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Backfill composite based on technogenic mining waste as a means of enhancing environmental and technological safety

Roman V. Klyuev
Moscow Polytechnic University, Moscow, Russia

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Abstract
Given the growing societal demand for the development of enterprises that ensure minimal environmental impact, there is a need to develop waste-free technologies. The concept of realizing the potential of technogenic waste is an integral component of creating a circular economy. The aim of this study is to utilize technogenic waste in a safe, environmentally balanced, and economically efficient deposit mining technology within the framework of a circular economy. The necessity of transitioning from a conventional mining system to multi-stage extraction systems for the mining of potassium-magnesium (water-soluble) ores is substantiated. The possibility of completely replacing specially mined components of the backfill composite with technogenic waste, including potassium-magnesium ore beneficiation waste, granulated blast-furnace slag, and deactivated ZSM-5 zeolite, is confirmed. It is established that the use of ZSM-5 as an activator and fiberglass as an inhibitor makes it possible to form a backfill composite with improved strength characteristics. The optimal composition of the backfill material includes 60 % beneficiation tailings, 29.7 % granulated slag, 0.3 % fiberglass, and 10 % ZSM-5. It is demonstrated that the use of multi-stage extraction with backfilling of the mined-out space enhances the environmental and technological safety of mining potassium-magnesium (water-soluble) ores. It is established that technological safety is achieved by minimizing horizontal deformations of the undermined rock mass, thereby ensuring the preservation of the water-protective stratum and relieving inter-chamber pillars from increased stresses, which contributes to their greater stability over time. It is determined that environmental safety is achieved through the utilization of technogenic waste in the backfill composite, as well as through the reduction of horizontal deformations of the undermined rock mass, thereby minimizing disturbance of the ground surface.

Keywords
safety; mining and processing enterprise; numerical modeling; computer modeling; deposit; technogenic waste; backfill composite; technological safety; circular economy; mineral resource; environmental safety

Finding
None.

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Introduction

Over the past decade, there has been an increase in anthropogenic impact on the environment, with the mining and processing industry having the greatest impact [1, 2]. Large volumes of mining and processing waste in the form of waste rock from overburden and/or development operations, beneficiation tailings, metallurgical slags, and other materials are stored in technogenic waste storage facilities [3-5]. The lower the content of the valuable component in the mined ore, the greater the volume of technogenic waste generated [6-8]. Consequently, the content of the valuable component in the ore directly characterizes the degree of technogenic impact of mining and processing operations on the environment [9-11].

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Due to the depletion of high-grade and/or shallow ore reserves, the global mining industry demonstrates a clear trend toward the exploitation of deep deposits and the extraction of low-grade ores [3, 11-13]. As a result, an exponential increase in the accumulation of technogenic waste is expected [14, 15]. In addition, the development of deep deposits causes previously known geodynamic manifestations to occur more frequently and on a larger scale [16-18], while the consequences of such manifestations are more destructive [19-21]. This trend predetermines the need to identify solutions that can reduce the negative impact of the mining and processing industry while simultaneously seeking ways to improve mining safety [22-24].

For a long time, the high cost of backfilling operations has been a limiting factor in the development of low-value georesource deposits using backfill technologies [25-28]. This is due to the high cost of the components of the backfill composite (BC) – cementitious binder and specially mined inert aggregate (sand, crushed stone, etc.) [27-30]. Currently, there is a need to increase the ore recovery ratio at potash deposits. The transition from the conventional (room-and-pillar) mining system to systems with backfilling of the mined-out space contributes to addressing this challenge [31, 32]. Consequently, there is a need to develop a high-strength BC with low shrinkage, the relevance of which increases as the mining depth of potassium-magnesium ores increases [33, 34]. At modern mines extracting metallic ores, the strength of BC reaches 10 MPa or more [35]. At the same time, at potash mines extracting water-soluble ores, the uniaxial compressive strength of hydraulic backfill based on beneficiation waste does not exceed 1-4 MPa [36].

The value of technogenic waste as a potential product for use in implementing a safe, environmentally balanced, and economically efficient deposit mining technology has long been overlooked [37-39]. One way of utilizing technogenic waste in the mining industry is to replace specially mined, expensive components in the BC formulation with such waste [40, 41]. The concept of realizing the potential of technogenic waste is an integral component of creating a safe, environmentally balanced, and economically efficient deposit mining technology within the framework of a circular economy [26, 42, 43].

Thus, the use of technogenic waste in the backfill composite meets the contemporary challenges of the mining and processing industry and the principles of the circular economy and is a relevant issue. To implement the concept of utilizing technogenic waste at a mining and processing enterprise, it is necessary to develop a BC composition based on technogenic waste and to propose a technology for mining a mineral deposit.

Methods

In the study, a comprehensive methodological approach was used, including:

- comparative analysis of existing deposit mining systems and technological solutions for backfilling;
- experimental studies of BC formulations based on technogenic waste;
- physical and mechanical testing of BC specimens;
- numerical modeling of underground excavation stability using the FLAC 3D software package.

This approach ensured the complementarity of experimental and calculated data, making it possible to objectively assess the effectiveness of the proposed technology.

Mining system. The study considered the conditions of underground mining of shallow potassium and/or potassium-magnesium (water-soluble) deposits characterized by increased geodynamic activity. The selection was substantiated by:

- a high accident rate caused by the failure of the pillars left in place and frequent manifestations of rock pressure under such conditions [36, 44-46];
- the limited effectiveness of conventional mining systems with natural support of the mined-out space [26, 37, 47, 48];
- the need to reduce the technogenic impact on the environment [49].

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At most potassium and potassium-magnesium deposits classified as water-soluble, reserves have traditionally been extracted primarily using the room-and-pillar mining system, without backfilling the stoping chambers [36]. Analysis of the causes of the high accident rate at mines extracting water-soluble ores demonstrated that the failure of load-bearing support elements occurs due to the development of subvertical disturbances and disruption of the continuity of the water-protective stratum (WPS) [50], resulting in the breakthrough of overlying brines into the mined-out chambers [36, 44, 45]. Under these circumstances, only a small proportion of water-soluble ore mines continue to operate, while in most cases the mine is completely destroyed, resulting in the loss of balance ore reserves intended for extraction by that mine [44]. The characteristics of water-soluble ore deposits and the principal methods used for their extraction are described in article [37].

Russia has long remained one of the world leaders in the production and export of potash fertilizers, ranking second only to Canada in terms of ore reserves and annual production volume. According to research [51] in 2021 Russia produced 9.1 tousand t of potash fertilizers, of which 8.8 thousand t were sold on the global market. In Russia, potash salt reserves are concentrated in the Verkhnekamskoye, Nepskoye, Gremyachinskoye, Nivenskoye, and Vostochno-Krasnoborskoye deposits. To date, industrial development has been carried out only at the Verkhnekamskoye deposit. These deposits were developed using conventional mining systems with natural support of the mined-out space, and backfilling of mined-out chambers for the purpose of achieving complete extraction was not employed. In view of this, it is possible to rely only on the experience available at this enterprise and to take into account the negative consequences caused by technogenic disasters: 1986 – BKPRU-1, mine flooding; 2006 – BKPRU, mine flooding; 2014 – SKRU-2, brine inflow into the mine [27, 36, 44, 50].

Development of the BC formulation and investigation of cured specimens. Preparation of the backfill composite using the same mixing technology, storage and curing conditions, as well as the creation of identical testing conditions, makes it possible to obtain reliable and representative results for BC compositions with different formulations. Established standard methods (GOST 5802-86 and GOST 10180-2012) exist for studying BC with different formulations. In the present study, a modified methodology [26] was used to investigate BC based on a cement-free binder, while the from smaller to larger mixing principle was applied to achieve better mixing of all components. Mixing was carried out using a laboratory planetary mixer: MIKS-D-C (Russia). Optimal and efficient mixing was achieved due to the characteristic planetary motion of the mixer, combining circular motion with rotation around its own axis. The planetary rotation speed was 62 rpm, increasing to 125 rpm, while the initial circular rotation speed was 140 rpm, increasing to 250 rpm. To simulate conditions close to those of underground mine workings, the specimens were stored and cured in specialized drying chambers (VSh 120 K1/3, Russia) at constant temperature and humidity $T = 20 \pm 2$ °C; $W = 95 \pm 5$ %.

