Interaction of rock-bolt supports while weak rock reinforcing by means of injection rock bolts

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Abstract

Purpose is to analyze changes in shape and dimensions of a rock mass area, fortified with the help of a polymer, depending upon the density of injection rock bolts as well as the value of initial permeability of enclosing rocks to substantiate optimum process solutions to support roofs within the unstable rocks and protect mine workings against water inflow and gas emission.

Methods. Numerical modeling method for coupled processes of rock mass strain and filtration of liquid components of a polymer has been applied. The model is based upon fundamental ideas of mechanics of solids and filtration theory. The problem has been solved using a finite element method. Its solution took into consideration both the initial permeability and the permeability stipulated by mine working driving, injection time of reagents and their polymerization, and effect of polymer foaming in the process of mixing of its components. Changes in physicomechanical and filtration characteristics of rock mass during polymer hardening were simulated. It has been taken into consideration that a metal delivery pipe starts operating as a reinforcing support element only after the polymer hardening.

Findings. If three and five injection rock bolts are installed within a mine working section then stresses, permeability coefficients, pressure of liquid polymeric composition, and geometry of the fortified area of rock mass have been calculated. It has been shown that rock bolt location is quite important to form a rock-bolt arch. It has been demonstrated for the assumed conditions that if five injection rock bolts are installed within the mine working roof then close interaction between rock-bolt supports takes place; moreover, the integral arch is formed within the mine working roof.

Originality. Dependence of change in the polymer reinforced area upon a value of initial permeability of enclosing rocks has been derived. It has been shown that in terms of low values of initial permeability, geometry of rock-bolt supports as well as its size is identified only by means of a value of the unloaded zone around the mine working. In this context, initial permeability increase results in the enlarged diameter of the reinforced rock mass area in the neighbourhood of the injection rock bolt.

Practical implications. The findings are recommended to be applied while improving a method to support the mine working roof and decrease water inflow as well as gas emission from the rocks, being undermined, into the working.

Keywords: support, mine working, rock bolt, geomechanical parameters, filtration parameters, modeling

1. Introduction

Injection rock bolts are applied to reinforce periphery rock mass while driving mine workings within the heavily disturbed unstable rocks [1]-[3]. An injection rock bolt is a metal seamless pipe with a sealer to deliver fortifying solution into the fissured rock mass. After delivery, the metal pipe is used as extra reinforcement facilitating high shear strength. Generally, the delivered solution consists of two liquid components pumped separately through the hoses. Then, the components mix in a blender, and deliver under high pressure to the rock mass by means of rock bolt system and a sealer. The reagent mixer is polymerized with 1.5-3.5 times increase in volume. Owing to high pressure, the foamed composition gets even in small fissures of the rock mass [4], [5]. After the hardening of a foamed elastic poly-

mer, a reinforced gas- and water-proof area is formed around the rock bolt. Its shaping depends upon the configuration and geometry of a filtration zone being a permeable space in the neighbourhood of an injection rock bolt within which a mixture of the delivered reagents spreads. The zone permeability is identified by means of natural fracture pattern as well as the technological one stipulated by an unloading degree of peripheral rock mass for a period passed from the moment of stope advance.

Numerical modeling is quite an expedient method to evaluate rock consolidation effect on the mine working stability. However, rock consolidation is usually simulated while assigning new characteristics to finite elements located at definite depth [6]. Previous research did not take into consideration the following:

– temporal development of polymer pumping and hardening;

– geomechanics of the formation of filtration area of liquid components of polymeric composition;

– operation of a steel delivery pump as an rock bolt;

– interaction degree of the reinforced zones around each rock bolt.

While developing a mine working support pattern using injection rock bolts, one should know how close is interaction of the reinforced zones and whether they form the integra-ted mechanical structure being a complete arch capable of protecting the mine working against failure, gas emission, and water inflows. If the reinforced zones are not interconnected then breakdown of the arch and roof failure are possible [7].

Consequently, the research is intended to study temporal changes in shape and size of polymer reinforced area depending upon the location of injection rock bolts as well as value of the initial permeability of enclosing rocks.

To achieve the objective, following problems have been formulated:

– develop numerical model of temporal rock mass strain and filtration of liquid components of polymeric composition in the mine working roof with several injection rock bolts;

– involve into modeling operation of a steel pipe as an rock bolt starting from the moment when the polymer starts hardening;

– analyze influence of the density of injection rock bolts on the changes in the reinforced area size and geometry;

– derive dependence of changes in the reinforced area dimensions upon the initial permeability of enclosing rocks.

