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Innovative approaches to stabilizing underground mine workings in unstable rock masses by creating a preliminary protective shield

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Abstract

Purpose. The research is aimed at developing the technology for chemical strengthening of mine workings using epoxy reagent to create a protective shield in unstable zones of rock masses, as well as at assessing the strength of the strengthened areas and improving the stability of mine workings.

Methods. During the research, core samples extracted from the epoxy reagent-strengthened mass were tested to assess their strength and resistance to external influences. Numerical modeling was performed in ANSYS Mechanical 14.5 to analyze the stress-strain state of strengthened and non-strengthened areas.

Findings. Tests of core samples taken from the Akbakai mine showed that failure mainly occurs in the zones of contact between the rock and the adhesive composition, with the share of new fractures not exceeding 15%. The adhesion strength was 0.15 MPa, which is three times higher than that of non-strengthened rock. The results of modeling confirmed the reduction of stresses and displacements in strengthened zones by 2-3 times compared to non-strengthened ones, which indicates the high efficiency of the proposed method to improve the stability of mine workings.

Originality. For the first time, an innovative method of chemical strengthening of mine workings with the use of protective epoxy shield, which significantly increases the stability of the mass when conducting mine workings under the influence of mineral salts and external loads, has been substantiated.

Practical implications. The developed technology of chemical strengthening of mine workings with the use of protective epoxy shield has a high practical significance for the mining industry. Its application will significantly improve the stability of rock masses, especially in unstable zones exposed to the influence of mineral salts, which contributes to improving the safety and durability of mine workings, reducing the risks of caving and cleavage, as well as increasing the efficiency of mining-tunneling operations.

Keywords: *mine workings, mass stability, arch caving, chemical strengthening, adhesion strength, modeling*

1. Introduction

Modern mining and tunneling operations face various challenges due to difficult mining-geological conditions, especially when mining deposits in unstable and prone to caving rock masses [1], [2]. The use of powerful technical equipment and high-performance technologies in such conditions is significantly limited, resulting in reduced productivity and safety of operations. In addition, the use of traditional methods of tunneling, supporting and ensuring safety of underground mine workings requires significant labor costs and financial resources, while not guaranteeing the proper level of long-term reliability [3]-[7].

This problem is particularly acute in Kazakhstan, where many mineral deposits are characterized by difficult mining-geological conditions [8], [9]. Unstable rock masses pose significant difficulties in mining these deposits. An example is the Akbakai mine, located in the Akbakai Industrial Zone, one of the key mines of the leading gold producer in the country [10]-[14].

To ensure the reliability and efficiency of mining-tunneling operations in such conditions, it is necessary to search for and implement new technologies aimed at improving the stability of mine workings and reducing the risks of caving [15]-[18]. One of the promising solutions is the application of chemical rock strengthening methods, which significantly improve the mechanical properties of the mass. Exploring this technology under real conditions is an important step towards improving safety and optimizing production processes. Problems with the rock mass condition negatively affect the intensity and efficiency of production processes (Fig. 1).

One of the key factors determining the effectiveness of strengthening unstable rocks is their mineral composition [19], [20]. Scientific evidence indicates that the minerals constituting rocks have different exchange characteristics [21]. Thus, montmorillonite has the highest exchange capacity, reaching 80-120 mg-eq per 100 g of mineral, while in muscovite this index is 10 mg-eq, in biotite – 30 mg-eq, and in kaolinite – 24 mg-eq.

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(a) (b)

Figure 1. Geomechanical condition of the rock mass in the eastern part of the Akbakai mine during sublevel drifting along the Pologaya ore vein

The exchange capacity depends on the specific surface area of the rock, which is mainly composed of clay-sand minerals.

The salts contained in the rocks also have a significant influence on the process of strengthening with chemical solutions. They are mobile components of the mass and determine the level of mineralization of void solutions, composition of convertible cations and salinity peculiarities [22]-[24]. For example, when using the silicate strengthening method, the rate of solution hardening depends on the degree of substitution of sodium ions in the sodium silicate with calcium ions.

As part of our research, the previously performed work was aimed at identifying the causes of rock mass spalling at the mines of the Akbakai Industrial Zone. The results indicate that spalling is associated with chemical and mechanical instability of the mineralogical composition of the rocks. The minerals found in these rocks include dolomite ($CaCO_3$-$MgCO_3$) at a concentration of 7.4%, albite (Na_2O-Al_2O_3-$6SiO_2$) – 6.6%, and muscovite ($Kal_2(AlSi_3O_{10})(OH)_2$) – 4.3%. These minerals reduce the overall rock mass stability. Dolomite dissolves when exposed to atmospheric moisture, breaking the adhesion strength between parts of the rock. Albitite is destroyed by both mechanical and chemical action, while muscovite decomposes, forming small fractures that disturb the rock continuity [25]-[28].

The salt content in rocks is the subject of active scientific research. Mineral salts play a key role in the silicification process, acting as an inert material [29], [30]. The interaction of salts with sodium silicate solutions leads to the formation of soluble and insoluble compounds, which occurs at a certain pH value. The pH level of the rock depends on the content of absorbed ions and dissolved salts. At pH greater than 10.5, an alkaline silicic acid gel is formed, which binds the dispersed structures. The conversion of silicic acid to gel occurs when the alkali is neutralized at a level of 25-45% [31]-[33].

Subsequently, laboratory tests were conducted to select the composition of the strengthening solution, which made it possible to choose its optimal structure for effective adhesion of rocks containing mineralogical salts, taking into account the chemical composition of samples from the Akbakai field, determined during the previous experiments [34], [35].

