Maintenance of reusable mine workings during the augering mining of coal seams

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Abstract. The augering mining of thin and very thin coal seams has been proposed for using the efficiency of this task, related to the stability of reusable mine workings. The interrelation has been established and optimized between the support loading parameters in the extraction working during the augering mining of thin and very thin coal seams with the stress-strain characteristics of the protective monolithic strip of variable rigidity. The strength properties of sand-cement stone for the erection of rigid and yieldable parts of the protective strip are studied. The regression equations are obtained, which allow to determine the rational force, deformation and geometric parameters of the "support – protective strip" system elements during the extraction workings maintenance.

1 Introduction

One of the main directions of production processes intensification of coal mining in thin and very thin seams, which were developed in the international practice, is the augering technology [1], which provides coal extraction without the breakage face support setting and the presence of people in it [2].

Many of these seams have already been entered and partially or fully prepared for extraction, so that the capital costs for these processes can be reduced significantly. Furthermore, the augering technology can also be applied to the development of established previously coal pillars of various purpose. The development of this direction will increase the recovery ratio of coal [3] also due to the partial extraction of non-commercial reserves and protective pillars. However, the efficiency of the augering mining is largely related to the stability of reusable mine workings [4 – 7], some of which should be maintained for a long period in the zone of coal-face work influence [8 – 11]. This problem is solved in a complex on the basis of linking the issues of fastening and protection of extraction drift as a single and mutually influencing system, which is proposed to be called as "support – protective strip". The maintenance of the extraction workings is achieved by low-cost methods based on bearing pressure control through the protective monolithic strips of variable rigidity (yield) [12].

Directly to the mine working the yieldable part of the strip with width of L_y adjoins,

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which is followed by a rigid part with width of L_r. The rigid part takes up the bulk of the bearing pressure $\Phi(\gamma H)$, but the yieldable part pushes back the maximum of the bearing pressure from the contour of the mine working deep into the mined-out space. An unloading zone is formed around the mine working, the tasks of which include: on the one hand, to reduce the rock pressure to a minimum; on the other hand – to prevent formation of a significant volume of unstable rocks which during collapse will form high vertical and lateral loading on the support. These tasks are realized by choosing the necessary width of the yieldable part of the strip and the required value of its yield.

Traditionally, the applied technology of a protective strip erection by the dry shotcreting method [13] has been improved [14] in terms of improving the quality by addition of water to a mix and air dedusting, reducing the rebound of the solid phase of the shotcrete flow by separating it on exit from the nozzle onto the solid and air phases, reducing the wear of the pipeline end section. For these purposes, more advanced designs of auxiliary equipment have been manufactured and used.

2 Main part

2.1 Loading of the “support – protective strip” system elements

The peculiarity of the coal-overlaying strata movement during the augering coal mining is that the rocks of the main roof smoothly descend to the interwell pillars and rock cushion in the exhausted wells with the discontinuity of the seam only mainly in the tensile stress area of the rock beam, thus forming a thrust system of large rock blocks, which takes up the weight of the overlying strata of rocks to the daylight area surface. Because of these reasons, the height h of the disturbed rocks is quite limited and, as a rule, not less than one order of magnitude smaller than the depth H of the coal seam occurrence [15, 16]. Accordingly, the weight of the hanging console rocks will be at least one order of magnitude less than the hydrostatic pressure γH. In addition, this small loading on the protective element repeatedly decreases due to the support of disturbed rocks, which is caused by the effect of their loosening and increase in volume.

The yieldable part of the strip is intended to provide a zone for the rock massif unloading in the vicinity of the mine working with width of $2(L_y + r_w)$, where r_w is the radius of mine working arch. The height h of unloading zone is determined by the height of the stable rock layer occurrence, which is determined by the thickness m_1, strength properties, span value l_1 of the natural equilibrium of rocks and by forces on the contact q_1 with the rocks of unloading zone. In such a case, the length l_1 of a span is less than the value $2(L_y + r_w)$ due to the formation of dome of natural equilibrium over the mine working in the off-loaded rocks. On the contact with mine working support the support reaction q acts on the rocks of unloading zone, as a resultant value of vertical $q_{ver} = \gamma h + q_1$ and lateral $q_{lat} = (\gamma h + q_1) tg^2 \frac{90 - \varphi_r}{2}$ components. The lateral reaction of support acts also on the adjacent yieldable part of the protective strip.

