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Rock exfoliation in the unstable formations during underground mine working driving and selection of efficient adhesive compositions for strengthening

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Abstract

Purpose is to identify factors favouring rock exfoliation in roof of underground mine workings while operating Akbakay deposit and determine optimum structure of adhesive reagents for the rock strengthening taking into consideration mineralogical composition of the formation.

Methods. The research was carried out in a lab environment. Chemical and ultimate composition of the rock mass samples was determined through x-ray diffraction method; the x-ray phase identification approach helped define their mineralogical composition. The optimum composition of adhesive reagents has been determined based upon the ambient temperature and hardening time. Viscosity durability of the adhesive compounds was assessed using a technique of uniaxial crack of the immovable samples. Statistical data processing involved determination of the required number of the samples to achieve the preset accuracy degree.

Findings. Exfoliation of the fragments of both fractured and unstable rocks from Akbakai deposit depends upon availability of such chemically and mechanically unstable salts as dolomite, albite, and mirror stone. Epoxide reagent in 9 to 1 ratio with polyethylenepolyamine catalyzer has been identified as the most effective adhesive compound. Epoxy adhesives have demonstrated higher cohesive resistance to compare with polyurethane analogues, and better compliance with requirements as for viscosity and hardening time.

Originality. Use of epoxy to strengthen both fissured and unstable rocks of Akbakai deposit containing mineral salts, helps increase tensile properties up to three times. Moreover, epoxies also demonstrate high adhesive characteristics; and they are resistant to moisture and temperature attacks being typical for mine environment. New logarithmic dependencies have been identified describing rock mass stability while applying the modified polyurethane with polyethylenepolyamine catalyzer in 9 to 1 ratio.

Practical implications. Various types of reagents have been considered for safe and effective strengthening of underground mine workings in the fractured rock masses having a tendency to caving. The proposed adhesive reagents resist efficiently the external share loads and stresses increasing structural stability and safety of rock masses.

Keywords: *mine working, ore, rocks, exfoliation, strengthening, chemical reagents, cohesive resistance*

1. Introduction

One of the key strategic goals of the Republic of Kazakhstan under the conditions of the current political and economic instability is to improve welfare of the country owing to technological breakthrough. The goal achievement involves innovative development of industrial sector; intensive use of production possibilities; and upgrading of managerial system as well as economic activity mechanisms through the use of efficient approaches [1], [2].

As part of measures intended to achieve the strategic goals, efficient methods are considered as for development of mineral resources of the country inclusive of discovery of new deposits as well as upgrading of operating ones [3]-[6]. The activities to commission new fields or upgrade productivity and quality of operating mining enterprises are connected with underground driving of different-purpose mine workings [7], [8]. The key factors to make technological decisions while such mine working driving and intensify development of the minerals are features of geological structure formation; stress state of the rock mass; and other mining and geological characteristics [9]-[13].

It should be mentioned that use of powerful technical and productive technologies in the process of road-heading in the unstable and prone-to-caving rock masses is limited considerably. The abovementioned results in sharp performance degradation as well as diminution of security of such operations [14], [15]. The traditional road-heading, supporting, and safety ensuring of underground mine workings under

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such complicated geological conditions involve considerable labour contribution and financial resources; in addition, they cannot provide adequate level of professional safety [16].

Unfortunately, numerous mineral deposits in our country are characterized by complex mining and geological conditions [17]-[19]. As it has been abovementioned, development of such fields and driving of underground mine workings in unstable rock masses result in a great number of difficulties and challenges. Currently, mines of the leading national gold manufacturer, arranged within Akbakay deposit, demonstrate problems connected with rock masses influencing negatively the production intensity [20]. Akbakay, Aksakal, Beskempir, Duman-Shuak, Karyernoe, Kenzhem, and Svetinskoye mines develop the fields of Akbakay industrial area (Fig. 1).

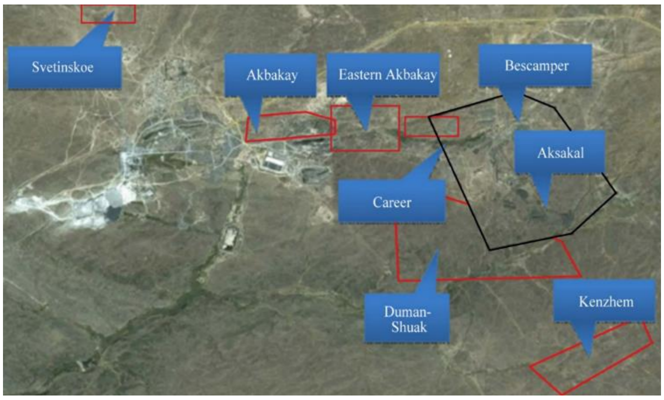

Figure 1. Plan of the industrial area of Akbakay deposit

Consideration of physicomechanical characteristics of rocks within Akbakay deposit should involve such a note that strength factors are rather high, i.e.: 135 MPa for average compressive strength of granodiorite; 160 MPa for average compressive strength of chert sandstone; 166 MPa for average compressive strength of quartz ore; and 125 MPa for average compressive strength of beresite. Lamprophyre dikes demonstrate the least strength value where compressive strength is 90 MPa [21].