Experiments on rock samples have shown that chemical stabilization methods using epoxy resins are the best solution for strengthening rock masses with such mineral composition. The interaction of calcium, magnesium and silicon salt crystals with functional active groups (OH, COOH, complex esters, etc.) in the epoxy adhesive composition promotes the formation of strong covalent and ionic bonds, which significantly increases the strength of joints between rock fragments. Based on the results of laboratory tests, including assessment of strength properties, safety and environmental friendliness, an epoxy reagent prepared in a 9:1 ratio with polyethylenepolyamine (PEPA) was found to be optimal.

After determining the optimal adhesive formulation, the key task was to test it under industrial conditions. In this regard, our further research will be aimed at solving the problem of developing a technology for preliminary chemical strengthening of unstable rock mass to increase its stability before mining-tunneling operations.

The analysis of domestic and foreign experience in the use of chemical rock strengthening shows that this method is widely used in various construction industries. In countries such as Austria, USA, Belgium and Japan, chemical rock strengthening technology has been used in the construction of subway tunnels, where a two-component silicification method prevailed [36]-[38]. In this process, each component is introduced into the rock one after the other. The first component penetrates unhindered into the porous structure of the mass, while the propagation of the second component is hindered by the formation of a siliceous shell when the components interact, which fills the cavities and prevents further penetration of the solution.

In the territory of the Republic of Kazakhstan, the technology of chemical strengthening of rocks was applied for the first time in underground mining of deposits in difficult mining-geological conditions. An example is the implementation of technology for strengthening inter-chamber weakened zones at the Zhezkazgan field using solutions based on urea resin. In addition, a combined rope-resin method for strengthening unstable rock mass was developed, which became an important step in improving the reliability and safety of mining operations [39]-[43].

The technology for strengthening weakened pillars at the 220 m horizon of the West Zhezkazgan mine was implemented on ore blocks No. 31, 36, 50 and 56. In the course of the work, drilling of 40-46 mm diameter boreholes of different lengths, directed perpendicular to the fracture zones was performed, taking into account the geometrical characteristics of the disturbed areas of the mass. The strengthening compound was injected with the use of pumping unit UN-35, providing the solution supply under high working pressure. The chemical composition was prepared directly in the mixing tank of the unit. It was prepared using urea-formaldehyde resin of KF-Zh grade mixed with water in the ratio of 2:1, followed by the addition of oxalic acid solution in the ratio of 10:1. The injection pressure of the solution into the boreholes varied in the range of 8-14 MPa.

The chemical compound injected into the rock mass propagated through fractures and pores, forming strong interparticle bonds, which increased the stability of weakened zones [44], [45]. Application of this technology allowed to effectively strengthening 65 rib pillars, which ensured extraction of additional 456 thousand tons of high-quality ore.

Analysis of existing technologies shows that they are mainly oriented to specific conditions of particular fields and take into account only local patterns of structure and distribution of injected chemical solutions. There is currently no universal technology suitable for a wide range of conditions. In this regard, we were faced with the task of developing an effective strengthening technology adapted to the mining-geological and mining-engineering conditions of the Akbakai field, as well as to the peculiarities of the chemical reagent used to stabilize the unstable rock mass, for further testing of the developed strengthening method in industrial conditions.

2. Methodology

Analysis of existing methods of chemical rock mass strengthening in mining construction shows that they mainly depend on specific types of reagents and mining-geological conditions of the places of their application. Therefore, the urgent task was to create a technology effectively adapted to the properties of the proposed epoxy reagent, prepared in the ratio of 9:1 with polyethylenepolyamine (PEPA), taking into account the mining-geological conditions of the Akbakai mine, the mineralogical composition of rocks and the requirements for strengthening the mass.

To realize this task, analytical and research work was conducted on existing methods of chemical strengthening of mine workings. The pre-strengthening method using elements of the New Austrian Tunneling Method (NATM) proved to be the most optimal. This approach involves creating a protective shield by injecting a chemical reagent into unstable mass zones that are located in the immediate vicinity of the extraction zone [46]-[48].

To assess the efficiency of proposed technology in industrial conditions at the Akbakai mine, test works were conducted along the Pologaya ore vein at +640 m horizon. The tests were conducted according to a specially designed project and included the following steps. Prior to the start of driving, 42 mm diameter and 3 m deep wells were drilled along the perimeter of the mine working arch to create a protective shield in the unstable rock mass of the field. The wells were drilled at an inclination angle of 20 degrees upward using a Rocket Boomer 282 drilling rig. The distance between wells was 0.4 m (Fig. 2).

The number of wells drilled along the perimeter of the mine working arch with a cross-section $S = 11.4$ m^2 was nine (Fig. 3). The distances between the wells were determined by the calculated epoxy reagent propagation radius found based on preliminary studies, injector diameter, the length of one injection cycle (2.5 m), and the inclination angle resulting from the value of the reagent absorption pressure on the rock mass.

A Meyco unit was used to inject epoxy resin and PEPA catalyst in a 9:1 ratio into the rock mass. The volume of epoxy resin consumed was 50 l and 5.5 l of PEPA catalyst.

The injectors were fixed to specially designed levers to ensure that the injectors were hermetically sealed in the wells. Hydraulic boom system fixed the injectors in the working position until they were completely compacted. Reagent injection into the wells located in the mine working arch part was performed at a pressure of 1.5 MPa. The reagent was injected sequentially: after treating one well, the process was moved to the next, starting from the left side of the well (Fig. 4). Wooden plugs were used to temporarily seal the filled wells. It took about 12-15 minutes to treat one well with epoxy adhesive. The total duration of the reagent application process for all 9 wells was 1 hour and 40 minutes.

Twelve hours after the epoxy adhesive was injected into the rock mass, three 15 cm long and 63 mm diameter cores were drilled, taken from the mine-working roof and from both sides.