The decrease in values of loading q_{ver} and q_{lat}, is carried out in two ways: by reducing the height h of the unloading zone through decreasing the width of the yieldable part of the strip or by the loading q_1 elimination, providing that the support and yieldable part of the strip are displaced in the vertical direction to the required value, when the rock pressure is applied to them. Therewith, the load-bearing capacity of support is significantly dependent on its vertical q_{ver} and lateral q_{lat} components ratio. Therefore, the two force criteria were formulated for support: the total loading along the mine working contour must tend to the minimum possible value and the ratio $\beta = q_{ver} / q_{lat}$ of vertical and lateral loadings should be such, wherein the support reaches its maximum load-bearing capacity Q. In addition, to avoid the negative impact of backing forces q_1 on the value of vertical yield of support U_{ver} and the yieldable part of the strip δ, the following condition is imposed: the yield of the strip δ at the value of the loading on it γh compensates for the increase in the volume of loosened rocks in height h.

As for the mine working support, then the predicted vertical U_{ver_1} and lateral U_{lat_1} displacements of rocks are also considered, which occurred before the beginning of coal-face works, that means $U_{ver} \geq U_{ver1} + \delta$, $U_{lat} \geq U_{lat1} + \delta tg \dfrac{90 - \varphi_r}{2}$ [17].

The set criteria complex has determined the requirements to the stress-strain characteristics of support and yieldable part of the protective strip. The width L_r of the rigid part of the strip is chosen from the condition of its non-destruction $Q_r \leq Q_{ad}$, where Q_r and Q_{ad} – acting and admitted loadings onto the rigid strip $Q_r = \gamma H\left(r_w + L_y + L_r\right)$. The load-bearing capacity of the rigid part of protective strip is determined according to the ultimate rock equilibrium theory, provided that all the material of the strip changes to the limiting state, described by the rectilinear envelope of Mohr circles:

$$Q_{ad} = 2C_r L_r \left[2 + F\left(\frac{L_r}{m}, \varphi_r\right)\right],$$

where C_r and φ_r are adhesion and internal friction angle of material of the rigid part of a strip; $F\left(\dfrac{L_r}{m}, \varphi_r\right)$ is tabulated function, which considers combined stress state in the rigid strip, is determined by [18].

From the indicated conditions, the minimum permitted width of the rigid part of a protective strip is determined:

$$L_r = \frac{\gamma H\left(r_w + L_y\right)}{2C_r\left[2 + F\left(\dfrac{L_r}{m}, \varphi_r\right)\right] - \gamma H}.$$

The numerical analysis of this expression led to the conclusion that for the depths of the mine workings embedding to 800 m and the mechanical properties of the hardened sand-cement mixture of the traditional formulation, the relative width L_r / m of the protective strip rigid part does not exceed, as a rule, one and half thicknesses of the coal seam m. For reliable protection of extraction drifts, primarily of interest is the dependence of the ratio of vertical and lateral loadings onto mine working support on the parameters of the protective strip yieldable part. The main of them are the ratio of the width L_y and height m of the strip, as well as internal friction angle φ_y of its material. The essence of this connection is that the finite width of the yieldable part of the strip affects significantly the value of the lateral loading and its ratio to the vertical one. The curves on Fig. 1 show that the function

$\beta\left(L_y / m\right)$ has minimum with variable internal friction angles of material of the protective strip yieldable part. At a narrow width ($L_y / m < 0.15 - 0.35$) of the yieldable strip the parameter β increases rapidly ($\beta > 5$). The same, but more smoothly, occurs when the strip width is increased ($L_y / m > 1 - 1.5$). It is quite natural a strong influence of the yieldable strip material on the parameter of the internal friction angle φ_y, as a parameter that determines the restraining tangential stresses along the slip line of the cleavage prism. From Fig. 1 it follows that the parameters L_y / m and φ_y of the protective strip yieldable part influence significantly on the ratio β of vertical and lateral loadings onto the support, on which its load-bearing capacity depends greatly. The research has established a rational range of the parameter $\beta = 2 - 3$ variation in terms of the maximum load-bearing capacity of the support. The required value of the parameter β is achieved by changing the width L_y / m of the protective strip yieldable part, with the internal friction angle of $\varphi_y \leq 30$º. At $\varphi_y > 30$º, regardless of the width L_y / m, the parameter β extends beyond the range of rational values. With decrease in φ_y, the rational width L_y / m decreases and amounts to $L_y / m = 0.5 - 0.9$ at $\varphi_y = 10 - 30$º.