In addition, the fields have single tectonic sub-meridianal extension faults and small fractures towards the directions [22]. The following belongs to factors complicated the deposit development: dikes, forming the ore, are fractured, and their structure is of the mottled nature; and significant fissility occurrence is observed in the intersection area of the quartz veins [23], [24]. Numerous fissures of the field are filled with mild clay; in this regard, fracturing ratio is 0.011-0.008.

Concentration of commercial reserves (i.e. useful minerals) of the deposit is stipulated by the fractured disturbances. It is characterized by the veined structure consisting of beresite quartzes with heavy (65-86°) and gentle (40-50°) dip. Ore veins are directed northerly; their bearing is significant; and thickness of the veins is 0.2-4.0 m [25].

In the zone of Akbakay deposit, five steep dipping ore veins have been identified: Glavnaya, Tukenov, Oktyabr, Frolov, and Zolotaya as well as the four low-angle ones: Yubileynaya, Glubinnaya, Pologaya, and Yuzhnaya [26]. In this context, the zone belongs to gold-quartzitic and low-grade sulfide ore area. The ore vein contains quartz, pyrite, and arsenopyrite; nonmetallic minerals are represented by calcite, sericite, chlorite, chalcopyrite, sphalerite, galenite, and black antimony [27]-[29].

Currently, development of ore vein Pologaya occurred within the eastern flank of Akbakay deposit, demonstrates significant decline in mining output; the abovementioned has resulted in 10% decrease of the total operating efficiency of the ore mine. One of the reasons is caving of exfoliating rocks from a domic roof share arising from sublevel mine working driving along Pologaya ore vein at +640-m level (Fig. 2).

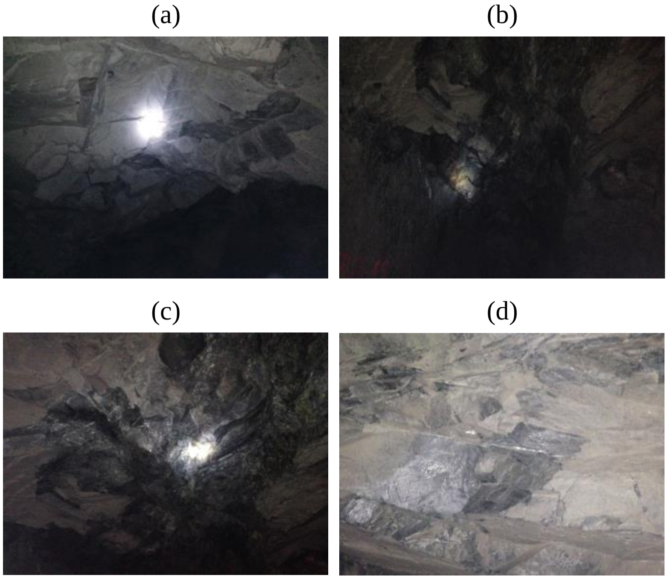

Figure 2. Caving of the rock mass layers while sublevel drift driving along Pologaya ore vein at +640-m level, Akbakay ore mine

Sizable rock mass caving within the domic roof share while driving eastern flank of sublevel drift 2 along Frolovskaya vein at +520-m level should also be mentioned (Fig. 3).

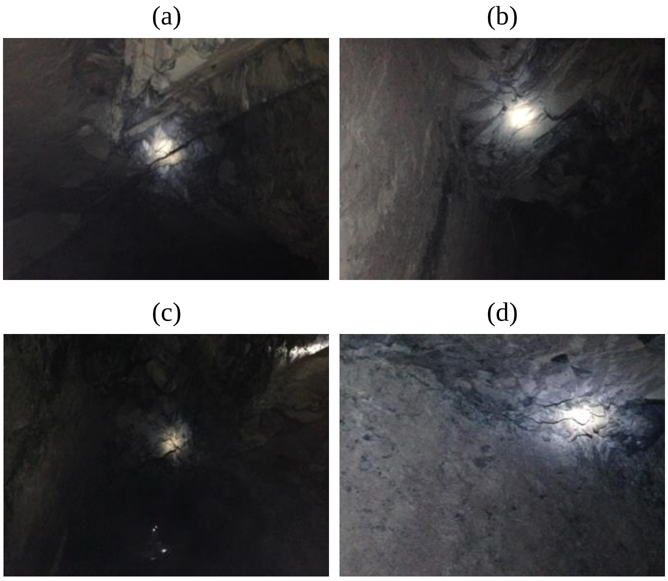

Figure 3. Rock mass caving within the domic roof share while sublevel drift driving along Frolovskaya vein

In the area, rock mass is characterized by significant fissility and minor tectonic disturbances. Average fissure geometry is 1.5-2.0 mm. Moreover, within the ore groups-rock contact zone, shear chlorite-carbonaceous minerals occur as well as calcite bodies. Rock mass caving appears in the form of exfoliating fall of minerals near the mine working roof (Fig. 4).

