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Impact involving the sealing degree of caving goaf with fine-fraction hydraulic mixtures on the ventilation parameters of longwall headings

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SUMMARY: The most common method to eliminate post-mining voids created after hard coal mining consists in natural filling them with rock rubble from the strata forming the roof the mining heading. Such rubble is characterized by free spaces that allow uncontrolled flow of air. The said flow is unfavorable due to disturbances in the distribution of airflow in the ventilation network, and it poses the risk of endogenous fire. One way to reduce such adverse phenomena is to fill the rubble with fine-fraction hydraulic mixtures, most frequently fly ash-water mixtures. The first part of the paper presents the method for determining the theoretical porosity of caving rubble. In the second part, the possibility of various degree of sealing of the numerically modelled caving rubble with a fine-fraction hydromixture was investigated in terms of assessing its impact on the ventilation parameters of a longwall working ventilated with the "Y" method. The presented numerical model was used to calculate the airflow distribution at various filling degrees of the rubble. The obtained knowledge involving the changes in the airflow distribution parameters, depending on the sealing degree of the rubble allows to define the possibility to slow down or to stop the development process of endogenous fire. In addition, it also allows to forecast the ventilation conditions of workings in the longwall area, limiting the development of other ventilation-related hazards, such as methane or climate hazards.

Keywords: gob grouting, fine-grained slurry, ventilation network, numerical modelling, air flow

1 INTRODUCTION

Underground coal mining is associated with the formation of post-mining voids, which often have considerable volumes. They are most commonly eliminated by means of natural filling with rock rubble from the strata forming the roof of the mining heading. The void with such rubble is characterized by the fact that it does not completely fill up the buried space, creating so-called goaf (caving) area with a certain volume of spaces. This allows an uncontrolled flow of air coming from headings with active ventilation, adjacent to the longwall panel, through the goaf. Such an airflow through the caving goaf is unfavorable for at least two reasons. Firstly, it causes disturbances in the distribution of air in the ventilation network of the longwall area, and secondly, it creates a risk of endogenous fire due to possible low-temperature oxidation of coal residues left over in the caving goaf.

One of the ways to reduce such unfavorable phenomena consists in filling up the free spaces of the caving rubble, which is technologically referred to as sealing of caving goaf, with fine-grained hydraulic mixtures produced and transported from the surface area through

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a network of pipelines. Currently, the sealing process of caving goaf with fine-fraction power production waste material, in particular fly ash, is one of the most effective methods of their reclamation, which allows to limit fire hazard, improve ventilation conditions, as well as reduce deformation of the surface area and rock mass. The amount of fly ash that can be fed into caving goaf depends on many factors, among which the most important are: the type and porosity of caving goaf, the height of caving, the type and properties of roof layers, thickness of the mined-out bed, tightening degree and accessibility of the goafs, sealing method of the goafs and the migration properties of fly ash-water mixture.

In fact, there is no technical possibility to fill 100% of free spaces in the caving rubble with fine fraction waste due to insufficient amount of sealing material that can be daily fed into the rubble, the change in porosity of the rubble over time effected by the impact of the weight of the overlying rockmass and free uncontrolled flow of hydraulic mixture through the caving rubble. As a result, we are facing an uncontrolled airflow through the void, unfilled spaces in the caving rubble, which adversely affect the airflow distribution in the underground ventilation network, and the extent of this airflow depends on the porosity of the rubble and on its sealing degree with fine-fraction material.

2 THEORETICAL FOUNDATION FOR THE DETERMINATION OF THE POROSITY (ABSORBENCY) OF CAVING GOAFS

The presented method of theoretical determination of the absorbency of caving goafs allows with sufficient accuracy in terms of mining practice to determine the volume of free spaces that can be filled with fine-fraction material.

The volume of fine-fraction power-generation wastes, e.g. fly ash that can be introduced into caving goafs, depends on:

- the type of rocks forming the caving rubble,
- porosity of caving rubble,
- type and properties of overlying layers,
- the height of the resulting caving,
- the thickness and dip of the mined-out bed,
- the extent to which the rubble is tightened under the weight of the overlying rocks,
- physical access to goafs which may have impact on the selection of technology to carry out the process,
- migration and penetration properties of fine fraction hydromixtures,
- execution technology for the sealing process of caving goafs.

