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FORMATION OF GAS- AND WATER-IMPERMEABLE AREA IN A MINE WORKING ROOF WITH INJECTION BOLTS

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ФОРМУВАННЯ ГАЗО- И ВОДОНЕПРОНИКНОЇ ОБЛАСТІ В ПОКРІВЛІ ГІРНИЧОЇ ВИРОБКИ З ІН'ЄКЦІЙНИМИ АНКЕРАМИ

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ФОРМИРОВАНИЕ ГАЗО- И ВОДОНЕПРОНИЦАЕМОЙ ОБЛАСТИ В КРОВЛЕ ГОРНОЙ ВЫРАБОТКИ С ИНЪЕКЦИОННЫМИ АНКЕРАМИ

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Abstract. Safety and efficiency of coal mining depend on natural geomechanical and hydrogeological conditions of mining operations. They initiate the processes of deformation and water and gas filtration in the cracked coal seams and host rocks. Abundant water and methane inflowing into the mine workings, as a rule, leads to accidents, increased downtime of longwall faces, reduced productivity and economic losses. One of the ways to prevent gas and water inflow is to create an impermeable zone in the rocks around the mine working with injection bolts. Formation of such zones depends on the filtration area size and the rock permeability inside this area. It is conditioned by the natural fracturing of the rocks and degree of their unloading during the technological cycle of the mine face advancing. The purpose of this work was to investigate the conditions for the formation of an impermeable area in the mine roof with using injection bolts.

A numerical model of the coupled processes of rock deformation and filtration of liquid polymer components was used for investigating the rock permeability in the mine working roof depending on the number of injection bolts. The host rocks permeability was calculated for cases when one, three or five injection bolts were installed in the mine roof. It is shown that permeability of the roof rock around the injection bolt decreases when polymer solidification process begins and the metal tube starts to work as a roof bolt. Diameter of the created polymer-reinforced rock-bolt support reaches 2.0 m, for the accepted initial and boundary conditions. When number of the bolts is three the polymer-reinforced monolithic rock-bolt supports are not interconnected; they are separated by fractured, disturbed rock, while installation of five polymer-reinforced supports in the mine roof form a rock-bolt canopy, which is practically impermeable. That is why density of the injection bolts installation plays a significant role in the formation of the rock-bolts canopy. With the increase of the number of bolts from one to five, average value of the permeability coefficients in the mine working roof decreases by 4 times. The formed rock-bolts canopy can serve as a barrier that restrains water and gas inflowing from the undermined rocks into the mine working.

Keywords: injection bolt, injection of the consolidating mixture, impermeable beam, numerical simulation of coupled processes.

Safety and efficiency of coal mining depend on natural geomechanical and hydrogeological conditions and their changes during mining operations. A lot of complications and accidents in mine workings are associated with the high gas and water content in the rocks. Mining operations initiate the processes of deformation, cracking and water and gas filtration into the cracked coal seams and host rocks. Abundant water and methane inflowing in the mine workings, as a rule, leads to accidents, lengthy downtime of longwall faces, reduced productivity and, hence, to economic losses.

Therefore, study of the joint course of geomechanical and filtration processes and improvement of methods for preventing gas and water inflows are of great importance today.

One of these methods is use of injection bolts for creating water and gas impermeable area in the host rocks around the mine working [1-3]. The injection bolts are made in the form of a metal tube with a tight seal, which feeds a consolidating mixture into the cracked rock. After the injection process, the metal tube acts as an additional reinforcement providing high shear strength. The injected mixture, which consists of two liquid components, is injected into the cracked rock under high pressure. The reaction of the polymer mixture is accompanied with its volume gain by 1.5-3.5 times. Under high pressure, the foamed mixture penetrates even into small cracks in the rock [4]. When the foam resilient mixture is solidified, a consolidated, gas and water impermeable zone is created around the roof bolt. Its formation depends on the filtration area size, and the permeability inside this area depends on natural fracturing of the rocks and degree of their unloading during the technological cycle of the mine face advance.