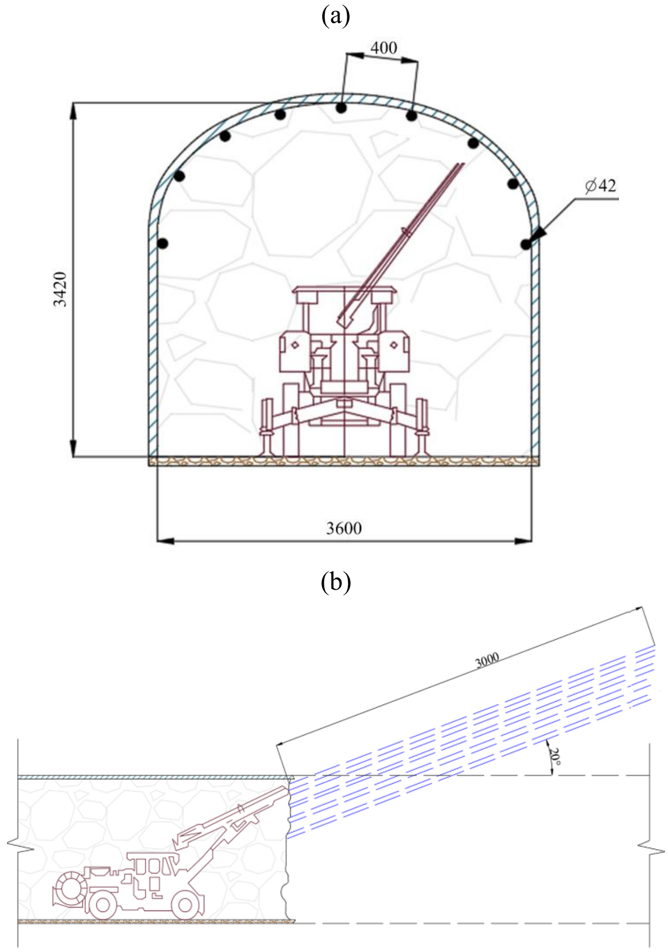

Figure 2. Layout of injection wells: (a) view of the face; (b) sectional view

Figure 3. Drilling of injection wells

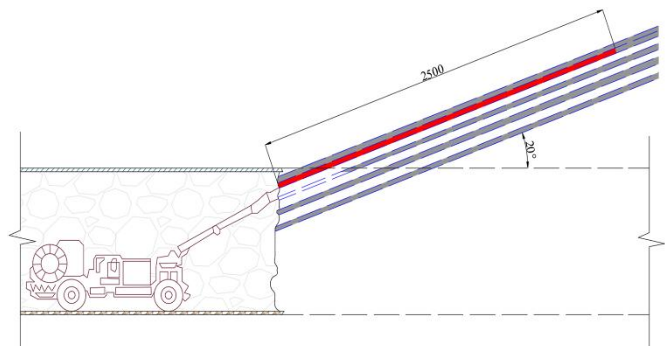

Figure 4. Schematic diagram of the process of epoxy reagent injection into the rock mass

The purpose of the drilling operations was to assess the increase in the mass stability and to compare the strength results obtained in laboratory conditions with the actual values obtained in the production environment.

The strength of the core sample under forced displacement (f_{vi}) and lateral compression stress (f_{pi}) are determined individually for each test sample:

$$f_{vi} = \frac{F_{i\,\max}}{2A_i}, \text{ MPa}; \tag{1}$$

$$f_{pi} = \frac{F_{pi}}{A_i}, \text{ MPa}, \tag{2}$$

where:

$F_{i\,\max}$ – the maximum displacement force value, N;

F_{pi} – the pre-applied compressive force, N;

A_i – the sectional area of the test sample, m^2.

The rock contact adhesion strength (f_{vi}) is determined by extrapolation to a value of $F_{pi} = 0$.

Tests aimed at studying the rock contact adhesion strength in core were conducted in laboratory conditions according to ISRM standard on UCT-1000 automated press, which fully meets the requirements set (Fig. 5).

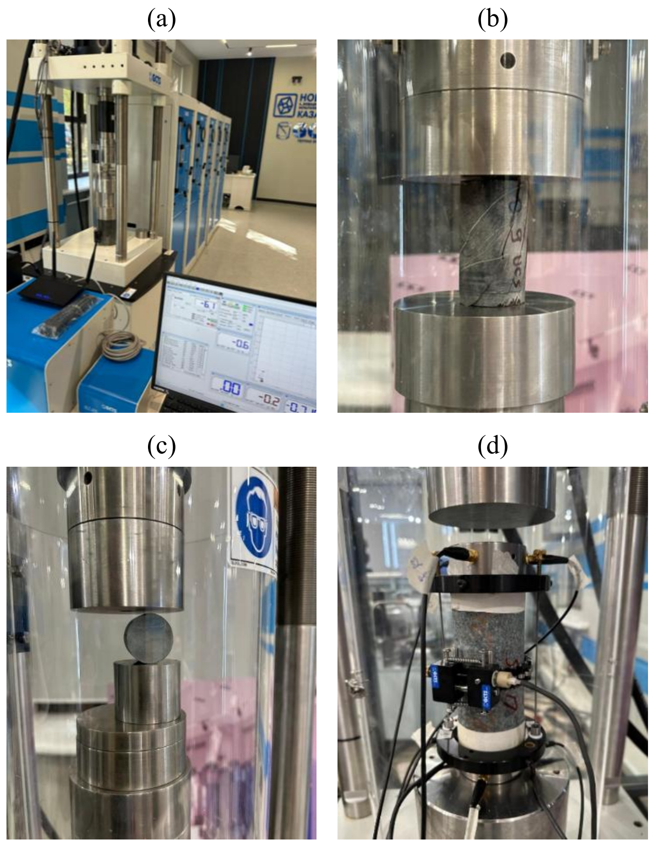

Figure 5. Process of testing core samples in laboratory conditions: (a) general view of the UCT-1000 unit; (b) testing of cores for uniaxial vertical compression; (c) testing of cores for uniaxial lateral compression; (d) testing of cores for uniaxial tension

To more accurately determine the possibility of safe mining-tunneling operations in the rock mass with specified strength parameters, the influence of mass stability on mining operations depending on the strength characteristics obtained during the tests was modeled and studied using the ANSYS Mechanical 14.5 software.