An overview illustration of the sealing process of caving goafs of a selected post-mining area of a seam deposit, depending on its dip is presented in Figures 1 and 2.

Theoretically, the volume of fine-fraction material that can be introduced into caving goafs should be equal to the volume of free spaces resulting from the porosity of the caving rubble. This porosity depends on the loosening coefficient k_r, which, depending on the rocks forming the roof layers over the mined out deposit, is changing within the range of $k_r = 1.15 - 1.35$ (Mysłek Z. 1999, Piotrowski Z., Mazurkiewicz M. 2006). The volume of free spaces which can be filled, up to the height of the mined-out deposit, can be determined from the difference between the volume of the mined-out deposit and the volume of roof rockmass forming the caving rubble:

$$V_{\mathrm{pz}} = V_p - V_z, \ [\mathrm{m}^3] \tag{1}$$

$$\mathrm{Vz} = \frac{V_p}{k_r}, [\mathrm{m}^3] \tag{2}$$

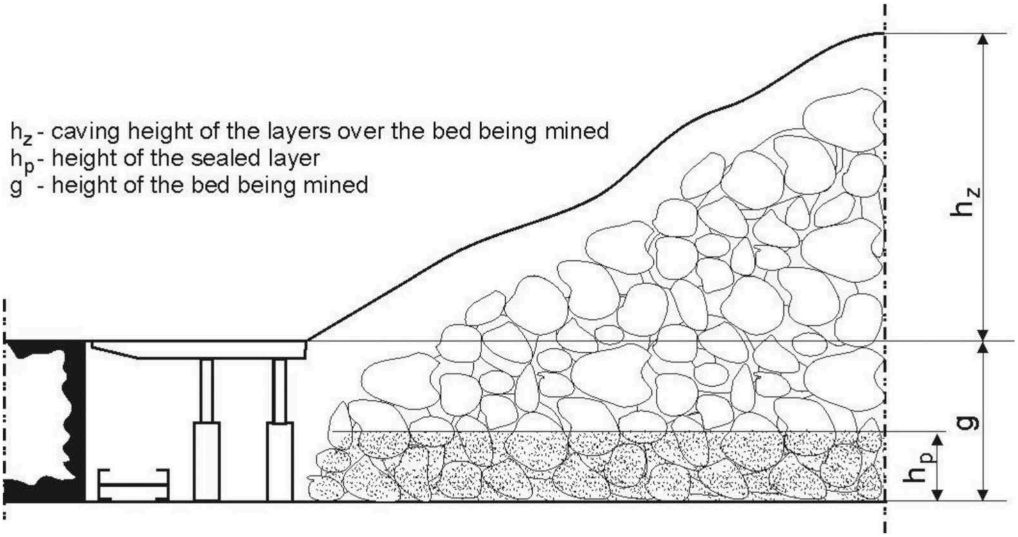

Figure 1. Sealing schematic of horizontal caving goaf with fine-fraction hydromixture.