In order to prevent fluid inflow and to develop a scheme for injection bolts installation, it is necessary to know the following things: how is the impermeable area formed around one roof bolt? Do the impermeable areas interact with each other when several bolts are installed? Do they form a solid canopy, which can protect the mine working from gas and water inflows? Therefore, the purpose of this work was to investigate the conditions for formation of gas- and watertight area in the mine roof by using the injection bolts.

Problem definition. The coupled processes of the rock deformation and filtration of the liquid polymer mixture in a disturbed area are described by the system of equations [5]:

$$c_g \frac{\partial u_i}{\partial t} = \sigma_{ij,j} + X_i(t) + P_i(t);$$

$$\frac{\partial p}{\partial t} = \frac{k}{\mu \cdot \beta \cdot m}\left(\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2}\right) + q(t),$$

where c_g is the damping coefficient, kg/(m^3·s); u_i is displacements, m; $\sigma_{ij,j}$ are the derivatives of the stress tensor components along x, y, MPa/m; $X_i(t)$ is projections of the external forces acting on the volume unit of solid body, N/m^3; $P_i(t)$ is projections of forces caused by pressure of the liquid polymer composition in the fractured space, N/m^3; p is pressure of the liquid polymer mixture, MPa; k is coefficient of permeability, mDa; μ is polymer viscosity, Pa·s; β is polymer-compressibility factor, 1/Pa; m is porosity, %; $q(t)$ is the foaming function.

Technological permeability k_{tech}, which is formed during the mine working driving and depends on the stress tensor components, overlaps the natural permeability field k_0, $k = k_0 + k_{tech}$. In these calculations the authors used the function $k_{tech}(\sigma_{ij})$, which was defined in [6]. This dependence takes into account that $k_{tech} \approx 0$ in undisturbed rocks in areas with elastic deformation and uniform compression. In the area of initial cracking, permeability is minimal. In the area of intense cracking, uncontrolled growth of cracks takes place; deformations rapidly increase due to the crack proliferation and ripping of the rock [7], and permeability coefficient increases. With the destruction of rocks, a sharp increase in permeability occurs under the condition of an increased volume of the deformed rocks [8].

The initial and boundary conditions for the task set are:

$$\sigma_{yy}\big|_{t=0} = \gamma H; \quad \sigma_{xx}\big|_{t=0} = \lambda\gamma H; \quad p\big|_{t=0} = 0.1\ \text{MPa},$$
$$u_x\big|_{\Omega_1} = 0; \quad u_y\big|_{\Omega_2} = 0; \quad p\big|_{\Omega_3} = p_0; \quad p\big|_{\Omega_4} = 0.1\ \text{MPa},$$

where σ_{xx}, σ_{yy} are components of the stress tensor, MPa; γ is average weight of the overlying rocks, N/m^3; H is the mining depth, m; λ is the side thrust coefficient; u_x, u_y are components of the displacement vector, m; p_0 = 6 MPa is polymer injection pressure; Ω_1 is vertical boundaries of the outer contour; Ω_2 is horizontal boundaries of the outer contour; Ω_3 is the filtering part of the borehole surface; Ω_4 is the contour of the mine working.

The problem was solved by the finite element method [9, 10] in the elastoplastic formulation by using the Coulomb-Mohr strength condition. At each time iteration i (is equal to 5 minutes), the following was taken into account [6]:

- influence of the stress field on the formation of the filtration area;
- influence of changes in the polymer mixture pressure on the stress state of the rock;
- change in physical, mechanical and filtration properties of the rock during solidification of the polymer.

As an example, we consider a mine working with 5.2 m of width and 3.0 m of height, which is driven through the weak rocks. One, three or five injection bolts are installed in its roof. It is assumed that the host rocks have an initial permeability k_0 = 0.01 mDa. Simulation of the injection process started from the second time iteration i. The injection time is four iterations (about 20 min), and the same time is required for the complete solidification of the polymer. It is further assumed that during the solidification of the polymer in each reinforced finite element:

- the modulus of elasticity increases linearly from 10^4 MPa to 1.7 * 10^4 MPa;
- ultimate compressive strength σ_c increases by 1.5 times;
- ultimate tensile strength increases by 2.0 times;
- the permeability coefficient decreases linearly to 0.