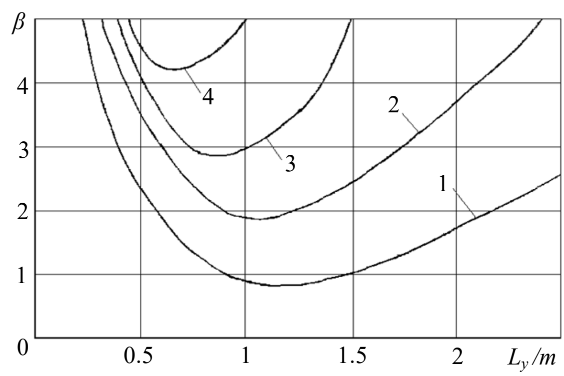

Fig. 1. Dependence of the parameter β on the relative width L_y / m of the protective strip yieldable part: 1 – $\varphi_y = 10$º; 2 – $\varphi_y = 20$º; 3 – $\varphi_y = 30$º; 4 – $\varphi_y = 40$º.

An analysis of the research results of the yield mode of the "support – protective elements" system in interaction with the enclosing rocks has determined the minimum required lateral and vertical yield of the drift support:

$$U_{lat} = w_{y_{lat}} = hL_y\left(\frac{\Delta}{m}\cdot\frac{\sqrt{h^2 + r_w{}^2} - r_w}{\sqrt{4h^2 + l_1^2}} - 4.6\cdot 10^{-4}\gamma\right); U_w = \left(h - r_w\right)\frac{\Delta}{2},$$

where Δ is coefficient of volumetric loosening of rocks.

2.2 Determination of the required mechanical properties of the protective strip

To perform a full calculation of rational parameters of the "support – protective elements" system, the laboratory studies have been conducted of the mechanical properties of the recommended combinations of rigid and yieldable parts of the protective strip in accordance with the requirements imposed on them: the dependences of adhesion *C*, internal friction angle of the strip material on different hardening mixture composition (Wat / Cem, $Sand / Cem$) and the age t of sand-cement stone, are studied. And based on the processing of test results by methods of correlation-dispersion analysis, the expressions were obtained for the strength properties determination of the rigid part of a strip:

$$C_r = 10.9\, exp\left(-0.28\frac{Sand}{Cem}\right)\left(\frac{Cem}{Wat} - 0.5\right) lg\left(t + 1.5\right);$$

$$\varphi_r = \left(13.7 + 17.25\frac{Wat}{Cem}\right) exp\left(-0.54t\right) - \frac{Sand}{Cem} + 34.$$

A significant dependence of the sand-cement stone compressive strength σ_{compr} on Add / Cem porous-filling additive content (aluminium powder) has been revealed. The general pattern is that with an increase in the content of the additive Add / Cem, the strength of the samples decreases, since the volume of pores and voids in the structure of the sand-cement stone increases. The highest intensity of the strength σ_{compr} reduction occurs in the range $Add / Cem = 0 - 0.5\%$. Then, with an increase in content of the additive (up to $Add / Cem = 2\%$), the compressive strength intensity of the samples decreases asymptotically approaching to a certain value in the range up to 0.1 σ_{compr} of non-porous-filled sand-cement stone.