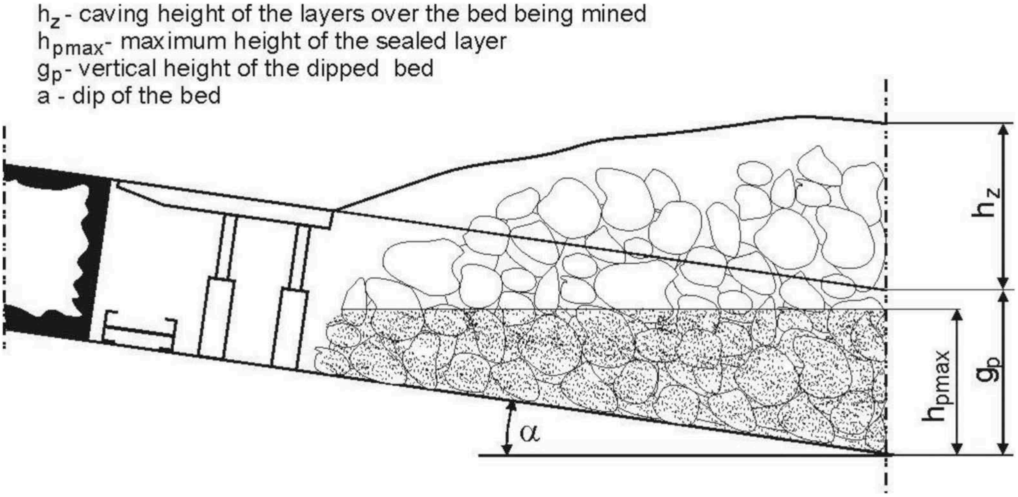

Figure 2. Sealing schematic of dipped caving goaf with fine-fraction hydromixture.

where:
V_p – volume of the mined-out bed, m^3,
V_z – volume of floor rock mass forming the caving rubble, m^3,
k_r – rock loosening coefficient.

Thus, the volume of the voids that can be filled up to the height of the mined-out deposit is:

$$V_{pz} = V_p - \frac{V_p}{k_r} = V_p\left(1 - \frac{1}{k_r}\right), [m^3] \tag{3}$$

And the dry mass of fine-fraction material that can be introduced into the free spaces of the goaf is:

$$m_p = V_{\mathrm{pz}} \cdot \rho_p = V_p \left(1 - \frac{1}{k_r}\right) \rho_p, [\mathrm{Mg}] \tag{4}$$

where:
ρ_p – the density of the fine-fraction material compacted after the draining of water, Mg/m^3
The relative amount of the fed fly ash in relation to the amount of extracted coal will be:

$$\frac{m_p}{m_w} = \frac{V_p\left(1 - \frac{1}{k_r}\right)\rho_p}{V_p \rho_w} = \frac{\left(1 - \frac{1}{k_r}\right)\rho_p}{\rho_w} [\mathrm{Mg/Mg}] \tag{5}$$

The filling degree of caving goaf with fine-fraction hydromixture is strictly dependent on the feeding method of the hydromixture. Depending on the filling degree of the goaf, the amount of hydromixture that can be introduced in relation to the amount of extracted coal in line with the notation in Figure 1 will be:

$$\frac{m_p}{m_w} = \frac{h_p\left(1 - \frac{1}{k_r}\right)\rho_p}{g \rho_w} [\mathrm{Mg/Mg}] \tag{6}$$

where:
h_p – height of the sealed layer of caving rubble, m
g – thickness of the extracted coal bed,m,
k_r – loosening coefficient of the caving,
ρ_p – bulk density of the fine-fraction material in compacted state, Mg/m^3
ρ_w – specific density of coal, Mg/m^3.
In the case when the height of the sealed caving layer is equal to the thickness of the extracted coal bed, i.e. $h_p = g$, the formula (6) has the following form:

$$\frac{m_p}{m_w} = h_p \left(1 - \frac{1}{k_r}\right) \frac{\rho_p}{\rho_w} [\mathrm{Mg/Mg}] \tag{7}$$

However, when the hydromixture fills up all voids of the caving rubble, i.e. when

$$h_p = g + h_z \tag{8}$$

where: h_z – caving height, m, equals

$$h_z = \frac{g}{k_r - 1} [m] \tag{9}$$

the expression (6) takes the following form:

$$\frac{m_p}{m_w} = \frac{(g + h_z)\left(1 - \frac{1}{k_r}\right)\rho_p}{g \rho_w} = \frac{\left(g + \frac{g}{k_r - 1}\right)\left(1 - \frac{1}{k_r}\right)\rho_p}{g \rho_w} [\mathrm{Mg/Mg}] \tag{10}$$

Using the relations given above, we can determine the theoretical absorbency of caving goaf for the extraction of coal beds.