Many scientific research works are devoted to the methods of calculating loads acting on underground mine workings, their supporting and lining [49]-[55]. Despite the variety of computational schemes, they can all be classified into two main directions:

1) loads acting externally on the mine working or its support are assumed to be known in advance;

2) the loads acting from outside are unknown and are determined by analyzing the joint deformation of the mine working supporting system.

Thus, within our research, radial change for the elastic plasticity model of the rock mass is determined based on the limiting state of the rock mass around the mine working. According to the applied tunneling technology, in our conditions, the mass strengthened with epoxy reagent begins to provide strength already after 1 minute. However, given that its maximum strength characteristics appear after 12 hours, we assume that the mass strengthened using the chemical method will begin to perform its supporting function after the same period of 12 hours.

Construction of the rock mass model, strengthened with epoxy reagent, for driving the ore drift mine working in the eastern direction at the horizon +640 m along the Pologaya vein at the Akbakai mine is based on the following conditions. As previously stated, the mass through which the mine working extends is characterized by relatively low rock strength parameters, multiple fractures, including intrusive fractures and tectonic faults, which contribute to rock fragmentation. The cross-sectional dimensions of the design mine working remain the same as previously stated.

The design scheme (model) is performed in spatial projection with dimensions of 228.42×103.7 m and thickness of 1 m. According to the design model, the distance from the zero horizon to the mine working point is 640 m. There are 50 m wide areas on both sides of the mine working and 25 m wide areas at the bottom of the mine working. The boundaries of the design model fulfill the requirements of the static problem.

The physical-mechanical characteristics of rocks used to calculate static stability of the mass within the design model are given in Table 1.

To assess the reliability of the protective shield operation in the studied mass, consider three tasks based on different conditions:

– the first condition is to model the area as a monolithic medium;

– the second condition is to analyze the mine working located in the zone of unstable mass with a width of 10 m and a height equal to the total length of the design model;

– the third condition is the modeling of a mine working in the zone of unstable mass with the same width and height parameters, but additionally strengthened by a protective shield of 1 m thick.

3. Results and discussion

Based on the conducted research, it has been found that the destruction of core samples extracted from the protective shield and pre-strengthened with epoxy reagent occurred mainly in the contact zones of rock particles with the adhesive composition.

Table 1. Physical-mechanical properties of rocks used to calculate static stability of the mass

Physical-mechanical characteristics of the mass	First condition (monolithic medium)	Second condition (unstable mass)	Third condition (mine working under the protective shield)
Main rock in the mass	Granodiorite	Siltstone granodiorite	Siltstone granodiorite
Rock strength coefficient (f)	12-14	6-8	11-12
Elasticity modulus (E), MPa	$5.198 \cdot 10^4$	$9 \cdot 10^3$	$4.56 \cdot 10^4$
Poisson ratio (v)	0.24	0.22	0.23
Internal friction angle (φ)	48º	48º	48º
Inclination angle, deg.	90º	90º	90º
Calculated compression resistance (R), MPa	124.7	25	105
Structural weakening coefficient (μ)	0.3	0.4	0.3
Adhesion strength (c), MPa	0.20	0.035	0.13
Shear modulus (G), MPa	$2.10 \cdot 10^4$	$3.75 \cdot 10^3$	$1.63 \cdot 10^4$
Density (ρ), kg/m^3	2600	2700	2600

The percentage of newly formed fractures under the influence of external load did not exceed 15%. The forces applied directly to the samples ranged from 0.08-0.1 MPa, while those applied to the samples from the upper and lower sides ranged from 0.1 to 0.2 MPa. The process of destruction of core samples when they were strengthened began with the opening of the joints connecting the rock particles. Particle separation was observed when a force of 0.08 MPa was reached, and complete core sample destruction occurred at a force of 0.15 MPa. The test results are given in Table 2.

Table 2. Results of uniaxial compression and tensile strength tests on cores extracted from a rock mass, pre-strengthened with epoxy resin and PEPA based reagent at a ratio of 9:1

Sample No.	Core type	Reagent specific strength, MPa	Contact joint strength, MPa	Internal friction coefficient
1	Core sample extracted from the mine working roof	11.3	0.15 0.13 0.13	0.5
2	Core sample taken from the right side of the mine working	11.3	0.08 0.08 0.09	0.5
3	Core sample taken from the left side of the mine working	11.3	0.11 0.9 0.1	0.6

From the test results, a dependency graph of the adhesion strength of the epoxy protective shield with the mass on the value of external impact and lateral compression stress has been obtained. Correction factor calculated on the basis of graph data does not exceed 15% (Fig. 6).