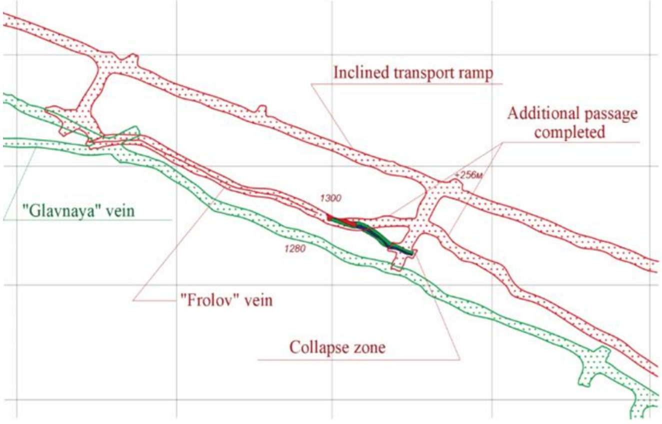

Figure 4. Caving schedule at +520-m level of Akbakay field

Since it is impossible to penetrate sublevel drift 2 in the design direction, a decision has been made as for correction of the road-heading route. As Figure 4 shows, the road-heading passes over the caving easterly and westerly. In the area, ore vein is relatively stable; however, considerable fissility volume in different directions is observed. In view of exfoliating rock caving in the domic roof share, a decision has been made to provide stability while mine working driving through the use of steel arch.

The performed analytical and research activities have helped understand that frequent caving of the domic roof share resulting from undetermined reasons of rock exfoliation within the mine working roof area in the eastern flank of Akbakay deposit factors into 9-12% decrease in the scheduled capacity of the mine (under annual production of the mine for 2023 being 325000 tons, its effective output was 295000 tons). Moreover, taking into consideration the undeveloped ore volume at 240 m, arising from caving during sublevel drift 2 driving along Frolovskaya vein within a level +520 m of Akbakay ore producer, it is possible to state that the analyzed problem is quite topical.

In addition, bearing in mind the expenditures connected with supporting materials used for mine working driving as well as the vital fact of danger for personnel operations, it becomes obvious that until the problem solution is not developed and implemented, it will not be impossible to provide efficient, safe, and qualitative underground mining.

To solve the problem, the specific laboratory research has been carried out identifying the reasons of the rock mass exfoliation, and substantiating selection of an adhesive material able to provide stable strengthening of the formation consisting of similar rocks.

2. Methods

2.1. Analysis of chemical composition of the rocks

The Chapter describes definition of chemical and material composition of samples resulting from the X-ray phase analysis and spectophotometery. To identify the reasons of rock mass exfoliation within Akbakay deposit, samples of rocks, having a tendency to caving, were taken from the mine zones being extracted including Frolovskaya vein at +520-m level; Pologaya vein at +640-m level; and Svetinskoye mine at +318-m level.

Analysis of the rock samples taken from the deposit started from determination of their chemical and ultimate composition. For the purpose, an x-ray diffraction method was applied making it possible to describe crystal phases of the samples. The approach helps x-rays to study crystalline structure of the samples in their natural conditions and identify separately different modifications in the composition. DRON-3 diffractometer was applied.

After determination of a chemical and ultimate composition of the rock samples, their material structure was analyzed. To do that, the X-ray phase study was performed. Using D8 Advance device, X-ray phase analysis was carried out with α-Cu voltage in a tube being approximately 40/40. EVA software processed the obtained diffractogram data as well as calculated interplanar distances.

Digital spectrophotometric analysis was performed using Lambert-Bouguer-Beer approach, which helped formulate following mathematical Equation (1):

$$E = K \cdot C \cdot d \,, \tag{1}$$

where:

E – extinction or optical density;

K – extinction ratio (the indicator is constant for accurate optical wavelength);

C – concentration of the analyzed material;

d – thickness of the radiated layer.

The infrared spectrophotometers record optical transmission and optical absorption coefficients by incident rays in terms of percentage points. Transmission coefficient-extinction ratio is described using following Equation:

$$T = \frac{I}{I_0} = e^{-KCd} \,, \tag{2}$$

where:

I_0 – radiant power incoming to the test material;

I – radiant power penetrating through the sample layer which thickness is d.

While calculating numerical value of an extinction ratio, its amount is expressed in concentration units (i.e. mol/l) where $l \cdot cm^{-1} \cdot mole^{-1}$ are units of a molecular index.

According to Lambert-Bouguer-Beer pattern, absorbancy of a sample is the total of transmission densities of all its components. Mathematically, the ratio can be written as follows:

$$\left(l_g \frac{J_0}{J} \right)_{try} = \sum_{i=1}^{N} \left(l_g \frac{J_0}{J} \right)_i \,, \tag{3}$$

where:

$l_g \frac{J_0}{J}$ – absorbancy;

N – the number of components.

Nevertheless, while the spectrometer setting for radiation velocity ν, passing through exit slit, the readings may show 2-3% deviations. Hence, to achieve the maximum accuracy, integral intensity should be involved while determining the absorption strength. Integral intensity can be defined using following ratio:

$$A = \int_{-\infty}^{+\infty} k_v dv = \frac{1}{C \cdot d} In \frac{I_0}{I} dv \,, \tag{4}$$

where:

v – a wave number.

The samples, prepared using KBr in 1:400 mass ratio with the help of a hand-operated press SPESTRA-TECH, were measured in such ranges: 421-469 cm^{-1} belonging to deformation vibrations δ(O-Si(Al)-O) and δ(O-Si-O); 749-792 cm^{-1} corresponding to symmetrical valence vibration; and 1032-1081 cm^{-1} belonging to antisymmetric valence vibrations νas(Si-O-Si) and νas(Si-O-Al(Si)). After absorption in terms of 1634 cm^{-1}, it corresponds to the crystallized water being available in the aluminum silicate composition.