Previous studies have shown that replacing 0.5 % of the cement binder in BC produced using water-soluble potassium-magnesium ore beneficiation waste with 8-10 % granulated blast-furnace slag makes it possible to preserve the rheological characteristics of the mixture and its mechanical properties after curing [23, 26, 34]. Based on the previously obtained results, it was hypothesized that, with appropriate preparation of granulated blast-furnace slag and regulation of the component composition of the backfill composite, the cement binder could be completely replaced with slag-based binding materials.

Studies of the influence of reinforcing inhibitors on an artificial mass formed from BC demonstrated the positive effect of various fibers [34, 35], nanocomposite fibers, and nanotubes [26]. Inhibitors, including fibers of various types and grades, demonstrate a multifaceted influence on the properties and characteristics of both the mixture and the cured BC. The introduction of 0.1 % fiber into the BC composition (of the total dry volume), regardless of its type or kind, leads to a simultaneous increase in both the development and peak values of strength characteristics. This trend persists

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for mixtures containing no more than 1 % fiber of the total dry volume. Increasing the fiber content above 1 % results in poor mixing within the composite and agglomeration (formation of nests/clusters – large accumulations in one location), which causes the formation of air voids and leads to increased porosity after curing [34, 36]. Thus, when the fiber content in the BC exceeds 1 %, there is a sharp decrease in its strength characteristics during curing and in already cured specimens. It has been experimentally established [34], that the optimal fiber content in the BC formulation is 0.25-0.4 % (regardless of the type and/or kind of fiber).

Studies [23] confirmed the positive effect of various activating additives on the technological and operational characteristics of BC. The optimal concentrations of activating additives in the formulation were determined experimentally [27, 29, 37]. Based on the analysis of previous studies, an algorithm for selecting the BC formulation was developed (Table 1). Concrete mixtures and/or BC based on a cement binder with specially mined sand used as an inert aggregate are the most extensively studied. In this regard, to investigate the possibility of replacing the binder with technogenic waste from metallurgical processing (specifically, granulated blast-furnace slag in this study), composition 1 was prepared as a reference composition. To investigate the possibility of using water-soluble ore beneficiation waste in the BC formulation (for this study, halite waste from the beneficiation of potassium-magnesium ores), an intermediate reference composition, composition 2, was prepared.

Table 1

Algorithm for selecting the composition of backfill material

Composition number	Components, %					
	Inert aggregate		Binder		Inhibitor	Activator
	Beneficiation tailings	Sand	Slags	Cement	Fiberglass	ZSM-5
1	0	99	0	1	0	0
2	99.0	0	0	1	0	0
3	60.0	0	40.0	0	0	0
4	60.0	0	39.7	0	0.3	0
5	60.0	0	35.0	0	0	5.0
6	60.0	0	30.0	0	0	10.0
7	60.0	0	39.7	0	0.3	0
8	60.0	0	34.7	0	0.3	5.0
9	60.0	0	29.7	0	0.3	10.0

Uniaxial compression tests at a loading rate of 0.5 MPa/s were performed on cylindrical specimens measuring 50×100 mm. To study the dynamics of strength development, uniaxial compression tests were conducted on the 7th, 28th, 60th, 90th, and 120th days of curing. The strength of the cured specimens was tested under uniaxial compression using an MTS Insight automatic laboratory testing press (MTS Systems Corporation, USA).

To obtain reliable and robust results, the methodology developed and tested in study [26] was applied. A high degree of reliability of the results was achieved by conducting a large number of experiments. The reliability of the results was confirmed by the repeatability of the experimental data obtained from a sufficient number of tests. For each BC composition, 18 specimens were prepared and subsequently tested under uniaxial compression. The obtained results demonstrated satisfactory convergence, and their mean values were used in the subsequent analysis and formulation of the study conclusions.

After testing, the results were evaluated for consistency. If more than 30 % of the specimens exhibited compressive strength values deviating by more than 20 % from the mean value, the batch was rejected and the test was repeated. Such deviations were considered indicative of specimen defects (e.g., voids, internal cracks, or insufficient compaction) rather than material-related properties. The results presented in this study reflect validated batches with a stable internal distribution.

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Methods for detecting damage and deformation of the micro- and mesostructure of BC include the ultrasonic pulse method (or acoustic emission method). In the present study, Russian (GOST 22690-2015; GOST R 59938-2021) and international (ISO 16836:2019; ISO 16837:2019; ISO 16838:2019) standards for the acoustic emission (AE) method for concrete testing were followed.

During mechanical loading of the cured BC specimens, AE analysis was used to study the process of microcrack initiation and propagation. During mechanical loading of BC specimens, internal microstructural changes occur at the moment of failure, generating released energy, which in turn produces transient elastic waves. In the present study, a PCI-2 AE system (Physical Acoustics Corporation, USA) was used to capture AE signals during mechanical loading. During loading and internal microstructural changes, two probes attached to the surfaces of the BC specimen collected acoustic emission signals. The sampling frequency was set at 140 kHz with a signal gain of 45 dB. The obtained results provided real-time data on the initiation and development of damage and final failure. This approach makes it possible to evaluate the mechanical behavior of the material, identify critical stress points, and determine failure modes. Consequently, AE analysis provides valuable information on material integrity and durability, facilitating a comprehensive assessment of performance under various additional conditions.

In recent years, SEM and XRD analyses have been conducted to study BC in greater detail, making it possible to investigate the morphology, microstructure, and crystalline phases of the material. This makes it possible to establish phase differences (the amount of C-S-H and/or N-A-S-H gels; the presence of hydroaluminates; the number and size of pores; the forms of the crystalline structures formed and their bonds, etc.) that explain the mechanical properties of the BC being produced (investigated). For the SEM and XRD analyses, the previously tested methodology [52] was used. All microstructural studies were performed on the fracture surface of the investigated BC material. Material for the study was collected after the specimens had been subjected to uniaxial compression testing; that is, the fracture was produced mechanically. Fine fractions and dust formed on the fracture surface were removed using an air jet [53, 54].

A Polam R-211M polarizing microscope (Russia) with a maximum magnification of 720 times was used for the microstructural investigation. The immersion method was used. The phases were identified based on refractive indices, birefringence, basicity, sign, elongation, and extinction angles [55]. Immersion liquids with known refractive indices were used as reference media. The quantitative phase ratio (crystallographic composition) was determined using the Stroyber method. In the study using the polarizing microscope, the maximum magnification of 720 times [56]. In addition to these studies, the specimens were examined using a more powerful scanning electron microscope ZEISS EVO18 (Carl Zeiss Industrielle Messtechnik GmbH, Germany). The use of this microscope makes it possible to achieve a maximum magnification of 2000 times at a primary electron accelerating voltage of 20 kV. During the examination, the pressure in the chambers was $2.67 \cdot 10^{-3}$ Pa ($2 \cdot 10^{-5}$ Torr).

Granulated blast-furnace slag – replacement of cement. The similarity between the chemical compositions of cement and blast-furnace slag predetermined the possibility of using the latter as a binder in BC. The main oxides determining the ability of slag to form a stable and strong crystalline lattice are lime CaO, silicon dioxide (silica) SiO_2, aluminum oxide (alumina) Al_2O_3, and magnesium oxide MgO. All of these oxides are present in both cement and slag. Lime and magnesium oxide have a positive effect on the formation of hydration products, whereas silica and alumina have a negative effect [56]. Granulated slag from the Chusovoy Metallurgical Plant (Russia) was used as the main binder. Its chemical composition was preliminarily determined by X-ray fluorescence (XRF) analysis and is presented in Table 2.