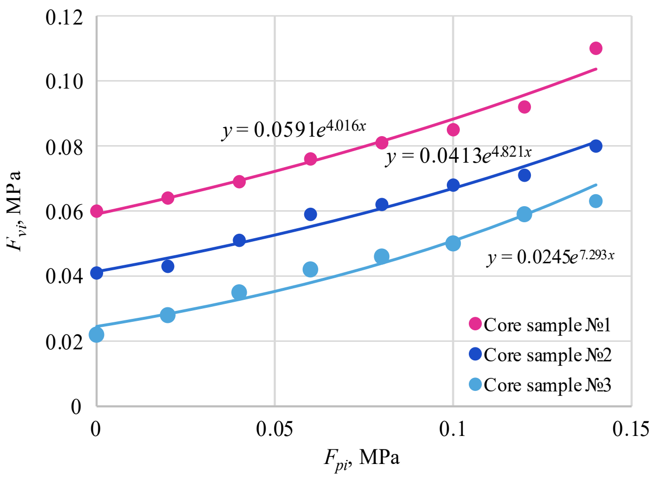

Figure 6. Dependence of adhesion strength and fixation of rock particles on the intensity of shear impact and lateral compression stresses

The analysis of Table 1 and Figure 6 shows that the maximum adhesion strength of the bonded rock particles is 0.15 MPa. This indicates an increase in strength of about 3 times compared to the natural strength of rocks fragmented by mineral salts (0.02-0.04 MPa).

The achieved increase in adhesion strength indicates the high efficiency of the epoxy reagent in unstable rock masses. A threefold increase in strength indicates a significant improvement in the mechanical properties of the rock, which is especially important for areas exposed to intensive impact of mineral salts, causing degradation of the mass structure. The use of epoxy strengthening makes it possible to compensate for strength losses caused by dissolution and leaching processes of rocks, as well as to minimize the risks of the formation of new fractures and cleavages.

In addition, the analysis of the obtained data shows that the particle bonding process not only increases the strength characteristics of the mass, but also contributes to its stability under external loads.

The results of calculations performed for the first task are presented in Figure 7. The determined values are presented in conventional units of measurement, since the ANSYS Mechanical 14.5 software package for modeling provides stresses in megapascals (MPa) and deformations in centimeters (cm).

As a result of the first task, the mine working modeling showed that the rock pressure does not experience significant changes. This is caused by the isotropic properties of hard rocks. The values of stresses and strains acting on the mine working remain extremely low. The maximum possible values of shear deformations on the different axes are: on the axis $X - C_{X1} = 2.65 \cdot 10^{-5}$; on the axis $Y - C_{Y1} = 6.52 \cdot 10^{-4}$; on the axis $Z - C_{Z1} = 6.17 \cdot 10^{-6}$; by total axes – $C_{XYZ1} = 7.54 \cdot 10^{-4}$.

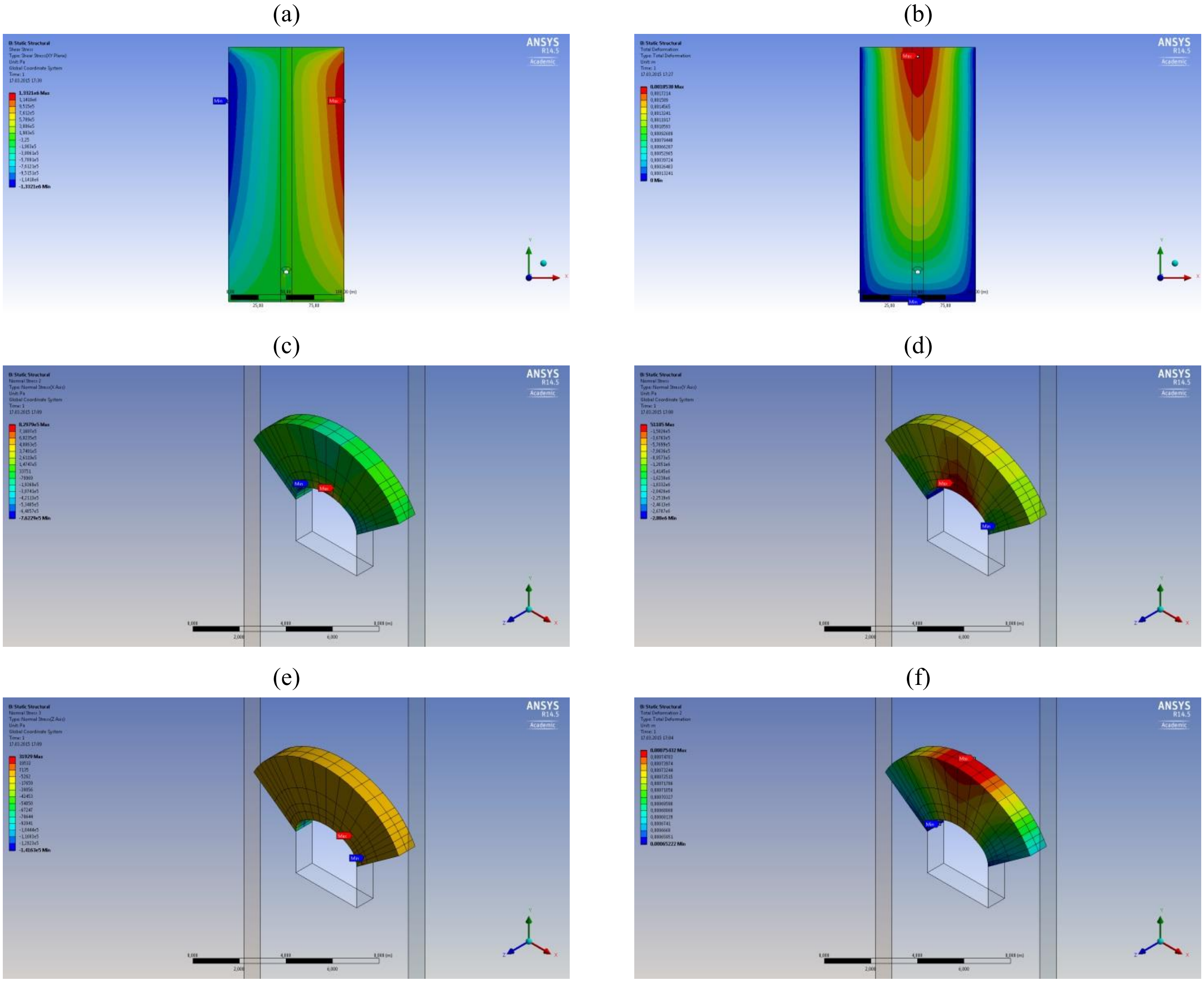

Figure 7. The results of calculations performed for the first task: (a) tangential stress of the design domain 1; (b) total displacement of the design domain 1; (c) stress on the axis X1; (d) stress on the axis Y1; (e) stress on the axis Z1; (f) total arch 1 displacement

The results of the calculations performed for the second task are presented in Figure 8.