2. Methodology

2.1. Mathematical model of rock strain and liquid polymer filtration

The coupled processes of rock mass strain and filtration of liquid components of polymeric composition are described with the help of the equation system [8]:

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

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

where:

c_g – damping ratio, kg/(c·m³);

u_i – shifts, m;

$s_{ij,j}$ – derivatives of strain tensor components in x and y, MPa/m;

$X_i(t)$ – projections of external forces acting on a volume unit of a solid, N/m³;

$P_i(t)$ – projections of the forces stipulated by pressure of the delivered composition within a fracture space, N/m³;

p – pressure of the delivered composition, MPa;

k – permeability, mDa;

μ – polymer viscosity, Pa·s;

β – coefficient of polymer compressibility;

m – rock porosity, %;

$q(t)$ – foaming function.

The problem is solved in elastoplastic formulation. Mathematical description of rock transition into the disturbed state involves Mohr-Coulomb failure criterion. It is widely thought that when a mine working is driving, a field of technological permeability k_0 stimulated by the process, is imposed on the initial permeability field k_{tech} depending upon stress tensor values [9] $k = k_0 + k_{tech}$.

The initial conditions and boundary conditions for the formulated problem are as follows:

$$\sigma_{yy}\big|_{t=0} = \gamma H; \quad \sigma_{xx}\big|_{t=0} = \lambda \gamma H; \quad p\big|_{t=0} = 0.1 \text{ MPa},$$

$$u_x\big|_{\Omega_1} = 0; \quad u_y\big|_{\Omega_2} = 0; \quad p\big|_{\Omega_3} = p_0; \quad p\big|_{\Omega_4} = 0.1 \text{ MPa},$$

where:

γ – aggregate weight of the overlying rocks, N/m³;

H – mining depth, m;

λ – horizontal stress ratio;

p_0 – delivery pressure, MPa;

Ω_1 – vertical outer boundaries;

Ω_2 – horizontal outer boundaries;

Ω_3 – filtering share of a borehole surface;

Ω_4 – internal boundary (i.e. mine working).

The solution involves a finite element method [10]-[13]. Each iteration i ($i \approx 5$ min) takes into consideration the stress field influence on the filtration field shaping; influence of changes in the polymeric composition on the stress state of the rock mass; and changes in physicomechanical as well as filtration characteristics of the rock mass during the polymer hardening. Roof bolting is simulated with the help of axial finite elements. Such geomechanical parameters as $Q^* = (\sigma_1 - \sigma_3) / \gamma H$, characterizing a degree of variety of the stress field components, and $P^* = \sigma_3 / \gamma H$, characterizing a probable rock failure mode, are applied to evaluate the stress state. Paper [14] describes simulation of rock mass reinforcement during polymeric composition delivering and hardening.

2.2. Formulation of the problem

Consider a rectangular cross-section mine working with 5.2 m width and 3.0 m height being driven through the soft rocks (elasticity modulus is $E = 10^4$ MPa; and compressive resistance is $\sigma_c = 28$ MPa). Analysis of geomechanical as well as filtration parameters involves consideration of two schemes helping install 2.5 m length injection rock bolts within the mine working roof:

a) number of rock bolts is $N_a = 3$; distance between them is $l_a = 2.0$ m;

b) number of rock bolts is $N_a = 5$; distance between them is $l_a = 1.2$ m.

Suppose that the initial permeability of enclosing rocks is $k_0 = 0.01$ mD.

Start a delivery process from the second iteration i. A delivery period is four iterations (about 20 minutes, iterations 2-5). Suppose that the same time is required for strain polymer hardening. $P_0 = 6$ MPa is the delivery pressure. Assume that 10^4 MPa up to $1.7 \cdot 10^4$ MPa linear increase in the elasticity modulus of a finite element takes place during polymer hardening within the finite components which fracture space is filled with the polymer; compressive resistance σ_c experiences its 1.5 times increase; ultimate tension σ_s increases its duplication; and permeability ratio of the finite element drops linearly to zero. A metal delivery pipe starts its operation as a reinforcing component after durable fixation within a borehole; hence, influence of the axial finite elements will be taken into consideration from $i = 6$ time moment.

3. Results and discussion

3.1. Changes in dimensions of the reinforced area depending upon the rock bolt density

The computations have helped obtain distributions of values of geomechanical and filtration parameters for itera-