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Table 2

Chemical composition of backfill composite components, %

Component	Slags	ZSM-5	Component	Slags	ZSM-5
SiO_2	20.23	84.89	Fe_2O_3	3.05	0.24
Al_2O_3	4.54	12.53	SO_3	2.56	–
CaO	61.45	0.18	Na_2O	0.51	–
MgO	2.74	1.52	K_2O	0.70	–
			Other	4.22	0.64

Note. Other – components neither identified nor isolated by difference from 100 %.

To improve the binding properties, prior to use the slag was subjected to mechanical activation treatment in a DESI-11 disintegrator at a rotor speed of 1500 rpm for 3 min, which provided a particle size of < 50 μm. The methods and techniques of disintegration treatment of backfill composite components are described in detail in [26]. During disintegration activation, the particle-size distribution of the slag was modified, resulting in an increase in the fine fractions (Fig.1). An increase in the fine fractions increases the total hydration surface area of the slag, which leads to improved binding properties [26].

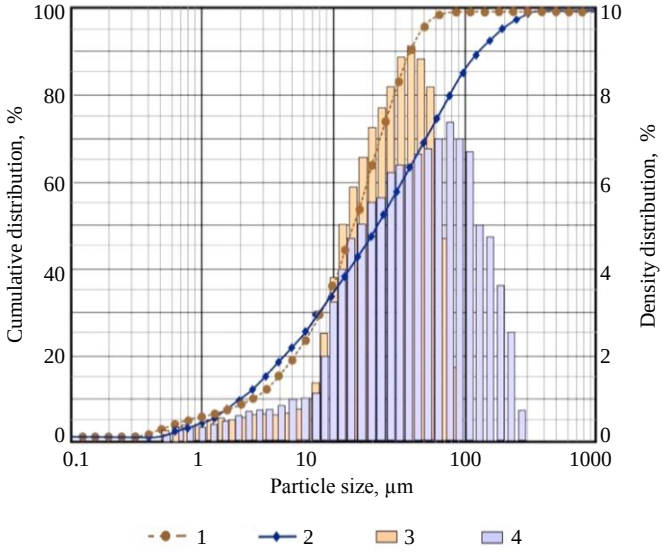


Fig.1. Fractional composition of blast-furnace slags

Integral slag content:
1 – activated blast-furnace, 2 – domain.
Differential slag content:
3 – activated blast-furnace, 4 – domain

Beneficiation waste – replacement of specially mined sand or gravel. The use of beneficiation waste in BC formulations is not new. In backfill composite formulations, the preferred and most economically feasible option for use as an inert aggregate under potash mine conditions is salt waste and/or clay-salt slurries. However, for a long time, studies did not take into account the negative influence of the chemical elements contained in these materials on the structure of the cement stone and the processes of hydration product formation [34]. In addition, the use of beneficiation waste in BC formulations without extracting the valuable component remaining in it to a zero level is an atavism [57] and does not comply with the principles of the circular economy [26]. In the present study, aged waste from the flotation beneficiation of potassium-magnesium ores, which had been treated to extract the remaining valuable components, was used as an inert aggregate. The properties of the beneficiation waste used and its chemical composition, obtained using X-ray fluorescence analysis followed by interpretation of the phase composition, are presented in Table 3.

Table 3

Chemical composition of waste from beneficiation of water-soluble ores, %

Beneficiation tailings		Compound	KCl	NaCl	$MgCl_2$	$CaSO_4$	I.R.	Br^-	H_2O_{cryst}
Halurgical	Old stock	Weight ratio	3.35	92.66	0.07	1.91	1.9	0.03	0.08
	Current		1.91	94.3	0.07	1.914	1.7	0.026	0.08
Flotation	Old stock		9.96	82.64	1.1	4.488	1.7	0.032	0.08
	Current		4.88	87.78	1.1	4.331	1.8	0.029	0.08

Note. I.R. – insoluble mineral residue – clay-aluminosilicate mineral components remaining in the solid phase; H_2O_{cryst} – water of crystallization (water chemically bound within the crystalline structure of the mineral).

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Activating additives. Activating additives (activators) have found widespread application in the construction of concrete structures and road pavements (in the construction and transportation industry), as well as in the construction of artificial backfill masses in the mining industry. Activators contribute to changes in or regulate the properties of BC. Three types are distinguished among them: catalysts, plasticizers, and inhibitors. Plasticizers are intended to regulate the rheological properties of the composite mixture; therefore, the possibility of their application was not considered in the present study. The present study focuses on catalysts and inhibitors because the objective of the research is to develop a BC formulation with strength characteristics that meet technological safety requirements.

Catalysts are usually chemical additives that react with the components of BC. To improve the structure of BC (as a catalyst), deactivated ZSM-5 zeolite from the Moscow Oil Refinery (Gazpromneft-MNPZ JSC) (fraction 10-40 μm) was used in the present study. The chemical composition of the deactivated zeolite used is presented in Table 2. Aluminosilicates such as ZSM-5 zeolite (Zeolite Socony Mobil-5) have found widespread application as cracking catalysts in the oil refining industry [58-61]. ZSM-5 zeolite is used for the drying, purification, separation, and recovery of gases and liquids during the separation of petroleum fractions [62-64]. During the cracking process, an isomerization reaction occurs in the pores of ZSM-5, which leads to its deactivation [65-67], making its reuse impossible [68, 69]. Thus, after a single use, ZSM-5 requires disposal, which, as in the case of waste generated during the production cycle of steel production and/or the extraction of water-soluble ores, results in the formation of technogenic waste disposal sites that have a negative impact on the environment [70].

In contrast to catalysts, inhibitors perform independent functions: can regulate the properties of the BC mixture or the properties of the formed artificial mass without reacting with the BC components. In this study, inhibitors were used to increase the strength properties of the artificial mass being formed – fiberglass manufactured by Pascal Plant Group of Companies (Russia). This material possesses the following properties: diameter – 19 μm; length – 6 mm; tensile strength – 369 MPa; elastic modulus – 4.8 GPa; density – 2.699 g/cm^3; and elongation at break – 36.5 %.

Modeling the stable state of the roof and elements of the mining system. The FLAC 3D 7.0 software package (Itasca, USA) was used to analyze chamber stability:

- Model geometry – a 100×100×100 m block simulating chambers 20 m wide and 15 m high.
- Mesh – tetrahedral, with a spacing of 0.5 m.
- Boundary conditions – the lower boundary was fixed in all degrees of freedom; the lateral boundaries were fixed in the normal direction; the upper surface was free.
- Loads – the vertical pressure corresponded to a depth of 400 m ($\sigma v \approx 20$ MPa).
- Material model – elastoplastic with creep (CREEP model).
- BC parameters – the elastic modulus and compressive strength were obtained in the present study.

The behavior of the rock mass was programmed using the built-in FISH language.

Results

Study of cured specimens. *Uniaxial compression*. Analysis of the results of uniaxial compression testing of the cured specimens demonstrated positive strength development regardless of the formulation (Table 4). Reference composition 1, which contained only specially mined components (cement and sand), demonstrated standard strength development dynamics and a standard increase at each stage of curing. Intermediate reference composition 2, in which sand was replaced with water-soluble ore beneficiation waste, also demonstrated an increase in strength characteristics with increasing storage time. However, the strength development dynamics and maximum values were lower than those of reference composition 1. The decrease in the strength characteristics of composition 2 can be explained by the fact that the initial strength of water-soluble ore beneficiation waste is lower than that of sand, which bears the main load in the mass after curing.