2.2. Assessing adhesive behaviour of various compounds

Test two was focused on the analysis of composition of adhesive agents, and selection of their optimum structure for the efficient adherence of rocks containing mineral salts. The study took into consideration mineralogical composition of samples from Akbakay deposit identified during previous laboratory analyses; the abovementioned has made it possible to develop adequate procedures for adhesion of the samples involving their physicochemical properties.

The crushed rock fragments were applied which helped obtain the most accurate data on interaction of the adhesive agents with different mineral components. Assessment of adhesive characteristics included use of such adhesives as cement; liquid glass silicate; modified polyurethane; epoxy adhesive in different proportions; bitumen; and primers [30], [31]. As part of the research, such various parameters were studied as adhesion period; adhesive strength; resistance to external influence; and durability of the adhesives.

Analysis of chemical interaction of the bonding agents with rock elements was among the key moments of the research. Minerals (namely, quartz, dolomite, and albite) impact adherence process; correction has been made as for composition of the certain bonding agents for the best result achievement. For example, field spar containing aluminium and silicium played important role in the catalysis of adhesive reactions of epoxies, which improved strength of the adhesives [32]-[34].

The special attention has been paid to mechanical properties of the bonding agents as well as to their economic efficiency. Both industrial and modified compositions have been tested which helped identify decisions being optimal from the viewpoint of cost and efficiency. The results have shown that the modified polyurethanes and epoxies differ in the best adhesive characteristics, and provide stable and durable junction of rocks even under the conditions of high loads and wet environment. Additionally, resistance of the bonding compounds to chemical decay and disintegration, resulting from the availability of such mineral salts as dolomite and mirror stone in rock samples, was analyzed.

2.3. Strength tests of the cemented rock samples

To carry out the research, eight pairs of 15×10×2 cm plates were cut from rock samples taken within unstable formation of Akbakay deposit containing such mineral salts as dolomite, albite, and mirror stone. Before pasting together, the plates were moistened to ensure compliance with natural conditions. The prepared four pairs of plates were glued using the modified polyurethane adhesive; and epoxy-based cement was applied for the other four pairs (Fig. 5).

Eight pairs of the glued plates were stored in moist environment simulating mine conditions. The glued-together rock samples were tested in twelve hours, twenty-four hours, seventy-two hours, and two hundred and forty hours after the adherence. Tensile machine IR-5046-5 was applied to test strength of the adhesives while bonding the rocks (Fig. 6).

The first tests of the samples were carried out after twelve hours. For the purpose, one sample glued using polyurethane adhesive and one sample glued using epoxy-based cement were selected and analyzed with the help of a tester (Fig. 7).

Figure 5. Conglutination of the plates from rock samples

Figure 6. Testing with the help of IR-5046-5 device

(a) (b)

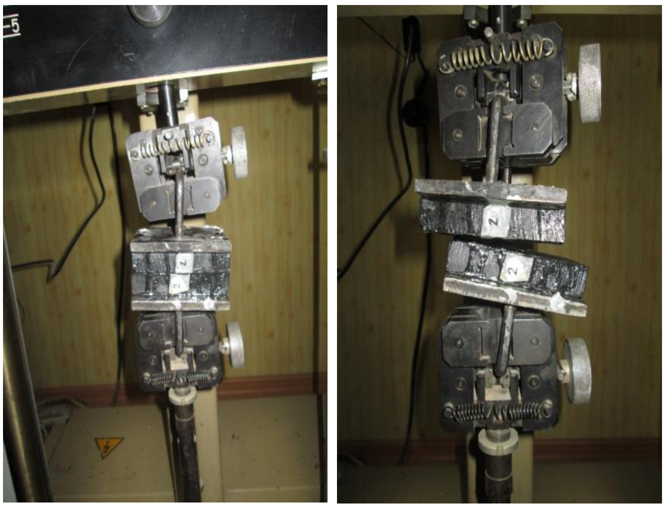

Figure 7. Uniaxial breaking test as for adhesive strength of the samples cemented using polyurethane adhesive and epoxy: (a) before testing; (b) after testing

Taking into consideration the fact that the adhesives are intended to be applied in mining industry, namely for rock mass strengthening while driving underground mine workings in unstable formations where the main task is reinforcement of rocks having a tendency to exfoliation and fragmentation, the decision has been made that study of adhesive strength of the glued samples will become the key factor while making the ultimate selection of an optimum binding material type.

3. Results and discussion

3.1. Analysis of ultimate and mineral composition of the rock samples

Laboratory tests have been carried out to study in detail chemical and mineral composition of rock samples taken from Akbakay deposit. The fundamental goal was to identify quantity of the key chemical elements as well as availability and distribution of the minerals in the samples. The data are important to understand composition of rocks; assess their physical properties; and evaluate their potential to be used in the process of various mining or construction activities. Table 1 demonstrates the results of ultimate analysis of rock composition.