tions if $N_a = 3$ and $N_a = 5$. In Figure 1, red colour shows nonelastic deformation zones and distributions of values of the variety of the stress field components Q^*. Figure 2 demonstrates distributions of permeability coefficients k within the studied area during the composition delivering and hardening.
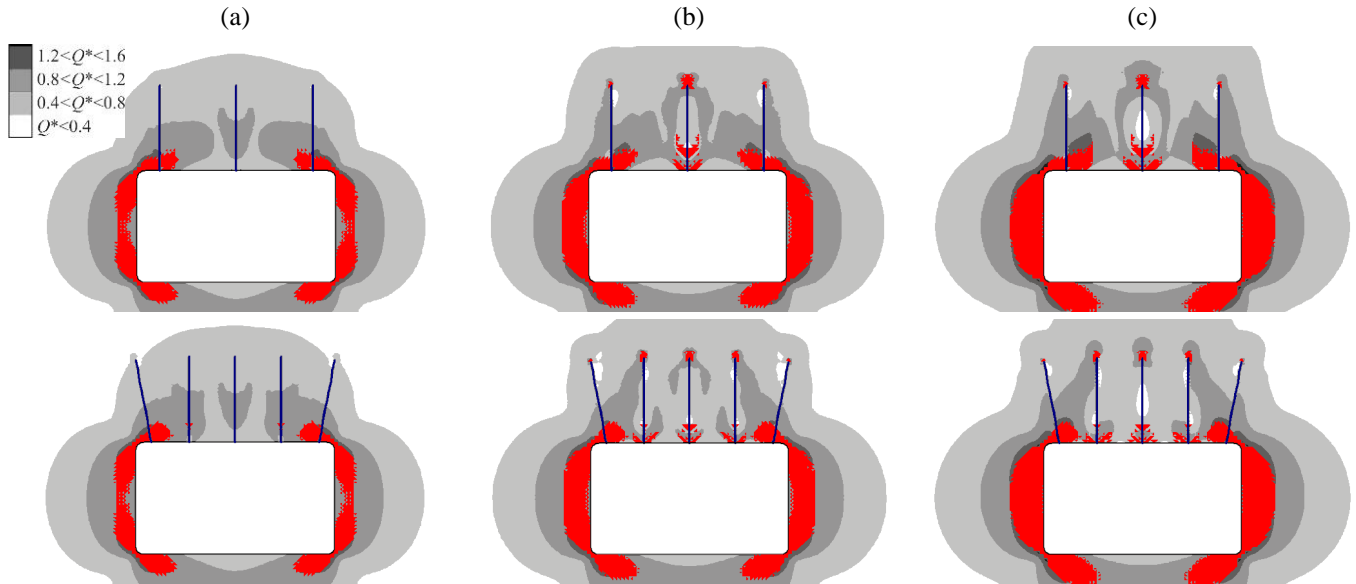

Figure 1. Distribution of Q^* parameter values and nonelastic deformation area if three and five rock bolts are installed within a mine working roof: (a) i = 4; (b) i = 6; (c) i = 10
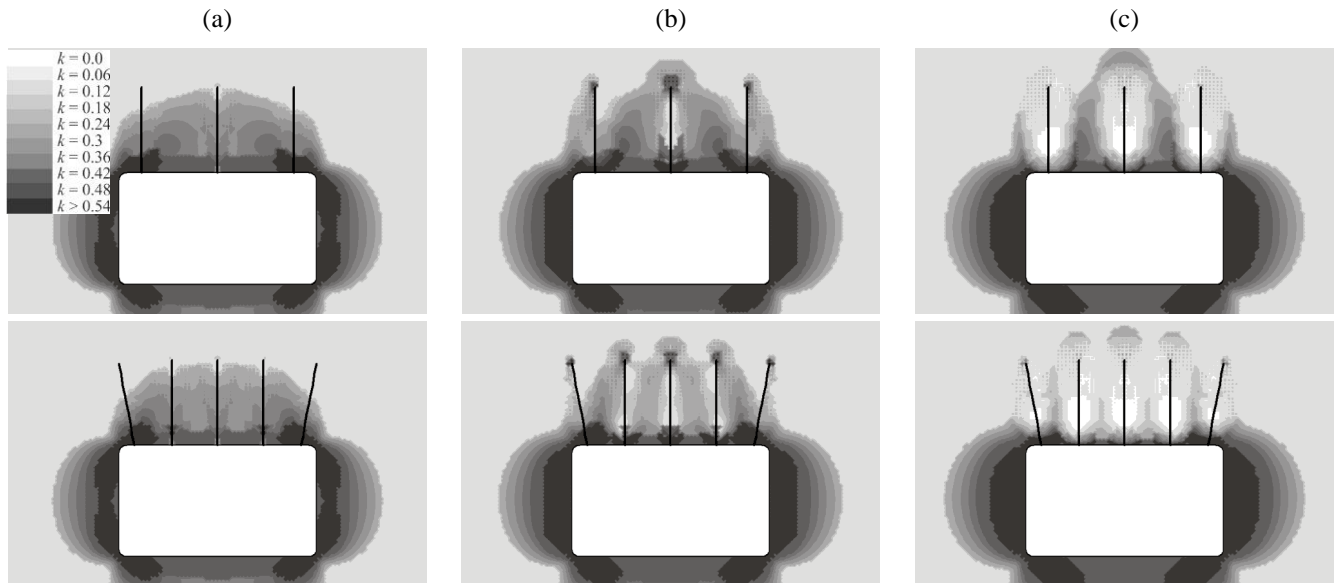