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Table 4

Test results of cured backfill composite specimens with different compositions

Composition number	Components, %						Rate of strength gain over 24 h, MPa				
	Tails	Sand	Slag	Cement	Fiberglass (inhibitor)	ZSM-5 (activator)	7	28	60	90	120
1	0	99	0	1	0	0	1.20	2.08	3.25	3.92	4.25
2	99.0	0	0	1	0	0	0.92	1.64	2.57	3.01	3.23
3	60.0	0	40.0	0	0	0	0.33	1.11	1.82	2.32	2.57
4	60.0	0	35.0	0	0	5.0	1.11	2.42	3.50	3.91	4.30
5	60.0	0	30.0	0	0	10.0	1.39	3.02	4.48	4.77	5.12
6	60.0	0	39.7	0	0.3	0	0.17	0.95	1.80	2.45	2.69
7	60.0	0	34.7	0	0.3	5.0	1.0	2.33	3.55	4.15	4.57
8	60.0	0	29.7	0	0.3	10.0	1.27	2.91	4.37	5.02	5.43

The complete replacement of specially mined BC components with technogenic waste (metallurgical slag and water-soluble ore beneficiation waste) (composition 3) demonstrated the potential of such compositions. However, the experimentally confirmed maximum strength of the cured specimens (on the 120th day) is insufficient for the application of compositions with this formulation in deposit mining using backfill systems with multi-stage extraction.

The introduction of activating additives (catalysts and inhibitors) into the BC formulation had a positive effect on the strength characteristics of the cured specimens. The strength of specimens of all formulations increased at all stages of curing and reached peak values on the 120th day. The strength characteristics of the experimental compositions exceeded the values of the reference composition specimens by 20.5 % when only the catalyst was introduced and by 27.7 % when the complex activator (the catalyst together with the inhibitor) was introduced. At the same time, it should be noted that the introduction of only the inhibitor into the BC formulation did not have a significant effect on the strength of the cured specimen. The increase was only 4.66 % relative to composition 3, while in comparison with the reference specimens, a significant decrease of 58 % was observed compared with reference composition 1 and 20 % compared with the intermediate reference, composition 2.

The strength development dynamics of the compositions containing activating additives in the BC formulation remained at the level of the reference specimens; that is, the strength characteristics of the specimens increased with increasing storage time. At the same time, it should be noted that the rate of strength development for different types of activating additives showed divergent values during the initial stages of curing (7th, 28th, and 60th days). The rate of strength development when catalysts were introduced into the BC formulation (compositions 4 and 5) increased up to the 60th day and, after the 90th day, assumed standard values. At the same time, the introduction of inhibitors into the BC formulation (compositions 6-8) initially (up to the 60th day of storage) contributed to a decrease in the rate of strength development, after which there was a sharp increase in the strength characteristics of the cured specimens.

Dynamics of stress development in specimens at the moment of failure. The development of damage (formation of microcracks) in the structure of cured BC can be monitored by measuring and analyzing changes in the deformation modulus during loading. Figure 2 demonstrates the following relationships – the change in stress over time (blue graph) and the rate of change (increase/decrease) in stress (red graph). For comparative analysis of AE results, deformation changes occurring in the specimens during loading (uniaxial compression) are generally plotted on the horizontal axis. In the present analysis, time was plotted on the horizontal axis to provide a more illustrative comparison. Vertical purple dash-dot lines indicate the boundaries between the phases (stages) of specimen deformation and failure. It should be noted that the relationships presented in Fig.2 reflect not only the change in the total stress in the specimen but also the rate of its change over time. Accordingly, the peaks of the corresponding curves may not coincide, since the maximum rate of stress change and the maximum value of the stress itself are different physical parameters. For heterogeneous backfill composites characterized by a porous structure, local stress redistribution, and the development of microdefects, such behavior is natural.

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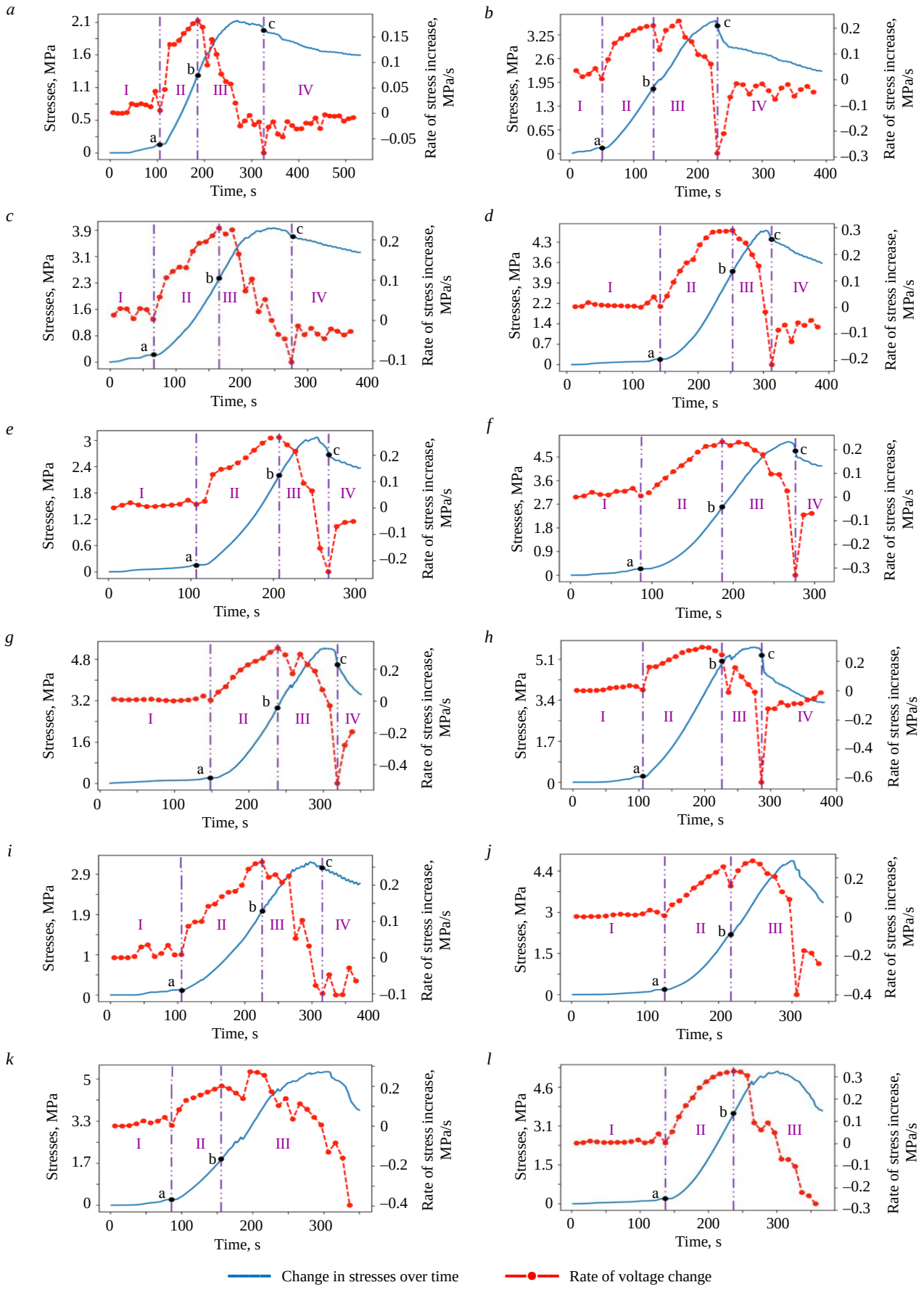


Fig.2. Functions of compressive stresses and stress rates of change (mix number/day of daytime curing):
a – 1/28; *b* – 1/60; *c* – 1/90; *d* – 1/120; *e* – 5/28; *f* – 5/60; *g* – 5/90; *h*– 5/120; *i* – 8/28; *j*– 8/60; *k* – 8/90; *l* – 8/120
Points on the horizontal axis a, b, c – deformational changes during loading

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In the present analysis of the obtained experimental data, we applied the method of controlled deformation changes during loading (uniaxial compression testing of the specimen). This made it possible to perform a linear correlation between the rate of stress increase and the modulus of deformation changes. This made it possible to bring the functions of deformation change as a function of load and stress change over time to an identical standard (the same comparative component) – time, that is stress change and the rate of stress change, and to plot them on the same graph for a better and more illustrative comparative analysis. AE energy during the progressive failure of the BC specimens was analyzed by comparing the graphs.

