mixtures in mine conditions.

Therefore, the research purpose in mine conditions is to analyze the compression effect of the destroyed floor rocks in the near-borehole zone of an individual borehole using mixtures expanding in the solid phase.

The observations are conducted in the main ventilation crossdrift at the 824m level of DP Shakhta im. M.S. Surhaia PK 4 + 8-PK 5.

In the immediate floor of the seam, there are mainly siltstone and sandstone, with a hardness coefficient according to M.M. Protodiakonov scale f = 1-2 – 7%, f = 2-4 – 53%, f = 3-5 – 40%. The mine roadway is fastened with a metal arch support KMP A5-15.5 with a spacing of 2 frames per meter. The mine roadway section before dinting was 4.1 m^2, after repair – 10.0 m^2.

Operations on dinting and replacing emergency frame elements are carried out only in the mine roadway. The floor rock state is highly disintegrated (Fig. 11a). The experiment is performed as follows. The boreholes with a diameter of 42 mm and a length of 1.5 m are drilled in the crossdrift floor. The inclination angle of the boreholes is in the range of 85-90 degrees. After drilling, the boreholes are blown out of the dust with compressed air. Then they are filled with a prepared solution of a non-explosive mixture, self-expanding upon hydration. Because of crystallogenesis, the rock mixtures around the borehole are exposed to compression. The experiment is conducted on a section of 2-5 m before the repair work plane (Fig. 11b) for the subsequent cutting of the borehole with an expanding mixture, dinting the face, as well as visual and instrumental examination.

Visual observations of the results of expanding the mixture in the boreholes, which were performed on rock cuts during dinting, have revealed that large rock blocks move along the sliding planes due to the mixture expansion (Fig. 12a). This is evidenced by open interlayer contacts. Compaction of fine-grained rocks has also been recorded.

It has been instrumentally determined that the opening of interlayer contacts at a depth of 0.5-0.7 m from the floor contour before dinting reaches 0.7-1.0 cm and is formed due to vertical heaving of blocks towards the crossdrift floor, which is caused by the presence of fold in the floor.

(a)

(b)

***Figure 11.** The floor rock state (a) and pouring the expanding mixture into the boreholes (b) during the experiments in DP Shakhta im. M.S. Surhaia*

The high degree of rock destruction does not allow to obtain a high compaction effect. The following disadvantages have been revealed:

– the actual consumption of the mixture in the boreholes exceeds the calculated ones by 2.5-3 times, which is conditioned by unforeseen losses of the mixture in the fractures crossing the boreholes (Fig. 12a, b);

– the spreading zone of the mixture exceeds 5 diameters of the borehole (Fig. 12b, c);

– in the conditions of rocks with high fracturing, there is an additional rock destruction (Fig. 12c);

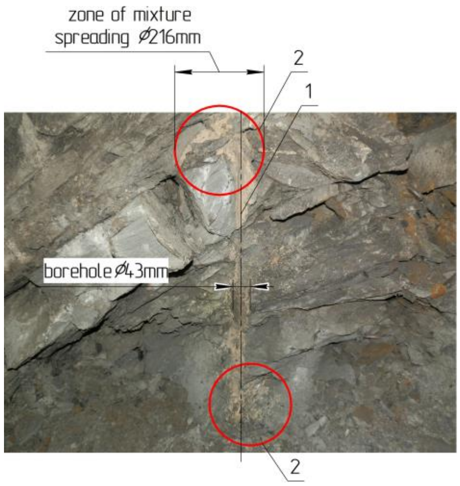
– due to the rock destruction and the formation of cavities, recrystallization of the mixture into powder is sometimes observed (Fig. 12c).

The main disadvantage of the presented technology in the conditions of rocks with a high degree of destruction is the loss of the mixture in cavities and fractures. To eliminate this effect, it makes sense to fill an expanding mixture into ampoules or other shells before placing into the boreholes. This can prevent the mixture from flowing outside the predetermined contour, thereby increasing the efficiency of the method implementation. To prevent the pressing out of the near-contour part of the rocks into the mine roadway cavity, it is expedient not to fill the mouth area of the boreholes with the working mixture, but to seal it.

An imaginary model for the method implementation to control the floor heave in the experimental mine roadway is presented in Figure 13.

