



Ensuring decarbonization underground construction technologies of backfilling based on the tailings

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Abstract. This study presents an innovative strategy for decarbonizing underground construction based on circular waste management by reducing coal mine methane emissions through goaf backfill. High methane emissions are often underestimated due to their low concentrations in ventilation air and leaks from abandoned mines. However, they significantly contribute to the global greenhouse effect. The study combines modeling and evaluation of the underground construction decarbonization effects and coal mining with the development and testing of goaf backfill monoliths based on tailings (Gai Mining and Processing Plant). By analyzing the methane emissions dynamics during coal and gas co-mining, we investigate and quantify gas losses arising from the low efficiency of the mine's gas drainage system, which could be converted into energy. It was found that activation of geomaterials increases the strength properties of backfill composites from 2.54 to 4.56 MPa. The use of activated tailings results in a denser and more homogeneous matrix with a more uniform pore space distribution. Furthermore, their use to ensure the stability of underground drainage boreholes will prevent the emission of 257,195 m³ of coal mine methane. This study confirms the viability of circular waste management in mining, demonstrating significant potential for additional benefits from the transition to sustainable underground construction.

Keywords: underground construction, geotechnology, backfill, circular waste management, decarbonization, tailings, methane emission reduction

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1. INTRODUCTION

The construction and mining industries urgently need to minimize greenhouse gas emissions (decarbonization) to transition to low-carbon and sustainable growth [1-4]. For example, the main areas of sustainable development in the concrete industry include: increasing the efficiency of kilns for heating limestone and clay mixtures, reducing clinker yield (when it is replaced, for example, with coal fly ash), reducing the percentage of cement in concrete (using superplasticizers), optimizing building structures to reduce concrete consumption, creating concrete capable of absorbing and accumulating CO₂, and others [5-7].

Underground mine construction has an advantage in this regard, since by optimizing security structures (erected in the mined-out spaces of existing working faces) and reusing enrichment tailings, it is possible to achieve a significant effect in reducing coal mine methane emissions. Numerous studies [8-10] have identified the key advantages of transitioning to roof management through backfilling in subhame geotechnologies: reduced stress concentration in the face margins, decreased roof-soil convergence, and preservation of the integrity of interlayer rock masses, which provide protection against flooding and increased methane emissions in the mining area [11-13]. However, the high proportion of cement used and the large volumes of construction work in challenging mining conditions hinder the widespread adoption of backfilling [14-16]. To reduce the cost of backfill construction, is quite promising to use enrichment waste as an inert filler or binder substitute [17-19].

Another important area of sustainable development is the introduction of the concept of circular waste management into underground construction, which means that resources are used for as long as possible throughout the life cycle of an enterprise [20-22]. However, the decarbonization effect of underground construction cannot always be definitively assessed by demonstrating a reduction in climate-active gas emissions. In this context, a key issue is ensuring the reliability of spatiotemporal models of gas flow distribution in the mined-out space of a longwall face for estimating methane emissions into the atmosphere. Many methods used data on the amount of gas in each coal seam and applies special weights [23-25]. However, the insufficient development of numerical modeling methods and the lack of large standardized data sets hinder the development of these models [26-27]. One relatively new method is the use of actual experimental data from underground drainage boreholes for three-dimensional predictive modeling [28-30]. The development of such models will reveal the hidden potential for reducing coal mine methane emissions when switching to roof management with partial backfilling of the mined-out space.

The objective of this study is to investigate the relationships between the parameters of backfill monoliths produced from mining waste and their strength properties, as well as the potential for reducing coal mine methane emissions when using partial backfill roof management. We hypothesize that the use of mining waste in backfill monolith structural systems can decarbonize mining operations by increasing the sustainability of underground boreholes. Therefore, this study aims to test the concept of decarbonizing underground mining construction, based on circular georesource management in the mining industry, by reducing coal mine methane emissions when using goaf backfill.

2. METHODS AND MATERIALS

Creation and testing of paste backfill arrays from mining waste. The object of the study was the enrichment tailings of the Gai Mining and Processing Plant (Orenburg region, Russia). Tailings samples were processed in a disintegrator to achieve activation of geomaterials by high-energy impact. Tailings treatment was carried out by grinding in a DESI-11 device. The fractional composition was determined using the laser diffraction method described in detail by Kaung et al. [31-32]. To improve the quality of component mixing, the principle of adding components from smaller to larger particle sizes was applied, with the tailings replacing traditional specially-mined inert fillers (sand, gravel, cement grade M-500 etc.). For this purpose, a laboratory mixer MIX-D-Ts (EN 196-1, EN 196-3, EN 413-2, EN 459-2) was used. Optimal and efficient mixing was achieved due to the characteristic planetary motion of the mixer, namely, a combination of circular motion and rotation around its own axis. The planetary rotation speed ranged from 62rpm to 125rpm, with an initial circular rotation speed

from 140rpm increasing to 250rpm. Then, samples were prepared using verified (calibrated) molds meeting the requirements of GOST-22685.