The metal injection tube acts as a roof bolt after the polymer has solidified in the borehole. Therefore, we take into account the reinforcing effect of rod finite elements that simulate roof bolts from the moment i = 6 (about 30 min).

Change in rock permeability when one injection bolt is installed in the mine roof. As a result of the modeling, we obtained the values of geomechanical and filtration parameters at various time iterations. In Figure 1, we can see distributions of values of the coefficients of rock permeability around the mine working with rectangular cross-section when one injection bolt is installed in its roof.

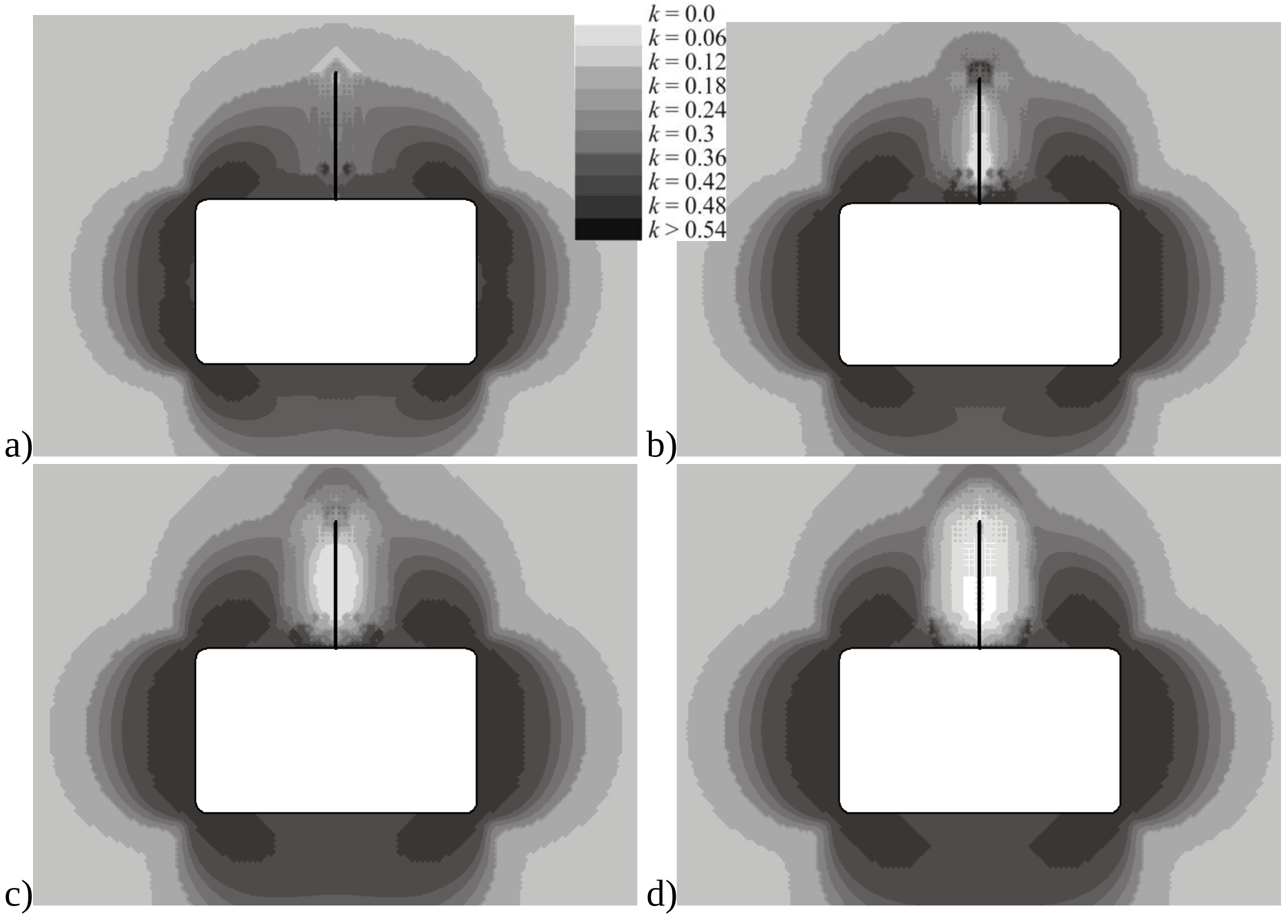

Figure 1 – Distribution of permeability coefficient values around the single injection bolt: a) t = 20 min; b) t = 30 min; c) t = 40 min; d) t = 50 min

As the mine working is driven, equilibrium state of the rocks is disturbed, and initial stress field is re-distributed. By the moment of the roof bolt installation, the boundary rocks have been partially unloaded from the rock pressure, and filtration area has been formed around the working where $k < k_0$.

When the hole has been drilled, injection bolt has been installed and polymer injection has started, permeability of the rocks around the bolt begins to change, Figure 1 a. When t = 30 min, the injection process is completed, the polymer is partially solidified. The metal tube starts to work as a roof bolt. The modulus of elasticity and the ultimate strength of rocks consolidated by polymer are increased. As a result, the