From the analysis of the graphs presented in Fig.2, it follows that, with an increase in the vertical axial load, the AE energy signals of BC specimens of all investigated formulations exhibit distinct phase characteristics: the initial or active phase (stage I); the quiescent or main load-bearing phase (stage II); secondary activity or peak phase (stage III); and the post-peak or residual phase (stage IV). However, for BC containing an inhibitor in its formulation (composition 8), the post-peak phase is not characteristic (Fig.2, *j*-*l*). While a clear sign of failure can be identified for specimens stored for 28 days (Fig.2, *i*), no clear sign of failure was observed when studying inhibitor-modified BC specimens stored for longer periods; consequently, stage IV (post-peak phase) was not distinguished separately.

The initial or active phase (stage I) in BC specimens of all investigated formulations is practically identical and includes the dense stage of the compressive stress-time curve, the linear elastic stage, and the early part of the plastic compaction stage. There are no significant corrections in stress and/or the rate of stress change. The duration of the active phase is practically identical for the investigated BC specimens of all formulations and all curing periods. The exceptions are specimens of the reference formulation at the early stages of storage (Fig.2, *a*-*c*) and compositions modified with an inhibitor up to 28 days of storage (Fig.2, *i*).

The main load-bearing phase (quiescent phase, stage II) is characteristic of the plastic-yielding stage. At this stage, the AE signal for all investigated specimens, regardless of formulation and curing time, was stable, while the AE energy rate intensity was low. This indicates that a destabilization process occurred in the specimens and the evolution of failure began – the formation of microcracks and their subsequent propagation. The main load-bearing phase is shorter in duration than the initial active phase. The results of this phase make it possible to understand the onset of destabilization of the BC specimen structure and obtain information about its changes.

The peak phase or secondary activity (stage III) is characterized by the peak of the stress-time curve and an intensified failure process: enlargement of previously formed cracks and weakening of the structural bonds of the BC. At this stage, an increase in the AE signal and significant fluctuations in the AE energy rate are observed. It is during the secondary activity phase that the peak AE energy rate is observed for all formulations and at all stages of curing. This confirms an increase in the propagation rate and size of microcracks, as well as the formation of new ones. A sharp increase in the AE energy rate is characteristic of stepwise destabilization of the structure and stepwise failure. Such behavior is observed for specimens starting from the 60th day of curing and indicates a transition from plastic to brittle deformation. The exceptions are specimens whose formulation contained an inhibitor (Fig.2, *j*-*l*).

In brittle structures, AE energy propagates non-uniformly and at different rates, confirming the unstable (stepwise) propagation of microcracks, the formation of new macroscopic cracks, and/or the transition of microcracks into the category of macrocracks. Further development of micro- and/or macrocracks, changes in their configurations and/or propagation directions lead to the overall instability of the structure of the BC specimens. At the same time, after the peak of the stress curve, the specimens retain some load-bearing capacity characteristic of macroscopic rupture (failure of the BC specimen structure) with friction. A surge in the AE energy rate indicates the release of greater elastic strain energy characteristic of the sliding process occurring at the boundaries of the failed regions.

In the post-peak or residual phase (stage IV), the rate of stress increase stabilizes near a certain value (which varies depending on the formulation and curing time), reflecting the residual load-bearing

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capacity of the specimens. This phase is characterized by a lower and more stable AE energy rate without obvious fluctuations. These values confirm that the three-dimensional spatiotemporal evolutionary structural changes (i.e., the process of crack formation and development) during the uniaxial compression test have ended. Consequently, at the fourth stage, the internal structure of the investigated BC specimens is damaged and they have failed, indicating a loss of load-bearing capacity.

The exception was BC specimens whose formulations contained inhibitors. It should also be noted that the identification of different stages during uniaxial compression testing of BC specimens depends on the storage (curing) time of the specimen and the formulation. The reference specimens (composition 1 and 2) show a higher rate of AE decrease around point "c" compared with specimens strengthened with the ZSM-5 catalyst and reinforced with the SF inhibitor.

At the same time, stage I in inhibitor-reinforced specimens stored for long periods lasts longer and is characterized by more stable values compared with the reference specimens and catalyst-activated specimens, whereas stage IV is absent in inhibitor-reinforced specimens at the intermediate and late stages of curing. The experimental results are characterized by the absence of spontaneous (brittle) failure during uniaxial compression testing of inhibitor-reinforced BC specimens and by a transition to brittle-plastic behavior. The load-bearing capacity of such specimens is retained after the stress peak, indicating the formation of a bridging connection within the BC matrix. The inhibitor fibers perform the role of such a connection. It is also noted that the duration of stage IV for all specimens characterized by brittle failure decreases with age due to a reduction in the residual load as cement hydration reactions progress.

Microstructural analysis. The strength of BC is regulated by internal hydration products and the hydration process itself. SEM scanning of failed BC specimens after their uniaxial compression testing was performed to determine the influence of the components on the strength characteristics. Scanning electron microscopy methods make it possible to analyze the formation of the BC matrix, trace the hydration process, determine the presence and sizes of pores, etc.

ImageJ software was used to analyze brightness level values (grayscale) in the SEM image. Plotting brightness level values along a selected line makes it possible to assess microstructural heterogeneities (pores; grains) and/or phases (C-S-H, C-H, etc.). Using this software, the SEM image values were also converted into 3D images, which made it possible to study the structure of the BC matrix, the number, volume, and sizes of pores, i.e., to create a roughness map for the selected area (Fig.3).

The analysis of the study makes it possible to conclude that BC composition 3, formed without the use of activating additives (inert aggregate + binder), has a highly porous structure (Fig.3, *a*). The brightness level shows a large difference between the maximum and minimum values, indicating significant phase differentiation. The roughness map of the specimens of composition 3, similarly to the brightness level, demonstrates significant irregularities and variations, accompanied by both high peaks and deep drops.

The introduction of the ZSM-5 zeolite activator into the BC formulation (composition 4) makes it possible to "accelerate" the hydration process and form a denser matrix characterized by a smaller pore volume and fewer pores (Fig.3, *b*). Although the brightness level demonstrates an increase in the frequency of peaks, the differences between the maximum and minimum values decreased, indicating the formation of a denser structure. The roughness map of the specimens of composition 4 shows no significant irregularities or variations, which also confirms the more uniform structure of the BC matrix.

The introduction of an inhibitor (fiberglass) into the BC formulation (composition 6) practically did not change the BC structure compared with composition 3. The loose and porous structure was preserved (Fig.3, *c*), with the inclusion of fibers around which the hydration process and the formation of C-S-H gels are concentrated. The fibers themselves do not participate in the reaction. The brightness level demonstrates large variations with a reduced frequency of peaks. The roughness map, as in the case of the specimens of composition 3, is also characterized by significant irregularities.