Uniaxial compression test and bending test were carried out in accordance with methodology described in [33]. The compressive strength was determined by testing cubes measuring 10 cm, similar to previous work [34]. For these tests, an MTS 816 testing machine (MTS Systems Corporation, USA) with TestWorks® 4 software, version 4.11 (Fig. 1), was used. Compression testing was performed at predetermined intervals following the classical methodology guidelines (Methodological recommendations, 1990): 7, 28, 45, 60, and 90days.

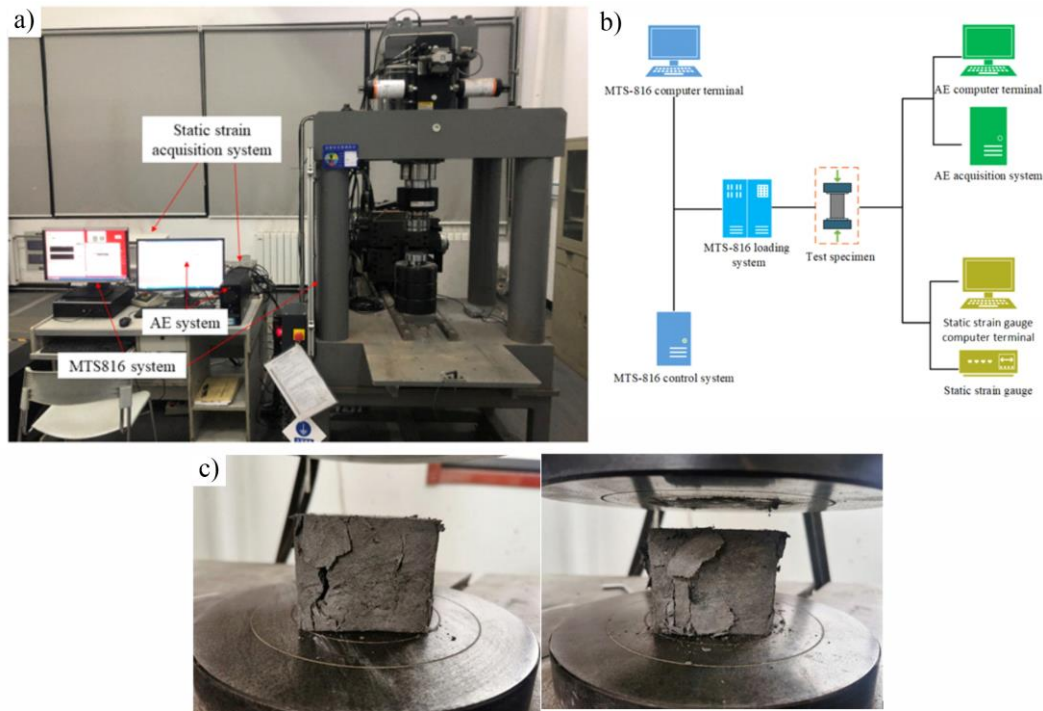


Fig. 1. System for determining the strength parameters of samples under uniaxial compression: a) – MTS 816; b) – research scheme; c) – compression examples (4 repetition).

The optical method of digital image correlation (3D-DIC) was used to track and automatically record the deformation patterns. The 3D digital image correlation method was utilized to examine surface displacement and deformation changes on the RUDIC setup (Inteltest LLC, Russia). Deformation changes in the samples were selected for primary analysis, since tensile deformation during bending is a critical indicator of damage. Microstructural analysis of the monolith was performed on the fracture surfaces of the samples after removing fine dust, using a Zeiss EVO 18 scanning electron microscope (SEM). Selected samples were sent to the laboratory for physical examination. The samples were further analyzed by X-ray diffraction (XRD) using a DRON-3M device. The study was conducted utilizing the co-radiation method with an Fe filter.

Assessing the effect of decarbonization. The second stage involved assessing on the decarbonization effect of the backfill arrays construction in the longwall mined-out space by reducing coal mine methane emissions. For this purpose, the potential for reducing methane emissions from coal mines extracted from degassed coal-rock massifs during combined coal and gas co-mining was investigated (using coal production from seam m3 in the 18th eastern panel as an example). In this case, wells were drilled in the 18th eastern ventilation drift (over 1,500m long, with a longwall of over 300m). Mining operations occurred at a depth exceeding 1,300m. To assess the features of the degassing network, whose inefficiencies result in additional methane emissions wells with the following location parameters were selected: inclination angle β (40°); hole azimuth φ (35°); drillhole spacing (25m); hole length (120m); diameter (120 mm); casing length (15m).