Figure 2. Distribution of the permeability coefficients while installing three and five injection rock bolts within the mine working roof (a) i = 4; (b) i = 6; (c) i = 10

In both cases, the areas of high component variety and nonelastic deformations extend in the course of time (Fig. 1); and rock mass releases gradually from lithostatic pressure. However, if rock bolts are installed then a zone of high fracturing $(0.8 < Q^* < 1.2)$ within the mine working roof decreases (Fig. 1a). In such a way, strengthening influence on the stress state of peripheral rocks starts manifesting despite the rock bolts are still surrounded with a zone where $0.8 < Q^* < 1.2$ and roof rock permeability k have experienced minor changes (Fig. 2a).

In terms of $i = 6$, a delivery process is over, and the polymer has hardened partially. A metal pipe starts operating as

an rock bolt. Both elasticity modulus and strength limits of the polymer-reinforced rocks increase. Decrease in the variety degree of the stress field components and the rock mass permeability is the common result of such transformations. Q^* parameter values around the rock bolts reduce. In terms of $N_a = 3$, central rock bolt is surrounded with an area where $Q^* < 0.8$. The same is true for three central rock bolts if $N_a = 5$ (Fig. 1b). The values of permeability coefficients drop down the initial permeability coefficients (Fig. 2b) neutralizing changes caused by the mine working driving. If $N_a = 5$ then the greater rock amount is involved.

After a hardening process in terms of $i = 10$ is over (Fig. 1c), the area of the reinforced rock around rock bolts expands; diameter of a zone where $0.4 < Q^* < 0.8$ and $N_a = 3$ is 1.7 m. If $N_a = 5$ then the diameter is 3.2 m. The area of uniform compression $Q^* < 0.4$ arises around the central rock bolts. Since the moment, each rock bolt is surrounded with a zone of completely impermeable rocks with more than 0.6 m diameter shown clearly in Figure 2c.

However, if $N_a = 3$ then highly permeable rocks (in our case, their permeability is more than 0.4 mD) occur between the impermeable areas. Three monolith polymer-reinforced rock-bolt supports are not linked; they are separated by zones of the fissured disturbed rocks where $0.4 < Q^* < 0.8$ and $k > 0.4$ mD.

In case 2 when $N_a = 5$, almost impermeable rock-bolt arch is formed from five polymer-reinforced supports. The Figure explains that the area with $Q^* < 0.8$ parameter values has spread towards the mine working walls occupying now greater share of the rock bolted mine working roof. Owing to the increased value of minimum component of the basic stresses as well as the decreased maximum component, the stressed condition of rocks went into volume compression state and became stable. As a result, the system, consisting of five injection rock bolts, has formed the high-strength uniform arch blocking the potential for spontaneous failure.

Figures 3 and 4 demonstrate graphs of changes in P^* parameter as well as rock permeability coefficients within the mine working roof at a 1.2 m distance from its surface concerning the two considered cases.
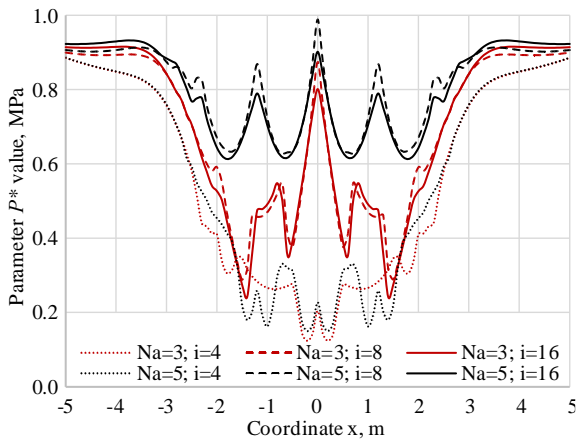

Figure 3. Changes in P^* parameter values within the mine working roof where three and five rock bolts are available