3 ABSORBENCY ANALYSIS OF CAVING GOAFS FOR SELECTED MINING CONDITIONS

In order to verify the derived theoretical relations, we carried out a comparative analysis of the absorbency of caving goaf of an exemplary bed of the thickness of 1.7-1.8 m, with a slight dip of bed (several degrees), and an average loosening degree of the goaf adopted at the level of 1.25 with the use of sealing technology of caving goafs. With such assumptions, we can conclude that the height of the sealed layer of the goaf will not exceed the thickness of the extracted bed layer. The calculations carried out on the basis of formula (10) demonstrate that for the given conditions, the theoretical absorbency of goaf will be about 170 kg of fly ash per 1Mg of the extracted coal.

In the case of a completely tightened goaf, i.e. when the subsidence trough becomes fully developed and the subsidence coefficient reaches the maximum value, i.e. $a = 0.7 \div 0.8$, then the amount of fly ash possible to be deposited will decrease to 20-30% of the initial value for not tightened goaf. It is estimated that with the subsidence coefficient $a = 0.7$, depending on the thickness of the layer being sealed and on the loosening coefficient of the caving for the analyzed operating conditions, it will be within 9 to 257 kg/Mg of the extracted coal. With the height of the layer subject to sealing equal to the thickness of the mined bed, the absorbency of the goaf will be about 51 kg/Mg. However, for the subsidence coefficient $a = 0.8$, the absorbency of the goaf will be changing within the range from 6 to 171 kg/Mg.

With the 50% tightening of caving goaf and with the subsidence coefficient within the range of $a=0.7 \div 0.8$, the maximum absorbency of the goaf is about 60÷65% of the absorbency of the non-tightened goaf. The amount of fly ash that can be deposited in such conditions, depending on the height of the sealed layer and the loosening coefficient of goaf area for $a=0.7$ will be from 20 to 557 kg/Mg and for the coefficient $a=0.8$ it will be from 18 to 514 kg/Mg of the extracted coal.

Considering the above and taking into account coal density at the level of 1.3 Mg/m^3 and the conversion factor of 1Mg of ash as 0.8 m^3 of hydromixture fed into the goaf area, we can estimate that the theoretical porosity of the caving rubble in the first stage after the advance of the longwall and before the acquisition of the subsidence coefficient of $a=0.7$-0.8 can be estimated at the level of 8 to 15% with respect to the extracted volume. For further considerations of the model of airflow distribution, the porosity of the rubble was assumed to be at the level of 10%.

4 SIMULATION OF AIRFLOW MIGRATION THROUGH THE CAVING GOAF

The application of the sealing of caving goafs in the case of the potential fire hazards is an indispensable element of fire prevention. Hard coal mines often use hydromixtures made on the basis of fine-fraction power generation wastes (fly ash), which are introduced into caving areas from the excavation face of the mining front or from the return airway. This allows to reduce air migration through caving goaf, and thus to reduce the inflow of oxygen to it, which reduces the risk of endogenous fire and extends the incubation time of the fire or even prevents the initiation of this process. The effectiveness of the sealing process of caving goaf can be assessed, among others, by measuring the volume of airflow at the inlet and outlet of the longwall.

In order to assess the impact of caving goaf sealing on the ventilation parameters of the longwall heading, a model of the ventilation area of the excavated longwall ventilated by the "Y" method was developed (Musioł D. 2009), with the refreshment of unmined coal in the return airway and the discharge of the used air along the caving goaf. The diagram of the model is presented in Figure 3.

For the calculations involving airflow distribution in the ventilation network in the vicinity of the longwall area, the VENTGRAPH program (Dziurzyński W. et. al. 2010) was applied – a system of programs for ventilation engineers for the analysis of ventilation network in a coal mine in normal and emergency conditions, which has been developed by the Institute of Rock Mechanics of the Polish Academy of Sciences in Krakow. The said program enables digital modeling of airflow and the flow of other gases through mine headings and offers multi-variant