The calculation performed for the second task showed the extremely unstable location of the mine working, as well as the possibility of caving or displacement of the rock mass in the mine working roof. The elasticity modulus of the rock in this case is $E = 9 \cdot 10^3$ MPa, indicating the presence of unstable rocks in the studied area. The maximum possible displacement value on the *X*-axis was $C_{X2} = 0.008$; on the *Y*-axis – $C_{Y2} = 0.022$; on the *Z*-axis – $C_{Z2} = 0.002$; and on total increase *XYZ* – $C_{XYZ2} = 0.1$.

The results obtained show that the rock displacement in the arch part of the mine workings can reach up to 10 cm, which indicates the probability of the arch caving in the process of mine working driving.

The results of the calculations performed for the third task are presented in Figure 9.

The solution of the third task showed that the fragmentary displacement of rocks in the arch part of the mine working on the model of the mass strengthened with epoxy reagent does not exceed 2 cm. The calculated values of displacements on the axes are: on the *X*-axis – $C_{X3} = 8.9 \cdot 10^{-4}$; on the *Y*-axis – $C_{Y3} = 4.5 \cdot 10^{-4}$; on the *Z*-axis – $C_{Z3} = 2.6 \cdot 10^{-6}$, and on total displacement – $C_{XYZ3} = 0.045$. This indicates the high efficiency of the epoxy reagent, which, penetrating between fractures and crevices in rocks, reliably binds them.

Comparison of the results obtained in the first task (monolithic stable medium) and the third task (strengthening using epoxy reagent) showed similar displacement and stress values. While the results of the second task, modeling the mine working in the zone of unstable mass, showed a 2-3 times increase in instability.

The developed technology of tunneling mine workings in unstable masses with the use of pre-strengthening, including the creation of epoxy protective shield based on the elements of the New Austrian Tunneling Method, has shown high efficiency in preventing failures in the conditions of the Akbakai mine and improving the safety of mining-tunneling operations in zones with unstable rocks containing mineral salts. The proposed method is recommended for use in the construction and operation of mine workings in similar geological conditions, which helps to increase the durability and safety of mining facilities.

The developed technology, based on the use of epoxy adhesive protective shield for bonding of rock fragments containing mineral salts, showing a tendency to cleavage and caving of the mine working arch, has shown its high efficiency.