diversity of the stress field components is decreased. The values of the permeability coefficients are decreased, at least in a small volume of rocks: k is getting lower than k_0. During the next 10 min (Figure 1 c), the area of consolidated and impermeable rocks around the roof bolt is expanded. By the moment t = 40 min, diameter of the area where $k < 0.1$ has become 1.1 m. At the moment t = 50 min, the polymer is completely solidified and the volume of impermeable rocks around the roof bolt is further increased. Diameter of area with such polymer-reinforced rock-bolt support now reaches 2.0 m, Figure 1 g.

Average values of the permeability coefficients in zone of roof bolt influence, with dimensions of 2.0 x 2.0 m, changes over time (Figure 2). For comparison, we show the curve of the average permeability change in the same area with no roof bolts.

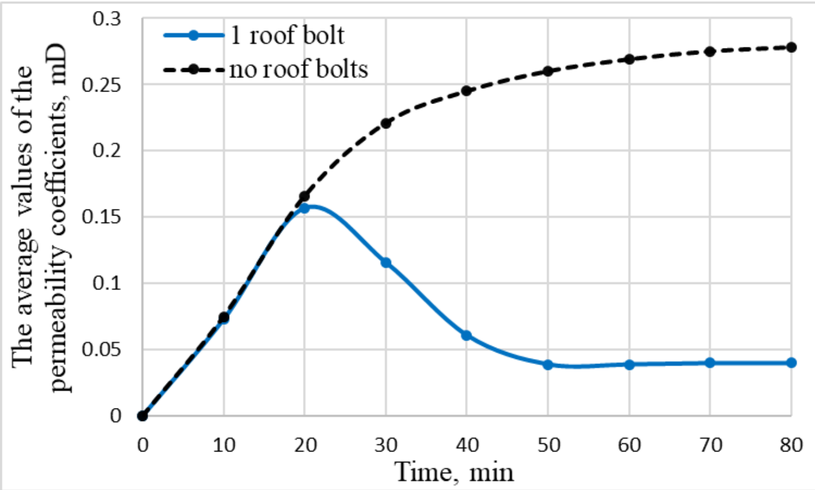

Figure 2 – The average values of the permeability coefficients in the zone of roof bolt influence

One can see that before the start of the polymer solidification process (t < 20 min) the permeability curves for both cases - with and without injection bolt - practically coincide. At t > 20 min, permeability of the roof rocks around the injection bolt begins to decrease because the polymer solidification process starts and metal tube begins to work as a roof bolt. At the same time, such processes as unloading of the roof rocks from rock pressure, crack proliferation and increase of the rock filtration permeability continue in the mine working with no bolt.