In the graphs, $x = 0$ coordinate corresponds to the central share of the mine working (i.e. location of the central rock bolt). Coordinates of the mine working walls are ±2.6 m. P^* parameter characterizes a probable rock failure mode: the closer P^* value to a unit is, the more stable periphery rocks are. Graphs in Figure 3 show that at the start of a delivery process, $P^* \approx 0.15$ for $N_a = 3$ and $N_a = 5$ if $i = 4$. Such low P^* values stipulates beginning of roof rock transition to unstable state. P^* values increase after the delivery is over and polymer is hardened ($i = 8$-16). If $N_a = 3$ then average P^*_{cp} is 0.51; and minimum value is P^*_{min}- 0.24 within the mine working roof $x \in$ [-2.6; 2.6]. if $N_a = 5$ then $P^*_{cp} = 0.7$, and $P^*_{min} = 0.61$. The increased density of injection rock bolts results in 2.5 times increase of P^* parameter supporting the idea of roof stability improvement.
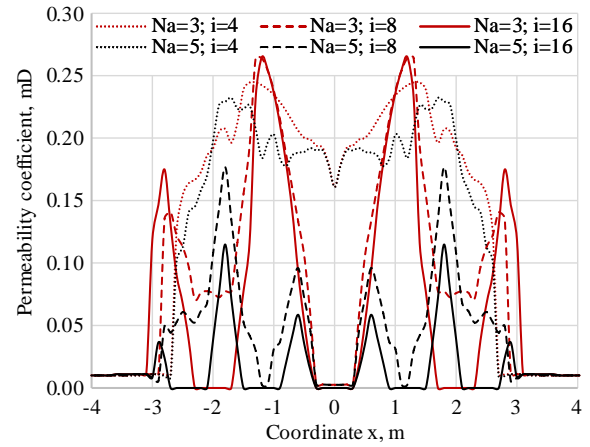

Figure 4. Changes in the values of permeability coefficients within the mine working roof where three and five rock bolts are available

It follows from Figure 4 that at the initial delivery stage (when $i = 4$), the values of filtration permeability k achieve 0.23 mD for both bolting patterns at a 1.2 m distance from the mine working roof. After the polymer delivery and its hardening ($i = 8$-16) when $N_a = 3$, k_{max} value increases up to 0.27 mD between the rock-bolt supports (for the assumed initial and boundary conditions). Deep in the rock mass at a 1.2 m distance from the mine working roof, the average permeability value is 0.08 mD. If $N_a = 5$ then $k_{mean} = 0.02$ mD, and $k_{max} = 0.11$ mD. Increase in the density of injection rock bolts results in 4 time decrease of the average value of permeability coefficients within the mine working roof.

Figure 5 demonstrates the areas where fracture space of the mine working roof are packed with the polymer at different time moments for the considered support schemes.

The hardening composition is delivered through the permeable surface of a borehole. Starting from the sixth iteration, the delivery stops. The polymer continues its hardening; its pressure drops gradually. A filtration process of a liquid polymer is restricted by the rock mass area with rather developed fracture network. When the components of polymeric composition are being mixed, chemical reaction behaviour increases its volume. While increasing the volume, the polymer generates extra pressure inside a pore-fractured space of the rock. Under pressure, the foamed composition gets even into small fractures of the rock mass.

In terms of the assumed initial and boundary conditions, a diameter of one reinforced area is 1.5 m (Fig. 5c). Nevertheless, in case one when $N_a = 3$, the areas are not interconnected; hence, they cannot protect a mine working against failure, gas emission, and water inflow. If sufficient number of rock bolts (five ones in the context of the case) are installed within the mine working roof then reinforced arch with low permeability appears (Figs. 5b and 5c). Such an arch is required for the mine working stability, and it becomes the barrier restricting water inflow and gas emission from the rocks, being undermined, into the mine working depth.

3.2. Changes in the reinforced area shape depending upon the permeability of enclosing rocks

The abovementioned computations have been performed if $N_a = 3$ and initial natural rock permeability is $k_0 = 0.01$ mD. It is quite obvious fact that other k_0 values will vary the diameter of the reinforced area around the injection rock bolt (Fig. 6).
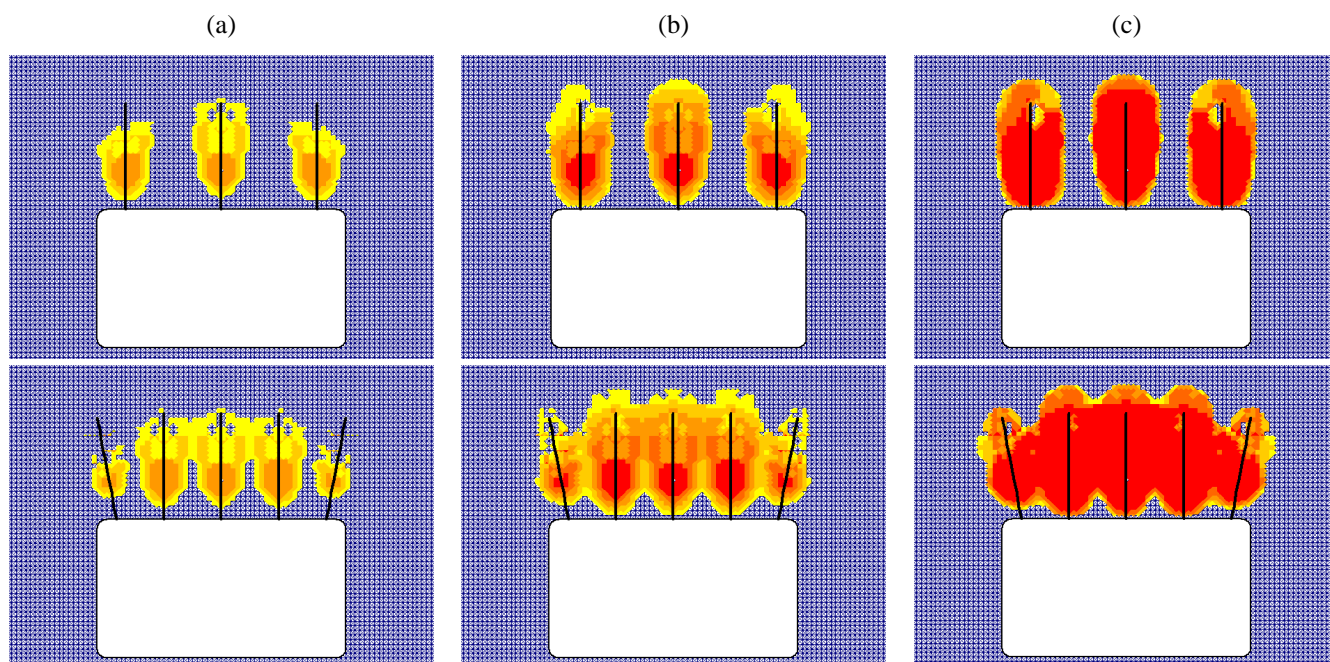
(a) (b) (c)