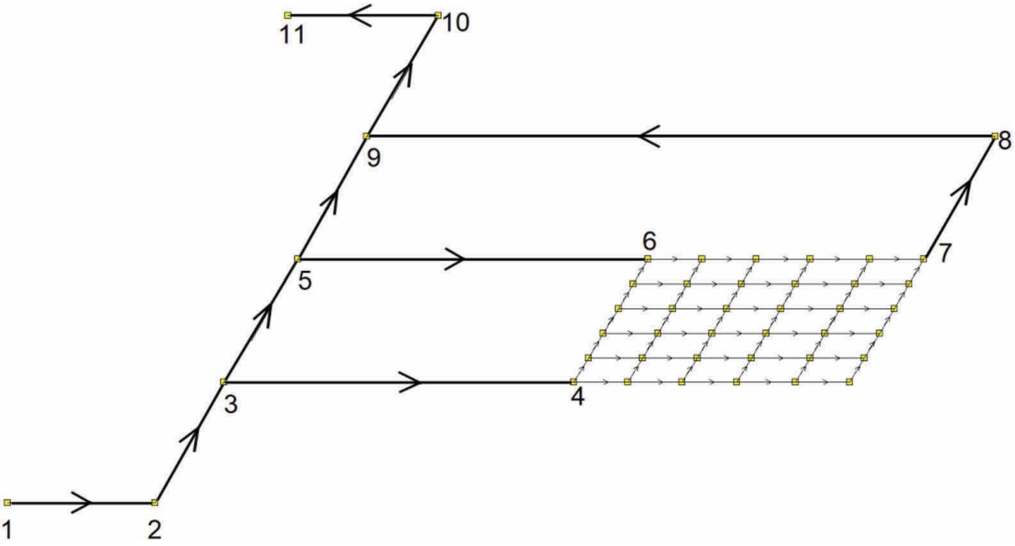

Figure. 3. Schematic of the model of the area of the excavated longwall ventilated by the “Y” method with the refreshment of unmined coal.

simulations of airflow distribution in mine ventilation networks. The calculation algorithm of the program is based on the one-dimensional mathematical model of airflow in a network and makes use of a system of equations describing the flow in the siding. The model describing a given flow is based on the equations of the conservation of mass and momentum in the following form:

$$G \; = \rho\nu a \; = \; const, \tag{11}$$

$$\Delta p = h_w + h_n - W_o - \sum W_i, \tag{12}$$

where:

G	- mass expenditure in the siding, kg/s,
$\rho = \rho(T, C, p)$	- air density, kg/m^3
$T = T(s)$	- temperature distribution, K
$C = C(s)$	- distribution of gas concentration, %
$p = \mathrm{p}(s)$	- pressure distribution along the siding, Pa
$\Delta p = p_2 - p_1$	- pressure difference at the outlet and inlet of the siding, Pa
$v = v\,(s)$	- flow rate, m/s
$A = A(s)$	- cross-section, m^2
s	- current coordinate of the length of heading, m
z=z(s)	- leveling depth of the siding, m
$h_n = -g \int_0^l \rho dz$	- natural air pressure, Pa
h_w	- depression of the ventilator in the siding, Pa
$W_0 = {}^{l}_{0} 2\rho\nu \vee \nu \vee \overline{2S} ds$	- loss of thrust on distributed resistances, Pa
$\sum W_i$	- sum of depression decreases on local resistances, Pa

The combination of these equations in the network through nodal and mesh equations makes a complete system of equations to be solved with the unknown mass expenditures G. The program adopts a numerical algorithm for solving this system based on the modified Euler method given by Hardy-Cross (Dziurzyński W. et. al. 1997, McPherson M., 1993).

4.1 *Preparation of the model for calculations and calculation methodology*

The digital model of the network was prepared in the VENTGRAPH program. Geometric parameters of sidings used in the model network were adopted as for real mine headings. The model of caving goaf was prepared in the form of a mesh with the square size of 50x50 m as presented in Figure 3. It was assumed for the numerical calculations of the basic model that the free spaces (porosity) occurring in the caving goaf, as assumed in point 3 of the work, constitute 10% of their volume along the entire length of the caving goaf in the longwall heading, which is equal to the area of 50 m^2. It was also assumed that the distribution of free spaces along the entire length of the caving goaf in the longwall heading is uniform. For such assumptions, airflow resistance through each “siding” of the goaf was calculated in line with the formula:

$$R = \alpha \frac{LB}{A^3}, \frac{kg}{m^7} \tag{13}$$

where:
R – aerodynamic resistance of the siding, kg/m^7,
α – aerodynamic drag coefficient, kg/m^3,
L – length of the heading, m,
B – perimeter of the heading, m,
A – cross-section of the heading, m^2.