Change in rock permeability in the mine roof with three and five injection bolts. During the first 20 min after the simulation starts (Figures 3 a and 4 a) the roof rocks permeability practically is not changed. After next 10 minutes, when the injection process has already been completed, the polymer is partially solidified, metal tube starts to work as a roof bolt, and rock permeability begins to noticeably decrease. The values of the permeability coefficients k decrease to the value of the initial permeability k_0 (Figures 3 b and 4 b) and with the number of bolts N_b = 5 in the much larger volume of rocks. This effect neutralizes changes in permeability caused by the working driving.

When the polymer solidification process is completed, at t = 50 min (Figures 3 d and 4 d), area of consolidated rocks around the roof bolts expands. From this moment, each of the roof bolts is surrounded by impermeable rocks with a diameter of more than 0.6 m. However, at N_b = 3, there is high permeability rock between impermeable areas. Three polymer-reinforced monolithic rock-bolt supports are not interconnected; they are separated by fractured, disturbed rock, where permeability k exceeds 0.4 mD. At N_b = 5, five polymer-reinforced supports in the working roof form a rock-bolt canopy, which is practically impermeable. The area where $k < k_0$ now occupies most part of the mine working roof. The stress state of rocks in this zone has transited into the uniform compression mode and is stabilized.

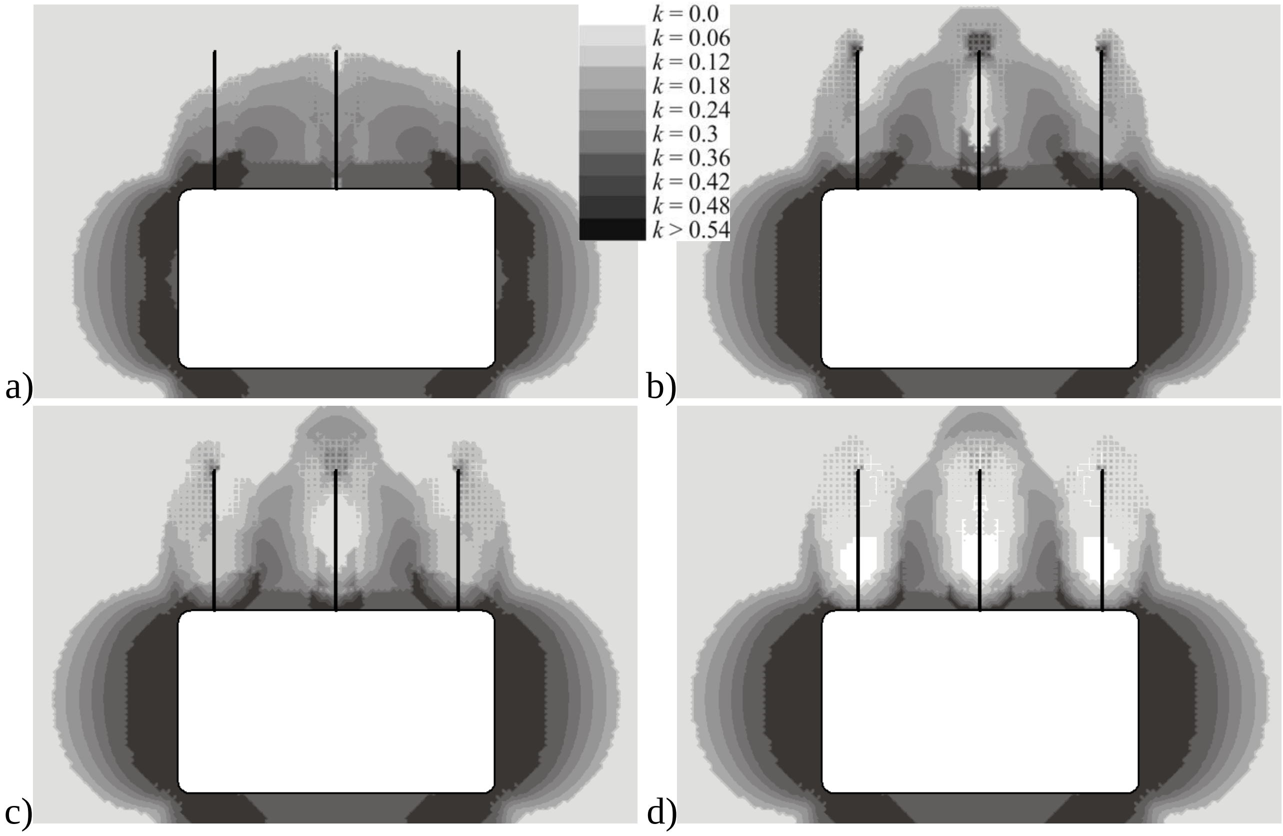

Figure 3 – Distribution of permeability coefficients values, N_b =3: a) t = 20 min; b) t = 30 min; c) t = 40 min; d) t = 50 min

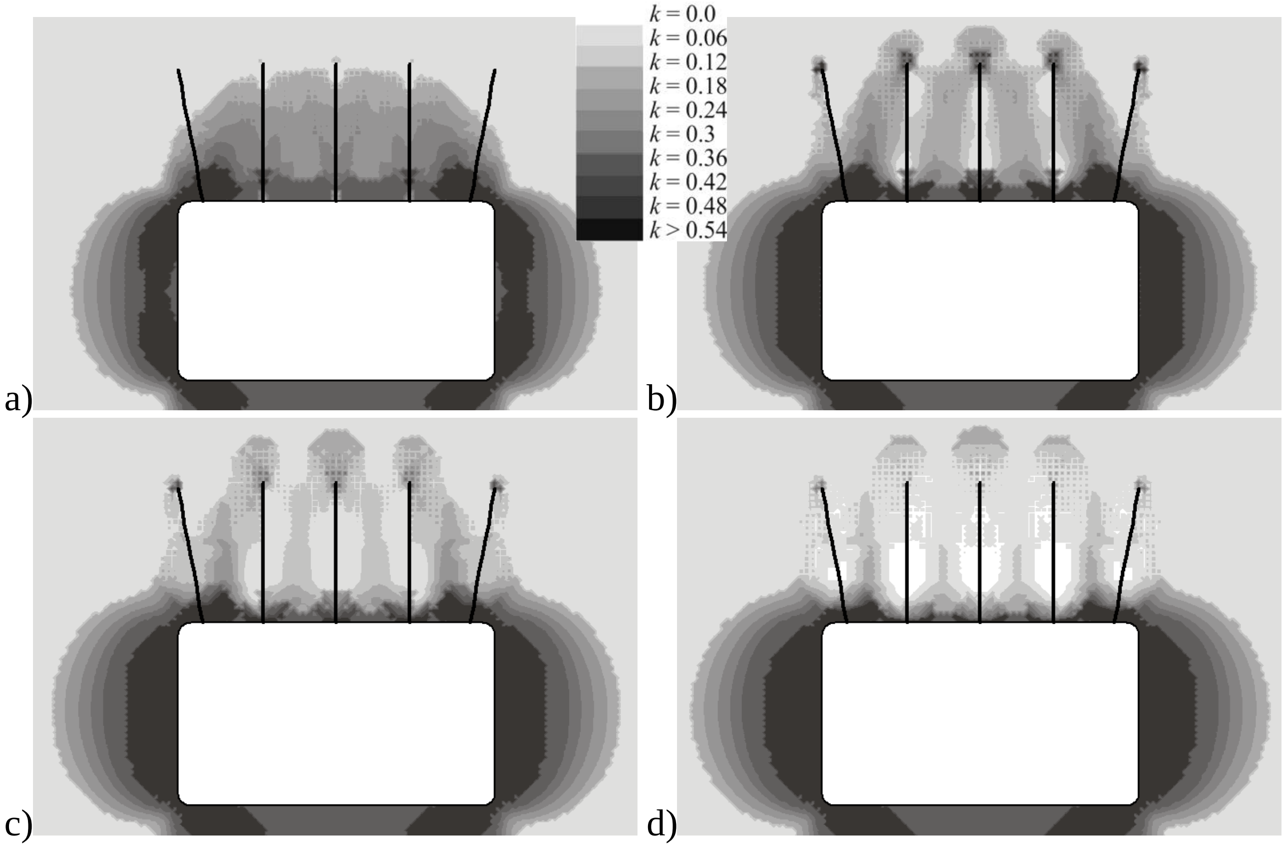

Figure 4 – Distribution of permeability coefficients values, N_b =5: a) t = 20 min; b) t = 30 min; c) t = 40 min; d) t = 50 min