Table 1. Chemical ultimate composition of the rocks sampled form Akbakay deposit

No.	Chemical element	Average concentration, %	Intensity of rays in terms of relative units
1	Ferrum (Fe)	33.023	807.26
2	Calcium (Ca)	5.056	41.13
3	Kalium (K)	13.001	45.32
4	Titanium (Ti)	1.329	18.79
5	Manganese (Mn)	0.147	3.12
6	Sulfur (S)	3.317	1.57
7	Aluminium (Al)	28.326	0.92
8	Silicium (Si)	15.399	1.13
9	Chrome (Cr)	0.052	1.11
10	Strontium (Sr)	0.200	2.96
11	Arsenium (As)	0.150	2.67

ASTM database and Search/Match functions have helped identify the test data as well as the sample phases (Fig. 8). The probable error assessment of the semi-digital analysis is ±5%.

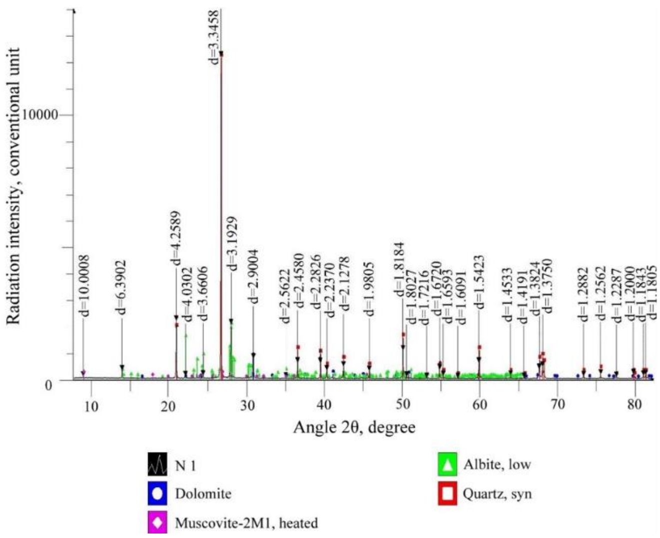

Figure 8. Diffractogram diagram obtained while rock sample analyzing with the help of D8 advance device

Relying upon the physicochemical analysis results, the selected from the deposit mineral samples consist of the four components: dolomite, mirror stone, albite, and quartz. Slow dissolving of the tested rock sample in a cold HCl supported dolomite availability in the sample cavities. It has been identified that dolomite content ($CaCO_3$-$MgCO_3$) is 7.4%.

Content of quartz, represented in the sample in the form of crystalline silicon dioxide, is 81.7%. Its density is 2650 kg/m³; mineralogical hardness is 7; and compressive resistance achieves 2000 MPa. At room temperature of the laboratory, quartz does not react to acids and alkalies.

The third component identified in the sample is field spar formed resulting from reaction between silicon oxides and aluminium with alkali metal oxides. Within the tested sample, field spar has been defined in the form of albite (Na_2O, Al_2O_3, $6SiO_2$) in the amount of 6.6%; it belongs to plagioclase group. Field spars vary in colour from white to purple and pink; their density is 2500-2760 kg/m³; hardness is 6; and compressive resistance achieves 170 MPa.

The fourth component, mirror stone, is represented in the form of mineral salt. Its content in the sample is 4.3%. Mirror stone ($KAl_2(AlSi_3O_{10})(OH)_2$) cleaves easily in thin plates which confirms its crystalline structure. The mineral density varies from 2760 up to 3200 kg/m³; and its mineralogical hardness is 2-3.

As it has been abovementioned, X-ray phase analysis of rock samples from Akbakay deposit showed availability of field spar with red structure. Since the mineral is of a red structure, it was analyzed additionally using digital-based infrared spectroscopy [35].

During the research, absorption in the infrared spectroscopy was recorded with the help of Fourier spectrometer NICOLET 5700 by Thermo Electron Corporation Company; concentration range is 400-4000 cm⁻¹ (Fig. 9).

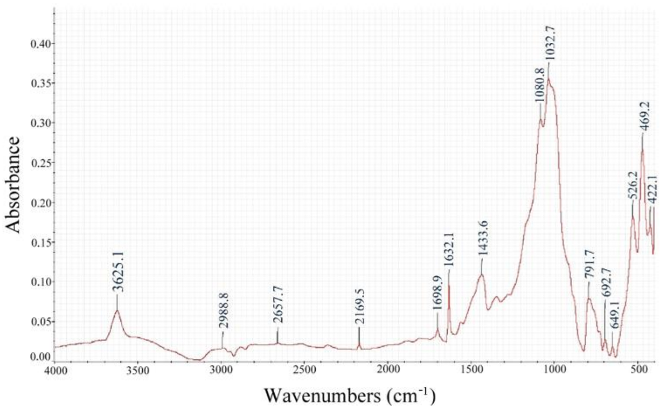

Figure 9. Infrared spectrum of the mineral absorption

The research has helped understand that the samples taken within Akbakay deposit contain chemically and mechanically unstable mineral salts. Namely, dolomite ($CaCO_3$-$MgCO_3$) is 7.4% of the total amount; albite (Na_2O Al_2O_3 $6SiO_2$) is 6.6%; and mirror stone ($KAl_2(AlSi_3O_{10})(OH)_2$) is 4.3%.

Among the listed compounds, dolomite differs in the greatest instability; it dissolves slowly under the effect of atmospheric moisture. Field spars also subject to failure resulting from mechanical and chemical weathering. In turn, mirror stone has a tendency to easy splitting into thin plates due to its crystalline structure.