When processing the obtained results and using the methods of correlation-dispersion analysis, the regression equation was determined in the form:

$$\sigma_{compr} = 27.2\, exp\left(-15.8\sqrt{\frac{Add}{Cem}}\right) exp\left(-0.23\frac{Sand}{Cem}\right)\left(\frac{Cem}{Wat} - 0.5\right) lg\left(t + 1.5\right).$$

On the basis of this equation, with account of the condition $\sigma_{compr} \le \gamma H$ for achieving a yield mode of the strip operation, the minimum required content of the porous-filling additive has been determined:

$$\frac{Add}{Cem} \ge 4 \cdot 10^{-3}\, ln^2\left[\frac{27.2}{\gamma H} exp\left(-0.23\frac{Sand}{Cem}\right)\left(\frac{Cem}{Wat} - 0.5\right) lg\left(t + 1.5\right)\right].$$

In the tests of a porous sand-cement stone the internal friction angle φ_{Add} has also been determined which depends on the porous-filling additive content. The general tendency is that with an increase in the content of the additive the internal friction angle of the porous sand-cement stone decreases. This fact is explained by the occurrence of pores and voids, which at the initial moment of the tested sample material shear are filled with the destroyed skeleton of the sand-cement stone and the friction forces along the slip line decrease.

By numerical analysis of the experimental data and with the use of the methods of correlation-dispersion analysis, the regression equation has been obtained:

$$\varphi_{Add} = \left[\left(13.7 + 17.25\frac{Wat}{Cem}\right) exp\left(-0.54t\right) - \frac{Sand}{Cem} + 34\right]\left[0.53 + 0.47\, exp\left(-317\frac{Add}{Cem}\right)\right].$$

The studies have confirmed the necessity to consider the change in the internal friction angle φ_r in time t when calculating the parameters of the rigid part of the protective strip. And based on the results obtained, a regression equation was formed for the dependence on time of the load-bearing capacity growth of the protective strip rigid part:

$$Q_{adm}(t) = 21.8\, exp\left(-0.28\frac{Sand}{Cem}\right)\left(\frac{Cem}{Wat} - 0.5\right) lg\left(t+1.5\right) L_r \times$$

$$\times\left(2+\left(2\frac{L_r}{m} - 1.87\right) exp\left\{0.074\left[\left(13.7+17.25\frac{Wat}{Cem}\right) exp\left(-0.54t\right) - \frac{Sand}{Cem} + 34\right]\right\}\right).$$

In this equation, as an argument, it is possible to use the distance X from the breakage face according to the known daily velocity V of its advance.

Thus, the calculation of rational parameters for extraction drifts fastening and protection scheme has been developed, based on consideration of its separate load-bearing elements as a single and mutually influencing system, in which the geometric and mechanical parameters of the protective strip of variable rigidity are the tools for formation of a favorable loading on the support.

3 Conclusions

It is established that the arched yieldable support with the circular arch has the maximum load-bearing capacity at the ratio of vertical and lateral loads in the range of $\beta = 2 - 3$, which is practically constant for most of typical cross-sections of mine workings.

The study of the yieldable part deformation of the protective strip with account of the slip prisms gradual cleavage and accompanying redistribution of the loading from the weight of the softening zone rocks, has indicated that the achievement of reasonable ratio of vertical and lateral loadings onto support is provided with the relative width of the yieldable part of a strip $L_y / m = 0.5 - 0.9$ with an internal friction angle $\varphi_y \leq 30^{\circ}$ of its material.

The control of the internal friction angle φ_y of the protective strip yieldable part is provided by addition of the required amount of porous-filling additive into hardening sand-cement mixture for adhesion of armour stone. The obtained dependence of the hardening mixture formulation and the internal friction angle φ_y of the hardened stone indicates its changes in the range of $\varphi_y = 10 - 30$ degrees with the addition of a porous-filling additive in an amount $1 - 4\%$ of the volume of grade M400 Portland cement at a sand-cement ratio $Sand / Cem = 3/1$ and water-cement ratio $Wat / Cem = 0.4$.

The calculation of the protective strip rigid (supporting) part parameters for strength shows that for typical mine working cross-sections, with the calculated width of the yieldable part of the strip at depths of $H = 300$ to 600 m, the reasonable relative width of the rigid part ranges from $L_r / m = 1 - 1.5$ with the use of a sand-cement hardening mixture $Sand / Cem = 3/1$ and $Wat / Cem = 0.4$ formulation.

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