The change in the average values of the permeability coefficients of the roof rock (in the area of 5.4 x 2.0 m) is shown in Figure 5 for N_b = 1, 3 and 5.

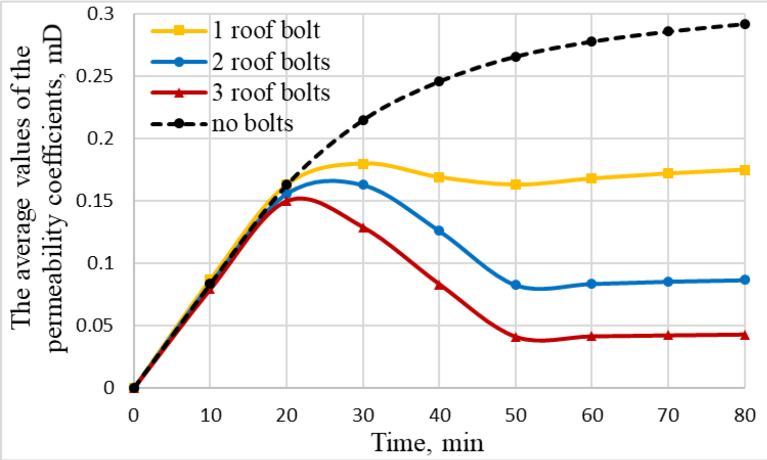

Figure 5 – The average values of the permeability coefficients in the zone of roof bolts influence

At the initial stage of the injection process, at t = 20 min, values of the average filtration permeability k_{av} in the consolidated area reach 0.15 mD for all considered cases. Then permeability of the rocks begins to decrease if bolts are installed in the working roof. When the processes of polymer injection and solidification is completed, at N_b = 1, the average value is k_{av} = 0.17 mD, at N_b = 3 k_{av} = 0.086 mD, at N_b = 5 k_{av} = 0.042 mD (for the accepted initial and boundary conditions). With increased density of the injection bolts installation, average value of the permeability coefficients in this area of the mine working roof decreases by 4 times. The formed rock-bolts canopy can serve as a barrier, which restrains water and gas inflowing from the undermined rocks into the mine working.

Conclusions. A numerical model of coupled processes of the rock deformation and filtration of liquid polymer components was used to investigate the rock permeability in the mine working roof depending on the number of injection bolts.

The host rocks permeability was calculated for the cases when one, three or five injection bolts were installed in the mine roof. It is shown that permeability of the roof rock around the injection bolt decreases when the polymer solidification process begins and metal tube starts to work as a roof bolt. Diameter of the created polymer-reinforced rock-bolt support reaches 2.0 m, for the accepted initial and boundary conditions. The polymer-reinforced monolithic rock-bolt supports are not interconnected; they are separated by fractured, disturbed rock if number of the bolts is three. Five polymer-reinforced supports installed in the mine roof form a rock-bolt canopy, which is practically impermeable. That is why density of the injection bolts installation plays a significant role in the formation of the rock-bolts canopy. With increase in the number of bolts from one to five, average value of permeability coefficients in the mine working roof decreases by 4 times. The formed rock-bolts canopy can serve as a barrier, which restrains water and gas inflowing from the undermined rocks into the mine working.

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Анотація. Безпека і ефективність освоєння вугільних родовищ залежить від природних геомеханічних і гідрогеологічних умов ведення гірничих робіт. Одним із способів боротьби з газовиділенням і водоприпливами є створення непроникної області в породах навколо виробки за допомогою ін'єкційних анкерів. Її формування залежить від розмірів області фільтрації, проникність в якій визначається природною тріщинуватістю порід і ступенем розвантаження приконтурного масиву за час, що минув з моменту посування вибою. Метою роботи є дослідження умов утворення непроникної області в покрівлі виробки.