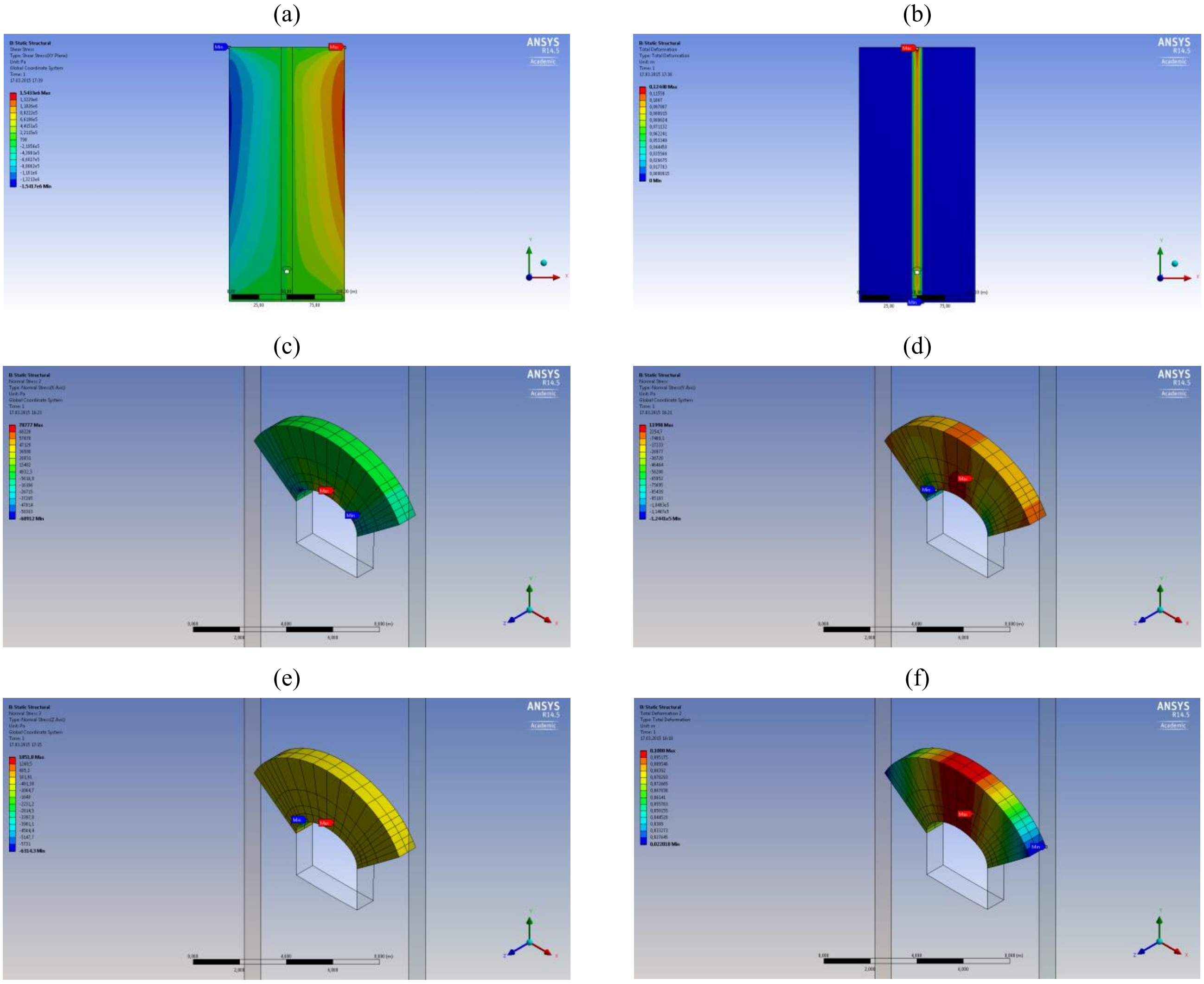

Figure 8. The results of calculations performed for the second task: (a) tangential stress of the design domain 2; (b) total displacement of the design domain 2; (c) stress on the axis X_2; (d) stress on the axis Y_2; (e) stress on the axis Z_2; (f) total arch 2 displacement

The use of epoxy reagent can significantly improve the bonding strength of rock fragments, increasing it up to three times compared to the original strength. This, in turn, significantly increases the rock mass stability and contributes to the safety of mining operations, reducing the risk of the mine working arch caving.

Comparison of the results obtained with the data of other scientific studies demonstrates the effectiveness of using epoxy reagents for strengthening of mine workings. In particular, studies show that the use of epoxy resins with the addition of nano-carbon materials helps to improve the strength properties of strengthened rocks.

Prospects for further research in the field of chemical strengthening of mine workings are related to optimization of epoxy reagent composition and its adaptation to different mining-geological conditions. One of the key directions is the development of modified compositions with improved mechanical characteristics, such as increased adhesion to different types of rocks and increased durability of the strengthened mass. It is also promising to study the effect of various additives, including reinforcing components and nanomaterials, which can increase adhesion strength and reduce fragility of the strengthened areas.

In addition, it is necessary to conduct research on the implementation of injection strengthening technologies using epoxy reagents in the conditions of real mining enterprises. This will make it possible to assess the effectiveness of the method at different depths of occurrence and shapes of mine workings, as well as to determine the optimal parameters for applying the composition. Automation of injection processes and quality control of strengthening remains an important aspect, which will require the development of specialized software solutions for monitoring the state of rock masses in dynamics.

4. Conclusions

As a result of the research, a technology for strengthening the rock mass containing chemically and mechanically unstable mineral salts using epoxy adhesive as a reagent has been developed and tested. The studies were conducted on the example of the Akbakai field, where the rock mass cleavage is associated with the presence of dolomite (7.4%), albite (6.6%) and muscovite (4.3%). These minerals contribute to cleavage and caving of the mine working arch, having low mechanical strength and weak adhesion ability.

Epoxy resin with PEPA catalyst in the ratio of 9:1 was used as strengthening reagent. This compound has demonstrated high efficiency in bonding of rock fragments, forming strong covalent and ionic bonds with metal atoms in the salt crystals, which has greatly improved their mechanical characteristics, enhancing the strength and stability of the rocks.