3.2. Adhesion efficiency while cementing rock fragments

As a result of the experiments, both small and large fragments of rocks were adhered; optimum adherence conditions were identified; several types of adhesive compounds were developed and tested; and the most efficient bonding adhesives were defined. Table 2 shows test data of the applied adhesives as well as their efficiency as for adhesive bonding of rocks.

Table 2. Efficiency factors of various adhesive compounds while adhesive bonding of rocks (room temperature is 24°C)

No.	Adhesive compound type	Adhesion interval, hours	Fraction of sample geometry, mm	Adhesion indicators
1	Cement grade M400	24	5.0-10.0	Bad
2	Liquid silicate-based cement	24	7.0	Bad
3	Modified polyurethane	0.5	10.0-15.0	Perfect
4	Epoxide resin (3:1 ratio)	24	7.0-20.0	Average
5	Epoxide resin (9:1 ratio)	12	7.0-20.0	Perfect
6	BND bitumen 60/90	24	5.0-10.0	Bad
7	Bitumastic enamel	24	5.0-10.0	Bad
8	Primer	24	7.0-10.0	Very bad

Figures 10-15 demonstrate results of adhesive bonding of rock samples using different adhesives.

(a) (b)

Figure 10. Rock samples taken from the unstable formations of Akbakay deposit: (a) are small rock fractions (i.e. 5-10 mm); (b) are large rock fractions (i.e. 15-20 mm)

(a) (b)

Figure 11. Rock samples: (a) being bonded by means of liquid silicate glass; (b) being bonded by means of epoxy with polyamine hardener (3:1 ratio)

It has been identified during the research that adhesion properties used to bond reliably rock samples improve significantly if high molecular resins are applied in combination with polyamine reagents and polyurethane adhesives (Figs. 12, 13). Adhesive bonding interval for two crystals using polyurethane adhesive is 5 to 30 minutes; at the same time, epoxide adhesive compounds need longer period for complete hardening lasting up to twelve hours.

Numerous types of gluing reagents demonstrating the best adhesive characteristics, are produced industrially in large volumes and differ in moderate cost.

(a) (b)

Figure 12. Bonding of rock fragments using a gluing reagent consisting of epoxy and polyamine hardener (9:1 ratio): (a) are large fractions; and (b) are small fractions

(a) (b)

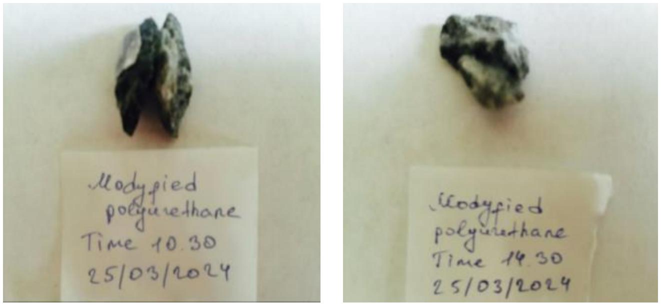

Figure 13. Bonding of rock fragments using the modified polyurethane: (a) if adhesion area is small; (b) if adhesion area is large

(a) (b)

Figure 14. Rock samples bonded with the help of a cement mortar: (a) are large fractions; (b) are small fractions

(a) (b)

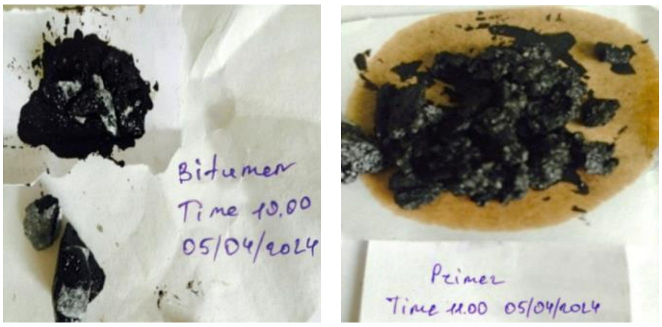

Figure 15. Rock samples bonded using: (a) asphalt mortar; (b) primer

1. The general structural formula of a polyurethane adhesive is as follows:

$$[-\underset{\underset{O}{\|}}{C}NH-(CH_2)_6-NH\underset{\underset{O}{\|}}{C}O-(CH_2)_4\,O-]_n .$$

It has been identified that in addition to diffusion and adhesion properties, polyurethane adhesive also has cohesive characteristics.

While adhesing, polyurethane adhesive react to moisture from air (or from rock sample surface); moreover, reaction between isocyanates and polyols may also be included.

Isocyanate reacts to water releasing carbon dioxide (CO_2) deriving amine. In turn, the latter reacts to secondary isocyanates deriving urea:

$R–NCO+H_2O \rightarrow R–NH_2+CO_2 \uparrow$;

$R–NCO+R–NH_2 \rightarrow R–NH–CO–NH–R$.

The principal reaction forming polyurethane chain is as follows:

$R–NCO+R'–OH \rightarrow R–NH–CO–O–R'$.

Resulting from the reaction, urethane links are formed (-NH-CO-O-); while contacting with rocks, it penetrates into the surface substratum layer and initiates synthesis of cohesion compounds. The interaction between two joinable rock fragments and adhesive composition factors into formation of mechanical adhesion; activates polymerization process; and favours buildup of a firm polyurethane network structure.