З використанням чисельної моделі зв'язаних процесів деформування породного масиву і фільтрації рідких компонентів полімерного складу виконано дослідження зміни проникності порід в покрівлі гірничої виробки в залежності від кількості ін'єкційних анкерів. При розв'язанні задачі враховується початкова проникність порід, що вміщають виробку, і проникність, обумовлена її проведенням, час нагнітання і застигання полімеру, ефект спінювання полімерного складу при змішуванні його компонентів. Моделюється зміна фізико-механічних і фільтраційних властивостей породного масиву при застиганні полімеру. Враховується, що металева нагнітальна трубка вступає в роботу в якості анкера тільки після застигання полімерного складу.

Розрахунки виконано для випадків, коли в покрівлі виробки встановлено один, три і п'ять ін'єкційних анкерів. Показано, що кількість анкерів грає важливу роль у формуванні породно-анкерного перекриття. Для прийнятих в даній задачі умов отримано, що при установці в покрівлі виробки трьох ін'єкційних анкерів три зміцнені полімером монолітні породно-анкерні опори не пов'язані між собою, їх розділяють ділянки тріщинуватих, порушених порід. При установці п'яти ін'єкційних анкерів із зміцнених полімером порід формується єдине перекриття, породно-анкерні опори щільно взаємодіють між собою. Середнє значення коефіцієнтів проникності в заанкерованій області зменшується в 4 рази. Сформоване породно-анкерне перекриття може служити бар'єром, що стримує водоприпливи і газовиділення з підроблених порід всередину виробки.

Ключові слова: ін'єкційний анкер, нагнітання зміцнюючого складу, непроникне перекриття, чисельне моделювання зв'язаних процесів.

Аннотация. Безопасность и эффективность освоения угольных месторождений зависит от естественных геомеханических и гидрогеологических условий ведения горных работ. Одним из способов борьбы с газовыделением и водопритоками является создание непроницаемой области в породах вокруг выработки с помощью инъекционных анкеров. Ее формирование зависит от размеров области фильтрации, проницаемость в которой определяется природной трещиноватостью пород и степенью разгрузки приконтурного массива за время, прошедшее с момента подвигания забоя. Целью работы является исследование условий образования непроницаемой области в кровле выработки.

С использованием численной модели связанных процессов деформирования породного массива и фильтрации жидких компонентов полимерного состава выполнено исследование изменения проницаемости пород в кровле горной выработки в зависимости от количества инъекционных анкеров. При решении задачи учитывается начальная проницаемость вмещающих пород и проницаемость, обусловленная проведением выработки, время нагнетания и застывания полимера, эффект вспенивания полимерного состава при смешивании его компонент. Моделируется изменение физико-механических и фильтрационных свойств породного массива при застывании полимера. Учитывается, что металлическая нагнетательная трубка вступает в работу в качестве анкера только после застывания полимерного состава.

Расчеты выполнены для случаев, когда в кровле выработки установлены один, три и пять инъекционных анкера. Показано, что количество анкеров играет важную роль в формировании породно-анкерного перекрытия. Для принятых в данной задаче условий получено, что при установке в кровле выработки трех инъекционных анкеров три упрочненные полимером монолитные породно-анкерные опоры не связаны между собой, их разделяют участки трещиноватых, нарушенных пород. При установке пяти инъекционных анкеров из упрочненных полимером пород формируется единое перекрытие, породно-анкерные опоры плотно взаимодействуют между собой. Среднее значение коэффициентов проницаемости в заанкерованной области уменьшается в 4 раза. Сформированное породно-анкерное перекрытие может служить барьером, сдерживающим водоприток и газовыделение из подрабатываемых пород внутрь выработки.

Ключевые слова: инъекционный анкер, нагнетание упрочняющего состава, непроницаемое перекрытие, численное моделирование связанных процессов.

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