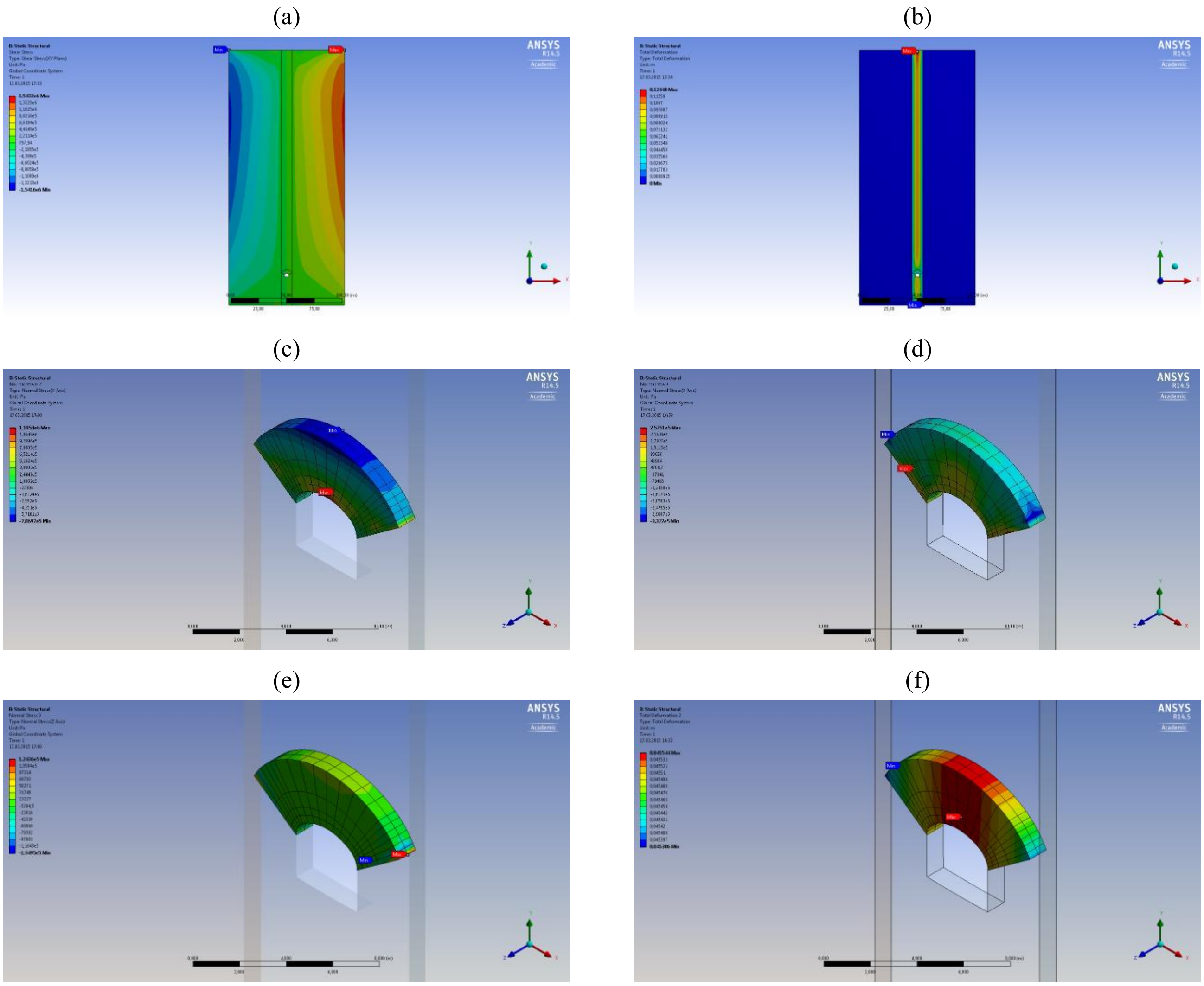

Figure 9. The results of calculations performed for the third task: (a) tangential stress of the design domain 2; (b) total displacement of the design domain 2; (c) stress on the axis X_2; (d) stress on the axis Y_2; (e) stress on the axis Z_2; (f) total arch 3 displacement

The technology of chemical strengthening of mine workings based on the method of pre-strengthening of the mass using the elements of the New Austrian Tunneling Method has been developed. This approach involves the creation of a protective shield by injecting a chemical reagent into unstable zones of the rock mass, which effectively increases its stability. The results of the research on core samples extracted from the Akbakai mine rock mass strengthened with epoxy reagent showed that failure occurred mainly in the contact zones of rock particles with the adhesive composition. The percentage of newly formed fractures did not exceed 15%. The forces applied to the samples ranged from 0.08-0.1 MPa, with ma-ximum adhesion strength of 0.15 MPa, which is 3 times higher than the strength of natural rocks exposed to fragmentation due to the presence of mineral salts (0.02-0.04 MPa).

The ANSYS Mechanical 14.5 modeling results confirmed that the maximum displacements and stresses in the strengthened areas were significantly lower than those in the non-strengthened zones, highlighting the effectiveness of using an epoxy reagent to prevent cleavage and caving. When modeling mine workings in the zone with unstable mass without strengthening, displacements and stresses were 2-3 times higher than in the strengthened areas. In particular, the maximum displacements on the *X*, *Y* and *Z* axes were 0.008, 0.022 and 0.002 m, respectively, while for the strengthened areas these values did not exceed 0.001 m, indicating a significant improvement in stability.

Author contributions

Conceptualization: YI; Data curation: YI; Formal analysis: DA; Funding acquisition: DA; Investigation: YI; Methodology: DA; Project administration: YI; Resources: DA; Software: ZK; Supervision: YI; Validation: YI; Visualization: ZK; Writing – original draft: YI; Writing – review & editing: YI. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Інноваційні підходи до стабілізації підземних виробок у нестійких гірських масивах шляхом створення попереднього захисного екрану

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Мета. Дослідження спрямоване на розробку технології хімічного закріплення гірничих виробок із використанням епоксидного реагенту для створення захисного екрану в нестабільних зонах гірських масивів, а також на оцінку міцності укріплених ділянок та підвищення стійкості виробок.

Методика. У ході дослідження проводилися випробування кернових зразків, вилучених з масиву, закріплених епоксидним реагентом, з метою оцінки їх міцнісних характеристик і стійкості до зовнішніх впливів. Чисельне моделювання виконувалось у ANSYS Mechanical 14.5 для аналізу напружено-деформованого стану укріплених та неукріплених ділянок.

Результати. Випробування кернових зразків, відібраних у руднику "Акбакай", показали, що руйнування в основному відбувається в зонах контакту породи з клейовим складом, при цьому частка нових тріщин не перевищує 15%. Міцність зчеплення становила 0.15 МПа, що втричі перевищує аналогічний показник для неукріплених порід. Результати моделювання підтвердили зниження напружень та зміщень в укріплених зонах у 2-3 рази порівняно з неукріпленими, що свідчить про високу ефективність запропонованого методу для підвищення стійкості гірничих виробок.

Наукова новизна. Вперше обґрунтовано інноваційний метод хімічного закріплення гірничих виробок із застосуванням епоксидного захисного екрану, який суттєво підвищує стійкість масиву при проведенні гірничих виробок в умовах впливу мінеральних солей та зовнішніх навантажень.

Практична значимість. Розроблена технологія хімічного закріплення гірничих виробок із використанням епоксидного захисного екрану має високу практичну значущість для гірничодобувної галузі. Її застосування дозволить значно підвищити стійкість гірських масивів, особливо в нестабільних зонах, схильних до впливу мінеральних солей, що сприяє підвищенню безпеки та довговічності гірничих виробок, зниженню ризиків обвалів і розшарування, а також підвищенню ефективності гірничопрохідницьких робіт.

Ключові слова: *гірничі виробки, стійкість масивів, склепіння, хімічне закріплення, міцність зчеплення, моделювання*

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