(a)

(b)



(c)

***Figure 12.** Photofixation of floor cuts from a borehole with a mixture expanding during experiments in DP Shakhta im. M.S. Surhaia: (a) cross-sectional view of the mine roadway, which is refastened; (b), (c) fragments of boreholes with an expanding hardened mixture: 1 – the borehole axis; 2 – the zone of the mixture spreading beyond the borehole contour*

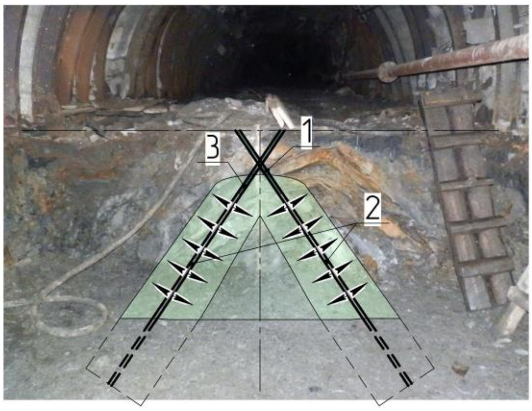


Figure 13. Imaginary model of forming the locally strengthened zones in the experimental mine roadway floor: 1 – borehole; 2 – expanding mixture; 3 – sealant

After eliminating the identified disadvantages in the formation of consolidated zones from destroyed rocks, the proposed method for controlling the floor heave can be tested in mine conditions. This is the immediate perspective of the authors' research.

4. Conclusions

Analysis of the state of coal mine roadways in Ukraine indicates that the problem of heaving the floor is relevant for most temporary roadways, especially in the longwall face impact zone. A review of the literature confirms the presence of a similar phenomenon in the coal mine roadways around the world. The most promising method to control the floor heave is to strengthen the rocks.

The performed full-scale mining studies on the nature of the mine roadway contour deformation and analysis of the floor cuts in the places of dinting in the Shakhta im. M.S. Surhaia make possible to suggest that the floor rocks in the zone of increased stresses are a block-discrete medium.

The authors have developed a method to control the floor heave in mine roadways, which is based on forming the locally strengthened zones of special shape in the mine roadway floor. Strengthening effect is achieved by consolidating the rocks due to their compression with mixtures expanding in boreholes drilled into the mine roadway floor.

The method parameters that make it possible to set the necessary expansion pressures for the formation of a stable strengthened zone of a certain shape in the mine roadway floor have been calculated. Known mixtures based on calcium oxide, expanding in the solid phase, can develop the necessary pressures in the limited space of borehole charges.

Studies on the creation of local strengthening of floor rocks with mixtures expanding in mine conditions have confirmed the fundamental possibility of rock consolidation. However, a number of disadvantages have also been revealed. The main disadvantages are associated with an uncontrolled increase in the mixture flow rate in boreholes due to leakage through cavities and fractures, which leads to a decrease in the strengthening effect.

After eliminating the identified disadvantages in the formation of consolidated zones from destroyed rocks, the proposed method for controlling the floor heave can be tested in mine conditions. This is the immediate perspective of the authors' research.

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Спосіб боротьби з підняттям підошви гірничих виробок у вугільних шахтах

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Мета. Розробка і дослідження способу боротьби з підняттям підошви гірничих виробок, які знаходяться в зоні підвищених напружень, шляхом локального укріплення порід сумішами, що розширюються в твердій фазі.

Методика. У роботі використано наступні методи дослідження: аналіз і узагальнення раніше виконаних досліджень процесу підняття підошви гірничих виробок; шахтні натурні спостереження, що включали інструментальні виміри на реперних станціях, експрес-виміри, фотофіксацію зрізів порід підошви в місцях ведення підривки.

Результати. Встановлено, що проблема підняття підошви є актуальною для більшості підготовчих виробок, що знаходяться в зонах підвищених напружень, наприклад в зоні впливу лави, як українських, так і закордонних вугільних шахт. Найбільш перспективним способом боротьби з підняттям підошви є укріплення порід. Проведені шахтні натурні спостереження в умовах ДП "Шахта ім. М.С. Сургая" свідчать, що породи підошви в зоні підвищених напружень знаходяться у зруйнованому стані і можуть бути представлені як блочно-дискретне середовище. Розроблено спосіб боротьби з підняттям підошви гірничих виробок, що ґрунтується на створені локально укріплених зон спеціальної форми у підошві виробки. Ефект укріплення при цьому досягається шляхом консолідації порід внаслідок їх стиснення сумішами, що розширюються у шпурах пробурених в підошву виробки. Проведені розрахунки параметрів способу дозволили встановити необхідні тиски розширення, для утворення стійкої укріпленої зони визначеної форми в підошві виробки. Відомі суміші на основі оксиду кальцію, що розширюються в твердій фазі, можуть розвивати необхідні тиски в обмеженому просторі шпурових зарядів. Дослідження створення локального укріплення порід підошви сумішами, що розширюються в шахтних умовах підтвердили принципову можливість консолідації порід.

Наукова новизна. Розвинуті уявлення про консолідацію блочно-дискретного середовища стисненням і формування стійких укріплених зон сумішами, що розширюються в твердій фазі.

Практична значимість. Розроблено спосіб боротьби з підняттям порід підошви і методика визначення параметрів способу. Отримані результати можуть використовуватися для забезпечення стійкості гірничих виробок в зонах підвищених напружень.

Ключові слова: *шахта, підняття підошви, підготовча виробка, зона підвищених напружень, лава, породи*