For the basic model prepared in that way, the airflow distribution in the ventilation network and airflows through the caving goaf were calculated. The results of the airflow distribution are presented in Figure 4.

The rectangles contain volume flow rates of air (m^3/min) passing through the sidings, while the values in the nodes represent the values of total pressure losses (Pa). For the sake of comparison, in subsequent numerical calculation steps, the size of free spaces occurring in the caving goaf was reduced by 1% until it reached 3% of its volume, while calculating at the same time the aerodynamic drag of the goaf sidings. Figure 5. and Figure 6. present an exemplary airflow distribution for 6% and 3% of the volume of free spaces in the caving goaf.

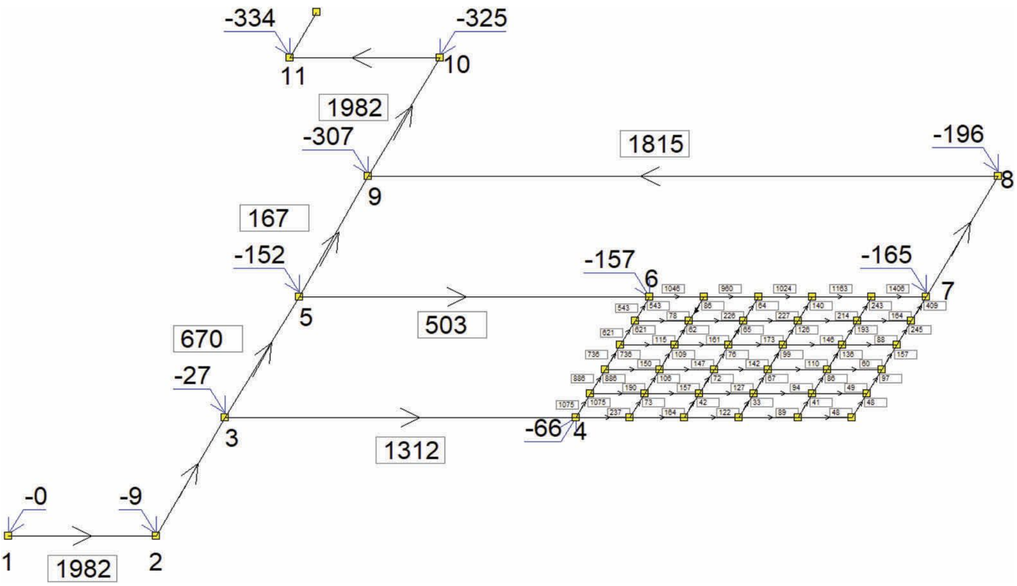

Figure 4. Graphic representation of the results of airflow distribution in the network of the basic model.