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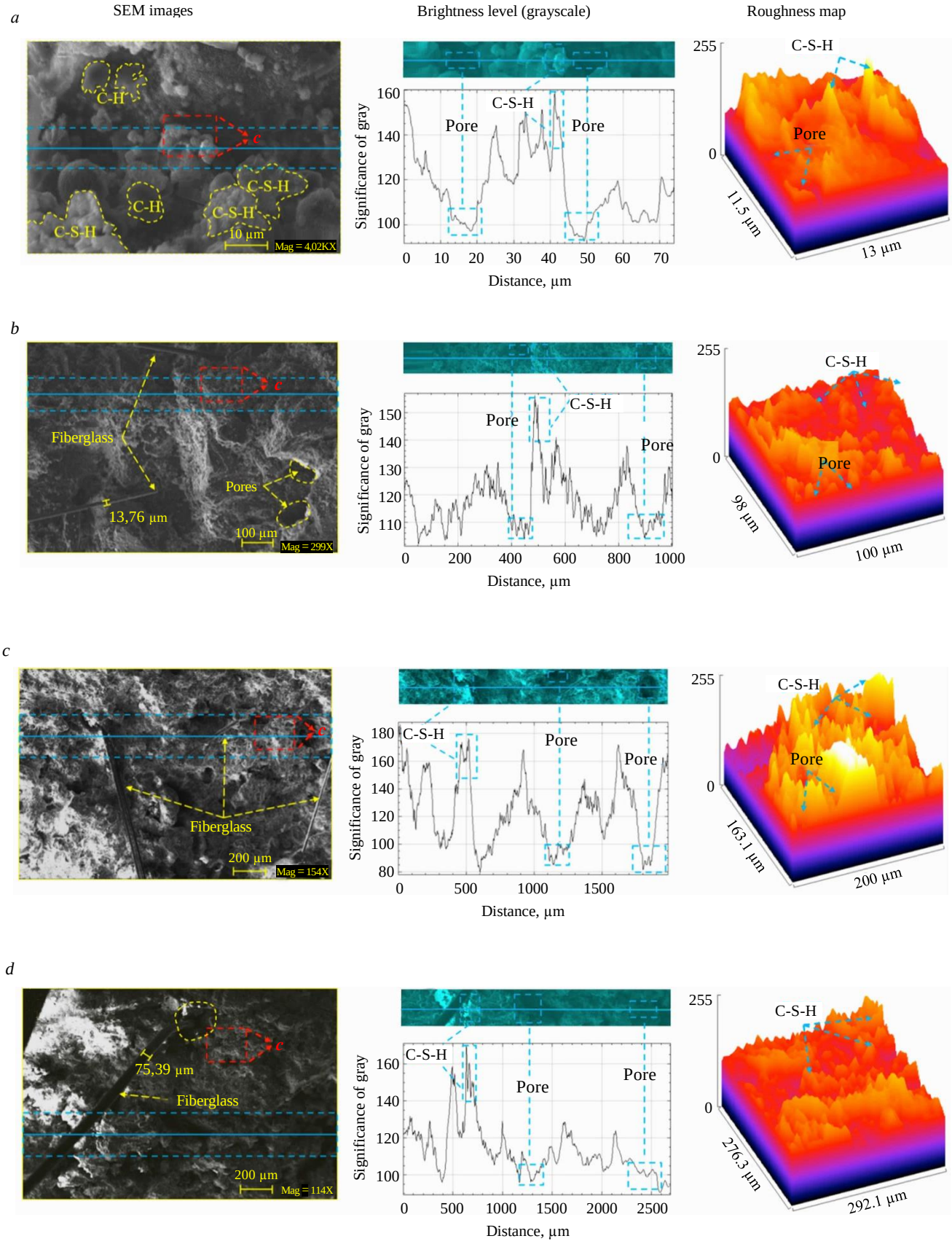


Fig.3. Microstructural investigation of BC samples, aggregate/binder: composition 3 (*a*), composition 4 (*b*), composition 6 (*c*), composition 8 (*d*)

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The simultaneous introduction of an inhibitor and an activator into the BC composition (composition 8) makes it possible to form BC with the highest values of uniaxial compressive strength. The activator accelerates the hydration reaction and enables the formation of a larger volume of C-S-H gel phases, while the fibers serve as a framework for their formation, which significantly reduces porosity (Fig.3, *d*). The brightness level is characterized by minor variations with an increase in amplitude frequency, while the roughness map has the smallest irregularities compared with the other compositions.

Calculation variants for mining a section of a potash deposit. Recently, mining enterprises extracting potassium or potassium-magnesium ores have been placing curing material (based on salt waste without the use of a binder) in the mined-out space [36, 47]. However, the proposed technology mainly addresses the tasks of reducing the volume of technogenic accumulations on the surface, strengthening inter-chamber pillars (ICHP), which reduces the risks of their failure; and reducing the volume of voids, which minimizes the risks of collapse of the undermined rock mass and deformation changes in the WPS. At the same time, the proposed technology does not provide for complete or partial extraction of the reserves left in the ICHP.

In this regard, the implementation of mining systems with multi-stage extraction and backfilling in the development of potassium and/or potassium-magnesium deposits is a highly promising option that makes it possible to find a more rational approach to resource development and eliminate (minimize) the regional hazard associated with potash mining enterprises engaged in reserve extraction. The implementation of multi-stage extraction with backfilling (with artificial support of the mined-out space) implies abandoning the conventional room-and-pillar system (a system with natural support of the mined-out space) and proposes a technology involving the alternation of extraction and backfilling operations within the section being mined, followed by the extraction of previously left ICHP (additional recovery of ore reserves).

To assess the environmental and technological safety of potash ore deposit mining (using the Verkhnekamskoye potassium-magnesium salt deposit as an example), mining situations were modeled for three different mining variants (Table 5):

• variant 1 – the section is mined using the conventional system (room-and-pillar) with rigid pillars left during the extraction of the AB seams (calculated loading degree $c \approx 0.24$) and with conditionally yielding pillars in the KrII seam (calculated loading degree $c \approx 0.67$); backfilling operations (model 1). In this variant, backfilling is not used;

• variant 2 – the section is mined using a modified system. The conventional mining system (room-and-pillar) is used with subsequent backfilling of the mined-out chambers in the KrII seam (model 2). Thus, in the KrII seam, extraction is carried out using a continuous mining system;

• variant 3 – the section is mined using the conventional system (room-and-pillar), with rigid pillars left during mining of both the AB and KrII seams (model 3) (for the AB seam, $c \approx 0.3$ and for the KrII seam, the loading degree is taken as $c \approx 0.38$). In this variant, operations are carried out without the use of backfilling.

Table 5

Modeling conditions for the variants under consideration

Parameter	Variant		
	1	2	3
Depth of the seam AB, m	290	290	346
Thickness of the seam AB, m	3.2	3.2	3.1
Width of ICHP seam AB, m	5.8	5.8	6.9
Width of formation chambers AB, m	3.2	3.2	5.1
Seam thickness KrII, m	3.7	3.7	5.9
WPS seam width KrII, m	2.9	2.9	6.9
Reservoir chamber width KrII, m	6.1	6.1	5.1
Thickness of the non-ore interbed, m	6.8	6.8	4.9
Distance between axes, m	9.0	9.0	12.0
Lag of extraction operations at seam KrII relative to seam AB, years	1	1	2
Lag of backfilling operations behind extraction operations in the seam KrII, years	No	2	No
Underfilling on the reservoir KrII, %	No	15	No

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Underfilling was adopted to assess the conservative scenario and corresponds to the maximum possible technological filling losses.

For numerical modeling, averaged physical and mechanical properties of the rocks composing the rock mass under consideration were used. The adopted parameters are based on an analysis of previously published experimental and computational studies devoted to the geomechanics of potassium-magnesium deposits and are presented in Table 6. In the modeling, the rock density was assumed to be 2200 kg/m^3 and Poisson's ratio was 0.35. The use of averaged values was determined by the need to obtain a representative computational model that makes it possible to correctly assess the stress-strain state of the rock mass and the stability of the elements of the mining system.