2. The general formula of epoxy is as follows:

$CH_2-CH-R-[-O-Ar-ORCH-CH_2]_n-O-Ar-R-CH-CH_2$

\ / | \ / .

O OH O

If polyethylenepolyamine is added to epoxy at 9:1 ratio and air temperature, the bonding adhesive starts hardening rapidly. Epoxies and polyethylenepolyamine undergo hardening reaction in terms of which epoxy resin groups interact with amino groups of the hardener; as a result, 3D polymer network is shaped. The epoxy group-amino group interaction can be described as follows. Epoxy group opens, and reacts to amino group of the hardener deriving secondary amino group:

$R–CH_2–CHOCH_2–R'+H_2N–R–NH_2 \rightarrow$
$\rightarrow R–CH_2–CH(OH)–CH_2–NH–R–NH_2–R'$.

Use of the epoxy composition factored into dissolution of a layer of contacting surfaces of rock fragments where metals and oxides (Si – 15.4%, Al – 28.32%, and Fe – 33.03%) reacted to an adhesive cement deriving chelate and organoelemental compounds being similar to salts. The availability of quartz (81.7% SiO_2) in the tested rock sample favoured catalysis of epoxide group opening in the adhesive composition; the abovementioned resulted in the adhesive dissolution as well as small particles at the rock surface providing solid mechanical bond.

Relying upon the results of the laboratory tests including assessment of strength characteristics, safety of use, environmental safety, and economic efficiency, polyurethane adhesive and epoxide reagent prepared with polyethylenepolyamine at 9:1 ratio were recognized as optimal.

Following problem of our research is to identify hardening regularities of the adhesive compounds and mechanical strength while pasting together rocks from Akbakay deposit containing mineral salts.

3.3. Strength tests of the cemented rock samples

While testing the key properties of polyurethane and epoxide adhesives defined as optimal according to the previous research findings, it has been defined that they demonstrate similar performance. The main difference between the two adhesives is their hardening periods: the modified polyurethane adhesive achieves its complete hardening during thirty minutes; in turn, it takes epoxy twelve hours to become as durable as possible. Nevertheless, even such a difference prevents from defining unambiguously which of them is perfect.

After twelve testing hours, adhesive strength of samples cemented by means of polyurethane adhesive was 0.07 MPa; the samples cemented with the help of epoxide adhesive demonstrated strength at the level of 0.099 MPa. Similar tests were carried out in twenty-four hours, seventy-two hours, and two hundred and forty hours. Table 3 shows findings of the research.

Table 3. Testing results of uniaxial tensile strength of bonds of rock samples cemented using polyurethane and epoxide adhesives

Types of adhesive compounds	Testing conditions	Adhesion under uniaxial tensile strength, MPa			
		Twelve hours	Twenty-four hours	Seventy-two hours	Two hundred and forty hours
Modified polyurethane	Moist air environment	0.070	0.073	0.073	0.072
Epoxide reagent with polyethylenepolyamine at 9:1 ratio	Moist air environment	0.099	0.130	0.133	0.133

Testing results concerning adhesive strength of rock samples pasted together with the help of the modified polyurethane and epoxy have shown that the latter demonstrates rather higher rates under uniaxial tensile strength to compare with the former. After twelve hours of application, epoxy composition achieves strength being 0.999 MPa which exceeds the maximum polyurethane index (i.e. 0.073 MPa) observed during the whole research period.

Adhesive strength of epoxy goes on its increase during the first twenty-four hours achieving 0.13 MPa, and stabilizes at a level of 0.133 MPa after seventy-two hours. Further changes are not observed; hence, the adhesive achieves its ultimate strength. To the contrary, polyurethane adhesive demonstrates only minor strength increase during the initial twelve hours; later, the value remains almost invariable (i.e. 0.073 MPa) during following twenty-four hours. The abovementioned denotes its fast stabilization; nevertheless, its ultimate strength characteristics are lower to compare with epoxy.

Consequently, epoxy differs in higher ultimate adhesive strength as well as in longer hardening process, which can be considered as advantage and disadvantage depending upon its use environment. Polyurethane adhesive demonstrates rapid maturing being preferable if rapid fastening of joints is required; however, its ultimate strength inferiors significantly to epoxy composition. Figure 16 shows the obtained dependence.

The research of adhesive strength of rock samples pasted together by means of polyurethane and epoxy has shown that adhesive strength of epoxy exceeds adhesive strength of polyurethane. The maximum strength of polyurethane adhesive is 0.073 MPa in terms of uniaxial tension; at the same time, the value is 0.133 MPa for epoxy.

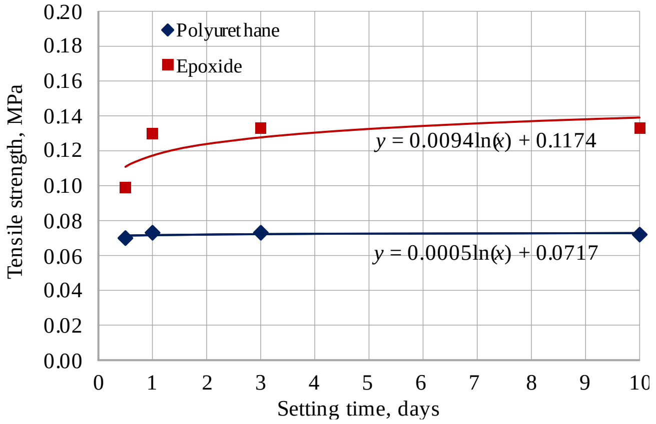

Figure 16. Dependence of the uniaxial tensile strength of rock samples pasted together by means of polyurethane and epoxy upon the hardening time

Moreover, the analysis of strength characteristics has demonstrated that adherence process of rock fractions starts from the first minutes. In this regard, the cementing agents achieve 90% of their ultimate strength at once; the remained 10% progress during twenty-four hours.