Figure 5. Roof rock fracture packing with the polymer while installing three and five injection rock bolts: (a) i = 4; (b) i = 6; (c) i = 10

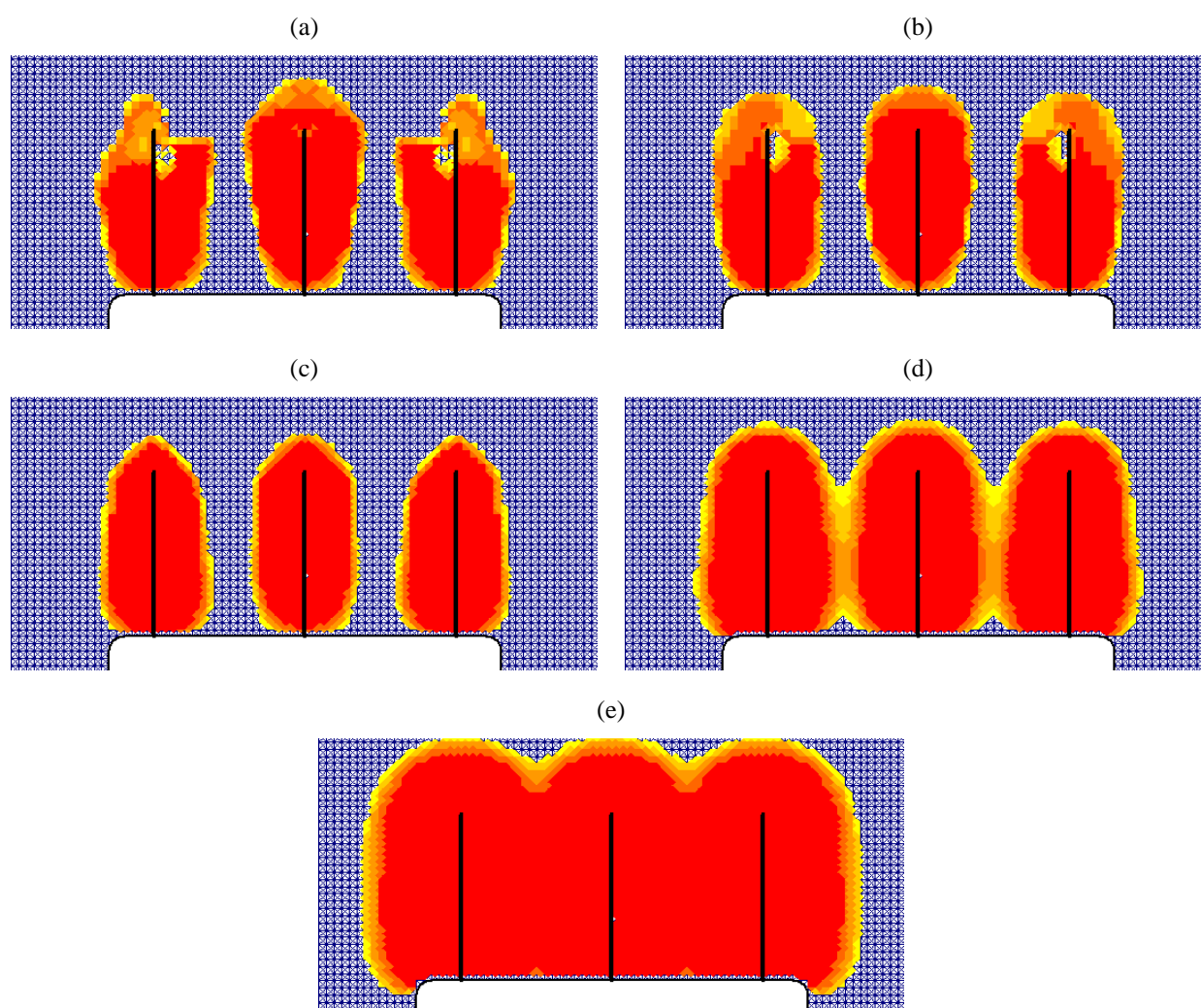(a) (b)