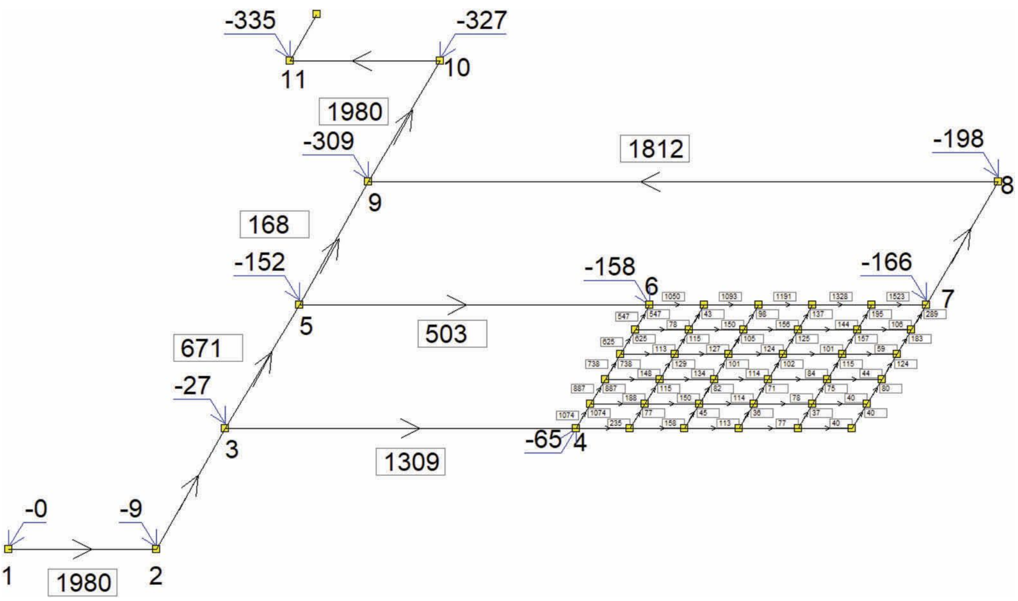

Figure 5. Graphic presentation of the results of airflow distribution in the network for 6% of free spaces in the caving goaf.

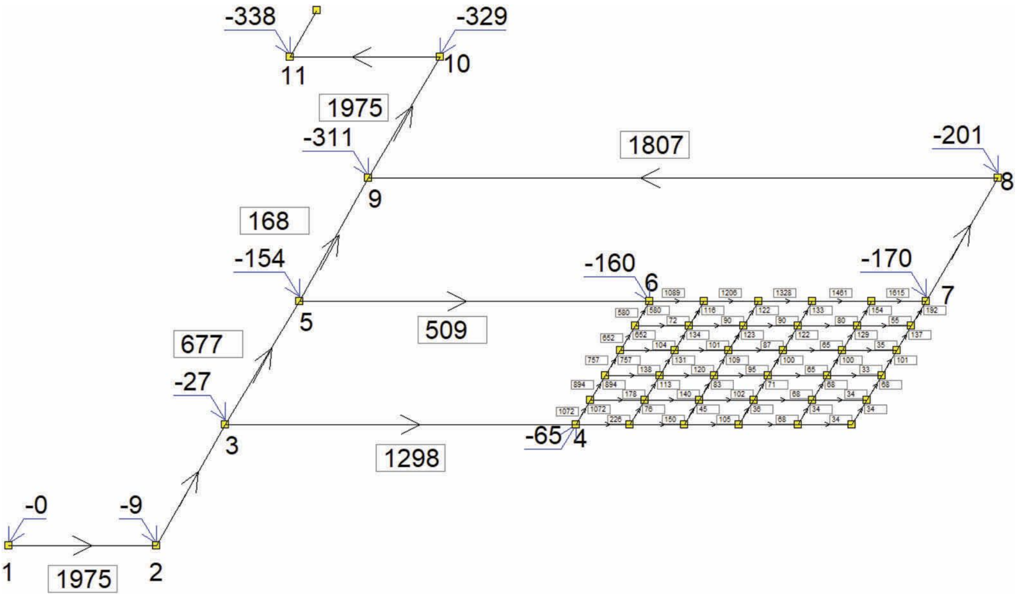

Figure 6. Graphic presentation of the results of airflow distribution in the network for 3% of free spaces in the caving goaf.

The numerical calculations made for the models in which the sealing degree of the caving goaf was being increased indicate that the amount of air migrating in it was reduced. The change in the volume of airflow migrating through the caving goaf in relation to the degree of its sealing is presented in Figure 7.