Table 6

Strength and deformation properties of the modeled rock

Parameters	Young's modulus, MPa	Angle of internal friction, deg	Cohesion, MPa	Tensile strength, MPa
Roof rocks	800	39.8	4.2	1.2
AB/AV-series seams	12,000	38.7	4.3	1.3
Interlayer rocks	13,500	39.2	4.7	1.4
Seam rocks KrII	13,800	38.4	4.9	1.5
Soil types	12,000	40.0	4.3	1.2

In variant 2, the geomechanical parameters of the undermined rock mass were modeled in order to assess the influence of backfilling operations on the environmental and technological safety of the mining system. The model of variant 2 included the condition that the created backfill composite has rheological characteristics similar to those of the rock and ore mass, and the obtained three-point bending strength characteristics were taken into account. The uniaxial compressive strength characteristics of the backfill composite were obtained during the investigation of uniaxial compressive strength characteristics (Table 6). Variants 1 and 3 were considered in order to compare the proposed mining technology (variant 2) with actual variants used in individual sections of the mines of the Verkhnekamskoye potassium-magnesium ore deposit (BKPRU-2 and BKPRU-4). When modeling the mining situations for variants 1 and 3, parameters corresponding to the actual mining and geological conditions at the mines were adopted.

Achieving the maximum recovery ratio in the section being mined is an advantage of the proposed variant. In order to ensure higher technical and economic performance of mining the section, backfilling of the chambers of the final stage may be performed partially or may not be performed at all. Such differentiation is possible provided that the preservation of the WPS is guaranteed. Depending on the selected technology, the period between mining the chambers of the first and second stages varies and may involve either a minimal (insignificant) technological delay or maintaining a sufficient period of time between the stages.

Modeling results of the load-bearing capacity of the structural elements of the mining system. The model considered a 50-year period of ground surface subsidence development and the rate of disturbance development (Fig.4). Variant 1 with yielding pillars in the KrII seam demonstrated the greatest intensity at the initial stage of mining (the first 26 years). In the middle of this period (13 years after the start of operations), the maximum subsidence rate was recorded at 105 mm/year, decreasing by year 26 and reaching a constant value of 10 mm/year. At the end of the modeled period (50 years), the total subsidence for variant 1 is 1.8 m.

Modeling of another system without backfilling (variant 3), with rigid pillars left in both seams, demonstrated more uniform rate dynamics. The displacement rate remained uniform throughout the entire investigated period and did not exceed 10 mm/year. The total ground surface subsidence at the end of the investigated period was no more than 0.5 m.

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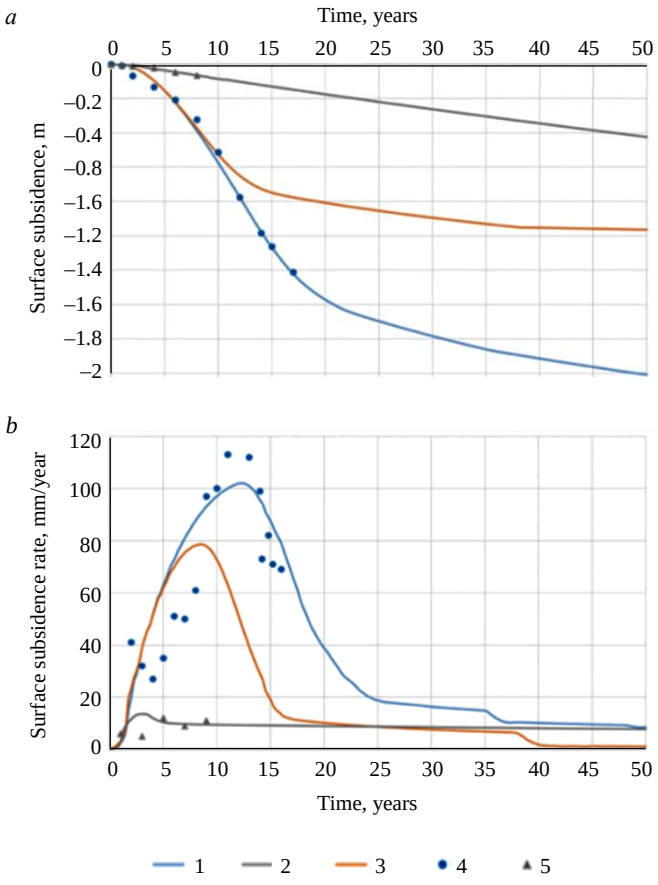


Fig.4. Development of deviations at the upper limit of variants 1-3 of the development models under consideration:
a – value; *b* – speed
1-3 – values for models 1-3;
4, 5 – actual values obtained from mine surveying monitoring for models 1 (4) and 3 (5)

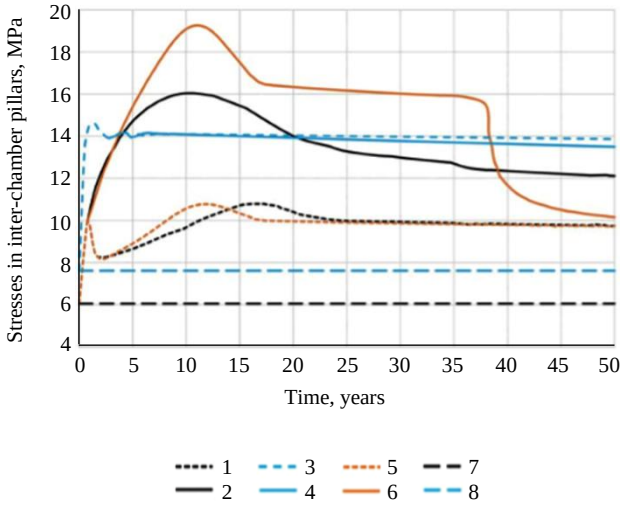


Fig.5. Development of stresses in inter-chamber pillars
1, 2 – values for model 1: seam AB (1), KrII (2);
3, 4 – model 2: seam AB (3), KrII (4);
5, 6 – model 3: seam AB (5), KrII (6);
7, 8 – actual values obtained from mine surveying monitoring for models 1, 2 (7) and 3 (8)

The modeling results for variant 2 were of the greatest interest. A significant effect from the application of mined-out space backfilling is evident by the 16th year after the start of mining the section. After this period, the displacement rate decreases, and by year 37 this process practically ceases. This indicates that the volume of voids above the backfill mass (underfilling) had been filled, i.e., the roof had completely subsided onto the backfill. After 37 years, there are no deformation changes in the inter-chamber pillars in the model. By the end of the investigated time interval, the subsidence over the entire investigated period amounted to 0.95 m, which is almost two times less than in the system used at the enterprise (variant 1).

The preservation of the ICHP and their load-bearing capacity demonstrates the technological safety of the mining system under consideration. Considering the history of stress development in the ICHP (Fig.5), it can be concluded that, for all modeled systems (variants), the pillars retain residual load-bearing capacity throughout the entire modeling period.

The conventional mining systems used at the Verkhnekamskoye potassium-magnesium deposit (variants 1 and 3) are characterized by differences in stress development in yielding pillars compared with rigid pillars. Yielding pillars are characterized by pronounced stress maxima that significantly exceed the level of the natural stress state of the rock mass. These maxima occur during the period of 11-13 years after the start of mining the section. When the conventional system is replaced by a backfill system, higher stresses in the rock mass are observed during the second quarter of the modeled time interval. At the same time, it should be noted that during this period there is a significant unloading of the ICHP due to backfilling of the first-stage chambers and subsidence of the roof onto the formed backfill mass. The obtained values make it possible to conclude that the reserves left in the pillars can be extracted, i.e., that multi-stage extraction can be implemented.