(c) (d)

(e)

Figure 6. Changes in the shape of the reinforced area depending upon the values of initial permeability k₀: (a) k₀ = 0.001 mD; (b) k₀ = 0.01 mD; (c) k₀ = 0.1 mD; (d) k₀ = 0.4 mD; (e) k₀ = 1.0 mD

In the context of three first cases (Figs. 6a-c), the polymer-reinforced areas around the rock bolts are independent; their diameters are almost similar (i.e. 1.5 m). In terms of low initial permeability values (Figs. 6a and 6b), the upper share of rock-bolt supports is not shaped completely. Proper packing of a fracture space is possible only within the area, influenced by a mine working zone, restricted by the filtration region (Fig. 2).

If $k_0 > 0.1$ mD then the initial permeability starts influencing the reinforced area diameter: if $k_0 = 0.4$ mD they contact (Fig. 6d); and if $k_0 = 1.0$ mD they form monolith arch (Fig. 6e). Generally, quite typical increase in the dimensions of the hardening zone is observed along the increase in the initial rock permeability. Figure 7 represents dependence of changes in the reinforced area upon the value of initial permeability of enclosing rocks for the mentioned conditions of the mine working driving.
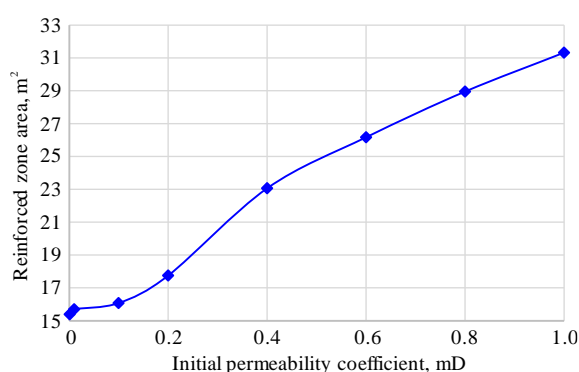

Figure 7. Dependence of changes in the reinforced area upon the value of initial permeability of enclosing rocks

Hence, development of schemes for the mine working support and computation of the polymer-reinforced area around the injection rock bolt should take into consideration the initial permeability of peripheral rocks.

4. Conclusions

A numerical model of the coupled processes of rock mass strain and filtration of liquid components of polymeric composition has been applied concerning certain changes in geomechanical as well as filtration parameters of the mine working roof depending upon the number of injection rock bolts and value of natural permeability of the enclosing rocks. The problem formulation takes into consideration the initial permeability of enclosing rocks as well as the permeability stipulated by the mine working driving, time of polymer delivery and hardening, and foaming effect of the polymeric composition in the process of mixing of its components. Certain changes in physicomechanical and filtration characteristics of rock mass during the polymer hardening have also been involved as well as the fact that a metal delivery pipe starts operating as a reinforcing element after hardening of the polymeric composition is over.

The computations have been performed for the cases if three or five injection rock bolts have been installed within the mine working roof. Calculation results concerning stresses, permeability, liquid polymeric composition, and geometry of the reinforced area of rock mass have been represented. It has been demonstrated that the location of rock bolts is important to form the rock-bolt arch. In the

context of the considered case, three to five increase in the number of injection rock bolts results in 2.5 times increase of minimum value of P^* parameter within the mine working roof; hence, its stability improves drastically, and average value of permeability coefficient experiences its 4 times decrease. The formed rock-bolt arch may serve as a barrier controlling both water inflow and gas emission from the rocks being undermined deep into a mine working.

Dependence of changes in the reinforced area upon the value of initial permeability of the enclosing rocks has been derived. If the values of initial permeability are low then size of the rock-bolt supports and their shape are determined using only a value of the unloaded zone around a mine working. In terms of $k_0 > 0.1$ mD, increase in the initial permeability results in the increased diameter of the reinforced rock mass area around the injection rock bolt.

It has been demonstrated that the development of a pattern as for the mine working support with the help of injection rock bolts should involve following factors determining formation of a permeable zone for a polymer filtration: time from the moment of a stope advance; initial rock permeability; and density of rock bolts. Consequently, to optimize schemes of the mine working support by means of injection rock bolts under specific mining and geological conditions, it is quite expedient to perform early computations using the proposed numerical model.