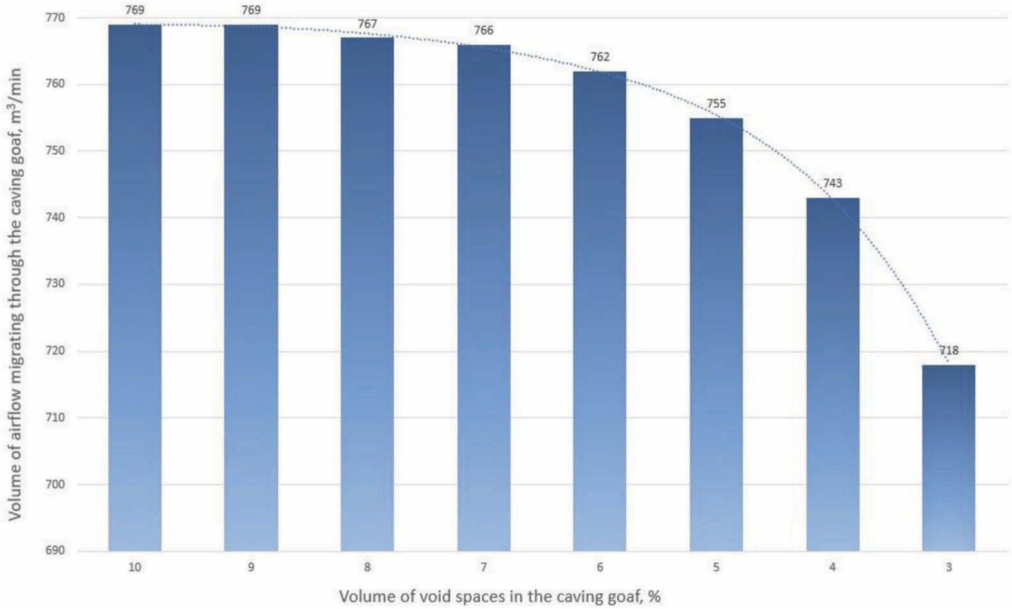

Figure 7. Impact of the sealing degree of the caving goaf on the volume of airflow migrating through it.

As we can see in Figure 7, along with the increase in the sealing degree of the caving goaf of the exemplary longwall, the porosity of the caving rubble decreases within the range from 10 to 3%. In effect, the migration of air passing through the goaf is reduced, which results in the rise of the airflow volume passing through the longwall heading. We can estimate that with the specified range of sealing, the said rise will be around 7%. Any increase in the airflow volume in the longwall heading contributes to the improvement of safety in terms of a potential hazard in the longwall by effectively reducing the concentration of methane. At the same time, the reduction of air migration through the goaf has a positive effect on the reduction of the risk of endogenous fires.

5 SUMMARY

The paper presents a theoretical foundation for the determination of the absorbency of caving goaf sealed with a fine-fraction (ash and water) hydromixture, which allows with sufficient accuracy in terms of mining practice to determine the amount of fly ash which can be located in caving goaf. As presented in the paper, this amount depends on many factors, among which the most important are: the type and porosity of caving rubble, height of caving, type and properties of roof rockmass, thickness of the extracted bed, tightness degree and accessibility of goaf, the sealing method of goaf, and migration properties of ash-water mixture.

The paper presents the ventilation analysis based on the numerical modeling of an exemplary longwall ventilated by the “Y” method, for which we considered a different sealing degree of the model caving rubble which was created after the longwall advance with a decreasing porosity within the range from 10 to 3%.

As presented in the work, along with the increase in the sealing degree of caving goaf, the porosity of the caving rubble decreases, which results in the reduction of the migration of airflow passing through the goaf, which in turn brings about the rise of airflow volume through the longwall heading. Model calculations demonstrate that the sealing of caving rubble in the presented scope will contribute to effective reduction of the amount of air migrating through the goaf and also to the rise of airflow volume in the longwall to about

7%. We can state that the said rise contributes to the improvement of safety in terms of methane hazard occurring in the longwall due to the reduction of methane concentration in the longwall. At the same time, the reduction of air migration through the goaf contributes to the minimization of the risk of endogenous fires in the caving goaf.

The model calculations presented in the paper enable to forecast ventilation conditions for headings in the vicinity of the longwall, aiming to reduce the natural hazards occurring in them.

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