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Discussion

Mining system. Safety, both environmental and technological, while maintaining economic performance, is a necessary condition for the implementation of multi-stage extraction with backfilling at potassium-magnesium deposits. All organizational, operational, and technical measures for the construction of an artificial mass lead to an increase in mining costs. However, the negative experience of mining water-soluble ore deposits, including potassium-magnesium ores at the Verkhnekamskoye deposit, where the use of conventional mining systems (without backfilling) led to large-scale disasters, predetermines that the costs of backfilling operations (construction of a backfill complex; installation of a pipeline transportation system; production of the backfill composite; its delivery and placement in the mined-out space, etc.) should be regarded as justified and unavoidable.

The costs of constructing a backfill complex cannot be regarded as a disadvantage of the transition from conventional mining systems previously used at potassium-magnesium mines (systems with natural support of the mined-out space) to the implementation of multi-stage extraction (systems with artificial support of the mined-out space). At the same time, it should be taken into account that the implementation of multi-stage extraction does not involve a significant change in the technological scheme of a mine that previously used a conventional mining system. Retaining the previously used technological scheme does not require an additional set of works and measures for the construction of additional development or opening workings, since the extraction of the remaining reserves (pillars) will be carried out in sections that have already been opened and prepared.

It should be taken into account that increasing the recovery ratio (through the extraction of previously left pillars) is not the only positive effect of multi-stage extraction. The proposed technology makes it possible to dispose of significant volumes of technogenic waste (as part of the backfill composite) in the mined-out space, which were previously stored on the surface, thereby reducing (up to complete elimination) the degradation impact on the environment and thus achieving a positive environmental effect.

Backfill composite. The artificial mass created on the basis of the backfill composite being developed and investigated is the most important component of the proposed mining system, simultaneously ensuring environmental and technological safety and completeness of extraction. At the same time, the physical and mechanical properties of the developed backfill composite ensure the effective and safe implementation of multi-stage extraction.

The reference compositions (composition 1) are characterized by the formation of a brittle BC matrix structure. Figures 2, *a-d* show that the specimens underwent brittle failure, as evidenced by the sharp "drop" in the stress graph. At the same time, the replacement of conventional BC components with mining and processing waste is characterized by a sharp decrease in strength characteristics. However, the introduction of an activator into the BC formulation (compositions 4 and 5) makes it possible to create a stronger BC. Such specimens retain a brittle matrix structure (see Fig.2, *g*, *h*), but the final (residual) failure phase is characterized by less spontaneous failure. The structure of this BC is characterized by a greater amount of C-S-H gels and a smaller pore volume (see Fig.3).

The introduction of an inhibitor into the BC composition (composition 6) did not make it possible to significantly increase its strength. The brittleness and high porosity of the BC matrix were also retained. The slight increase in uniaxial compressive strength is explained by the fact that the fiber served as a basis for the formation of hydration products on its surface (see Fig.3), while its (the fiber's) high tensile strength prevents spontaneous failure. The fiber acts as a connecting "bridge".

The simultaneous introduction of an activator and an inhibitor into the BC composition made it possible to create stronger specimens. The ZSM-5 activator accelerates the hydration process and the formation of C-S-H gels that fill the pore space (see Fig.3). The fibers, serving as an additional surface for the formation of C-S-H gels and simultaneously as connecting "bridges", prevent sudden and brittle failure (see Fig.2, *i-k*). During uniaxial compression testing of the specimens, the retention of resistance to vertical loads and an increase in the deformation value are observed. This matrix is capable of providing resistance even after failure. As the load is applied, the specimen (at later

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storage periods) demonstrates load-bearing capacity (see Fig.2, *k, l*), which is visible in the phase III (post-peak) of failure. Further application of the load preserved the resistance of the BC matrix, after which deformation and failure occurred. The present study demonstrated that BC containing both a catalyst and an inhibitor in its formulation possesses load-bearing capacity after damage. This demonstrates that the addition of the proposed activators to the BC composition leads to the formation of a ductile BC structure, while the fibers prevent sudden failure.

Modeling. Bearing the weight of the overlying rocks is the primary function of both natural and artificial pillars. In addition, the artificial mass must ensure a certain allowable magnitude of vertical exposures during the extraction of chambers of the second and/or subsequent stages. The study of the behavior of the rock mass (both undermined and being mined) using computer modeling made it possible to determine the nature of stress development in the pillars for different mining systems (the variants under consideration), as well as to establish the magnitude of ground surface subsidence and vertical convergence of the inter-chamber pillars. These processes are poorly studied in mining geomechanics, which is associated with the difficulty of accessing the mined-out space. This is characteristic not only of potassium-magnesium deposits.

As follows from the presented results, over time, stresses in the pillars left in place gradually decrease and tend toward the level of the natural stress state of the rock mass regardless of the variant (mining system) under consideration. In the backfill system (variant 2), the influence of the unfilled chambers of the upper AB seam is noticeable. This is expressed in the transfer of the load from the undermined rock mass (above the AB seam) through the pillars of this seam to the underlying KrII seam being mined using the multi-stage extraction system.

In order to eliminate the negative influence of the unfilled chambers, uniformly redistribute stresses in the rock mass, and reduce stresses in the pillars (to the natural state of the undisturbed rock mass), backfilling of all adjacent mined seams should be provided. The absence of deformation changes in the inter-chamber pillars left in place by 16 years after backfilling the first-stage chambers and the decrease in the displacement rate of the undermined seams by this period indicate that the roof collapsed in the first-stage chambers and that the collapsed rocks that had "settled" onto the backfill were recompacted. The stable stress-strain state of the rock mass indicates that, from this point onward, extraction of the second-stage chambers can begin.

The stable stress state in the ICHP and the undermined rock mass when using backfill systems (compared with conventional systems) indicates the greater technological safety of the proposed multi-stage extraction using the developed BC. With multi-stage extraction systems, the magnitude of ground surface subsidence over the entire investigated period does not exceed one meter, which is almost two times less than with the conventional system currently used at the potassium-magnesium mines of the Verkhnekamskoye deposit. It is precisely the combination of the modeling results obtained, namely, the smaller magnitude of ground surface subsidence and the more stable stress state in the inter-chamber pillars and the undermined rock mass that indicates minimization of the risks of ground surface degradation. If it is also taken into account that the backfill mass is formed entirely from technogenic waste from the region, this fully demonstrates that the proposed multi-stage mining system minimizes (practically eliminates) the impact of the mining enterprise on the environment and ensures the environmental safety of the region.

Conclusion

The proposed multi-stage mining system using the developed BC makes it possible to: increase the recovery ratio (through extraction/additional recovery of reserves left in the ICHP); facilitate the unloading of ICHP from increased stresses; stabilize the stress-strain state of the rock mass; minimize horizontal disturbances both in the undermined rock mass and in the pillars, which generally ensures technological safety, while the use of local technogenic waste in the BC ensures the creation of an environmentally safe technology for mining potassium-magnesium deposits.

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The present study:

• Substantiated the necessity of transitioning from a conventional mining system (with natural support of the mined-out space) to systems with multi-stage extraction (with artificial support of the mined-out space) when mining potassium-magnesium (water-soluble) ores.

• Confirmed the possibility of completely replacing specially mined components of the backfill composite with technogenic waste in its formulation.

• Demonstrated that the use of multi-stage extraction with backfilling of the mined-out space enhances the environmental and technological safety of mining potassium-magnesium (water-soluble) ores.

• Established that technological safety is achieved by minimizing horizontal deformations of the undermined rock mass, ensuring the preservation of the water-protective stratum and the unloading of inter-chamber pillars from increased stresses, which contributes to their greater stability over time.

• Determined that environmental safety is achieved through the utilization of technogenic waste in the backfill composite, as well as through the reduction of horizontal deformations of the undermined rock mass, minimizing disturbance of the ground surface.

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Author **Roman V. Klyuev,** *Doctor of Engineering Sciences, Professor* (*Moscow Polytechnic University, Moscow, Russia*), *kluev-roman@rambler.ru, https://orcid.org/0000-0003-3777-7203*.

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