Under the conditions of Akbakay mine, the dependence of uniaxial tensile strength upon a hardening period of the rock mass pasted together using the modified polyurethane adhesives is expressed through $y = 0.0005 \ln(x) + 0.0717$ equation. In turn, as for rock mass pasted together using polyethylenepolyamine catalyzer in the 9:1 ratio, strength in terms time is defined using $y = 0.0094 \ln(x) + 0.1174$ function.

4. Conclusions

The research has helped draw following conclusions. The research effort has shown that rock mass exfoliation within Akbakay deposit depends upon chemically and mechanically unstable mineral salts being available in its composition, i.e. 7.4% of dolomite ($CaCO_3$-$MgCO_3$); 6.6% of albite ($Na_2O \cdot Al_2O_3 \cdot 6SiO_2$); and 4.3% of mirror stone ($KAl_2(AlSi_3O_{10})(OH)_2$). Dolomite is the most unstable among them since it dissolves slowly under the atmospheric moisture effect disturbing strength of rock adhesion. Field spar subjects to disintegration under mechanical and chemical influence; while segregating into small fissures, mirror stone is prone to disturbance of continuity of the material structure.

As for chemical procedure of unstable formation strengthening within Akbakay deposit where mineral salts are available, mixture of epoxy and polyethylenepolyamine catalyzer in the 9:1 ratio is the optimum choice.

As part of epoxy, rock samples consisting of crystals of Ca, Mg, and Si salts interact with various functionally active groups (i.e. OH; COOH; esters etc.) forming covalent and ionic links with hydroxide group in the crystal and metal atoms. The abovementioned provides stable bond between two rock fragments.

Hardening period of the modified polyurethane adhesive is thirty minutes; the maximum viscosity is 468 MPa·min. A hardening period of epoxy elongates to twelve hours; the maximum viscosity is 480 MPa·min. Temperature conditions influence heavily the adhesive hardening time. A catalyzer added to the adhesive composition accelerates reaction achieving he maximum velocity at an ambient temperature being +20°C.

Author contributions

Conceptualization: DA; Data curation: BBa; Formal analysis: DA; Funding acquisition: DA; Investigation: BBe; Methodology: BBe; Project administration: DA; Resources: BBa; Software: BBe; Supervision: DA; Validation: BBe; Visualization: BBe; Writing – original draft: DA; Writing – review & editing: BBa. 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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Відшарування порід у нестійких масивах при проведенні підземних гірничих виробок та підбір ефективних хімічних зв'язувальних складів для їх зміцнення

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Мета. Виявлення факторів, що сприяють відшаруванню гірських порід у покрівлях підземних виробок під час експлуатації родовища "Акбакай", а також визначення оптимального складу адгезійних реагентів для зміцнення гірських порід з урахуванням їх мінералогічного складу.

Методика. Дослідження проводились у лабораторних умовах. Хіміко-елементний склад зразків гірничої маси визначений методом рентгенівської дифракції, мінералогічний склад – методом рентгенівської фазової ідентифікації. Оптимальний склад адгезійних реагентів встановлений на основі температури навколишнього середовища та часу затвердіння. Міцність в'язкості клейових складів оцінювалася методом одновісного розриву закріплених зразків. Статистична обробка даних включала визначення необхідної кількості зразків задля досягнення заданого ступеня точності.

Результати. Відшарування уламків тріщинуватих і нестійких гірських порід родовища "Акбакай" обумовлено присутністю хімічно й механічно нестабільних солей, таких як доломіти, альбіти та мусковити. Найбільш ефективним клейовим складом для зміцнення нестійких гірничих мас визначено епоксидний реагент із додаванням каталізатора ПЕПА у співвідношенні 9:1. Епоксидні клеї показали більш високу міцність зчеплення порівняно з поліуретановими аналогами та кращу відповідність вимогам щодо в'язкості та часу затвердіння.

Наукова новизна. Використання епоксидного клею для зміцнення тріщинуватих і нестійких гірських порід родовища "Акбакай", що містять мінеральні солі, дозволяє збільшити міцність на розтяг до трьох разів. Епоксидні клеї також демонструють високі адгезійні властивості, стійкі до впливу вологи та температури, притаманних для умов шахти. Виявлено нові логарифмічні залежності, що описують міцність масиву при використанні модифікованого поліуретану з каталізатором ПЕПА у співвідношенні 9:1.

Практична значимість. Розглянуто різні види реагентів для безпечного та ефективного зміцнення підземних виробок у тріщинуватих масивах гірських порід, схильних до обвалення. Застосування запропонованих адгезійних реагентів ефективно протидіє зовнішнім зсувним навантаженням та напруженням, збільшуючи структурну стійкість та безпеку гірських масивів.

Ключові слова: *виробка, руда, гірські породи, відшарування, зміцнення, хімічні реагенти, міцність зчеплення*

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