Acknowledgments

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Взаємодія породно-анкерних опор у процесі зміцнення слабких порід ін'єкційними анкерами

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Мета. Дослідити зміни форми і розмірів зміцненої полімером області масиву залежно від щільності установки ін'єкційних анкерів і величини початкової проникності порід, що вміщують виробку, для обґрунтування оптимальних технологічних рішень з підтримки покрівлі в нестійких породах і захисту виробок від водоприпливу та газовиділення.

Методика. У роботі використано метод чисельного моделювання зв'язаних процесів деформування породного масиву і фільтрації рідких компонентів полімеру. Основу моделі складають фундаментальні положення механіки твердого тіла та теорії фільтрації. Задача розв'язана із застосуванням методу скінченних елементів. При вирішенні враховувалася початкова проникність і проникність, обумовлена проведенням виробки, час нагнітання реагентів та їх полімеризації, ефект спінювання полімеру при змішуванні його компонентів. Моделювалася зміна фізико-механічних і фільтраційних властивостей породного масиву при застиганні полімеру. Враховувалося, що металева нагнітальна трубка вступає в роботу в якості армуючого елемента кріплення тільки після застигання полімеру.

Результати. Для випадків установки в перерізі виробки трьох і п'яти ін'єкційних анкерів виконано розрахунок напружень, коефіцієнтів проникності, тиску рідкого полімерного складу, геометрії зміцненої області породного масиву. Показано, що схема розташування анкерів відіграє важливу роль у формуванні породно-анкерного перекриття. Для прийнятих в задачі умов показано, що при установці в покрівлі виробки п'яти ін'єкційних анкерів породно-анкерні опори тісно взаємодіють між собою, а в покрівлі гірничої виробки формується цілісне перекриття.

Наукова новизна. Отримано залежність зміни площі зміцненої полімером області від величини початкової проникності порід, що вміщують виробку. Показано, що при низьких значеннях початкової проникності розміри і форма породно-анкерних опор визначаються тільки величиною розвантаженої зони навколо виробки, при цьому зростання початкової проникності призводить до збільшення діаметра зміцненої області масиву навколо ін'єкційного анкера.

Практична значимість. Результати рекомендується використовувати при вдосконаленні технології підтримки покрівлі гірничих виробок з метою підвищення їх стійкості, зниження водоприпривів і газовиділення з підроблених порід у виробку.

Ключові слова: кріплення, виробка, анкер, геомеханічні параметри, фільтраційні параметри, моделювання

Взаимодействие породно-анкерных опор в процессе упрочнения слабых пород инъекционными анкерами

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Цель. Исследовать изменение формы и размеров упрочненной полимером области массива в зависимости от плотности установки инъекционных анкеров и величины начальной проницаемости вмещающих пород для обоснования оптимальных технологических решений по поддержанию кровли в неустойчивых породах и защиты выработок от водопритоков и газовыделений.

Методика. В работе использован метод численного моделирования связанных процессов деформирования породного массива и фильтрации жидких компонентов полимера. Основу модели составляют фундаментальные положения механики твердого тела и теории фильтрации. Задача решена с применением метода конечных элементов. При решении учитывалась начальная проницаемость и проницаемость, обусловленная проведением выработки, время нагнетания реагентов и их полимеризации, эффект вспенивания полимера при смешивании его компонент. Моделировалось изменение физико-механических и фильтрационных свойств породного массива при застывании полимера. Учитывалось, что металлическая нагнетательная трубка вступает в работу в качестве армирующего элемента крепи только после застывания полимера.

Результаты. Для случаев установки в сечении выработки трех и пяти инъекционных анкеров выполнен расчет напряжений, коэффициентов проницаемости, давления жидкого полимерного состава, геометрии упрочненной области породного массива. Показано, что схема расположения анкеров играет важную роль в формировании породно-анкерного перекрытия. Для принятых в задаче условий показано, что при установке в кровле выработки пяти инъекционных анкеров породно-анкерные опоры тесно взаимодействуют между собой, а в кровле горной выработки формируется целостное перекрытие.

Научная новизна. Получена зависимость изменения площади упрочненной полимером области от величины начальной проницаемости вмещающих пород. Показано, что при низких значениях начальной проницаемости размеры и форма породно-анкерных опор определяются только величиной разгруженной зоны вокруг выработки, при этом рост начальной проницаемости приводит к увеличению диаметра упрочненной области массива вокруг инъекционного анкера.

Практическая значимость. Результаты рекомендуется использовать при совершенствовании технологии поддержания кровли горных выработок с целью повышения их устойчивости, снижения водопритоков и газовыделения из подрабатываемых пород в выработку.

Ключевые слова: крепление, выработка, анкер, геомеханические параметры, фильтрационные параметры, моделирование