This forms a multivariate regression problem with three independent variables (regressors), equivalent to two three-dimensional regressions:

$$CH_4 = f(t; S), \quad (1)$$

$$CH_4 = f(L; S). \quad (2)$$

there: CH_4 – the methane concentration, %; t – measurement day of the year; L – the distance between degassing borehole mouths and the advancing longwall face, m; S – the distance from face to beginning of panel, m.

The author's method of data processing, in contrast to known approaches [35-36], for a two-dimensional formulation of the problem consisted of only using the coefficient of determination as the "goodness of fit" criterion. For three-dimensional models, quality assessment combined the coefficient of determination with residual analysis and the construction of standard Q-Q plots. For the two-dimensional problem of selecting the appropriate type of trend line, the least squares method was applied using MS Excel, in which graphs and Q-Q plots were also constructed. For the three-dimensional problem, the initial data were first smoothed; next, the scattered data were interpolated using the R. Renka algorithm; finally, the response surface was generated using the standard B-spline procedure in the Gnuplot software (version 5.4).

3. RESULTS AND DISCUSSION

Strength characteristics of paste backfill with and without mechanochemical activation of geomaterial. At the first stage, the results obtained during the activation of enrichment tailings were processed. The objects of the research were enrichment waste of the Gai Mining and Processing Plant the parameters of which are shown in Fig. 2.

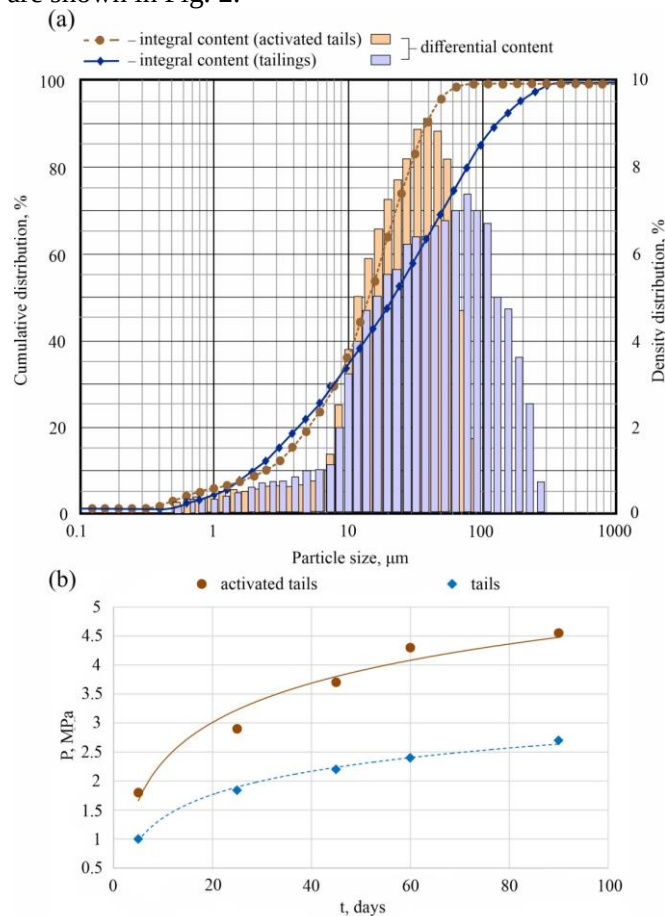


Fig. 2. The influence of geomaterial activation effect on the tailings granulometric composition (a) and strength parameters of backfill mass obtained on its basis (b).

As a result of Fig. 2b analysis, it was established that the function of the strength gain of monoliths for uniaxial elongation of the backfill mass with activated and non-activated filling depending on the hardening time has the following form:

– for non-activated ($R^2 = 0,96$):

$$P = 0.579 \ln t - 0.035, \quad (3)$$

– for activated ($R^2 = 0,98$):

$$P = 0.975 \ln t - 0.092, \quad (4)$$

From the analysis of the provided logarithmic analytical dependencies it follows that an increase in the strength of hardness leads to an increase in the tensile strength of the monoliths (σ_s), which is 2.54 and 4.56MPa, which corresponds to non-activated enrichment and activation tailings in the composition of the backfill.

Strength characteristics of monoliths under three-point bending. Next, a microstructural study of composite materials was carried out to establish a detailed image of the samples surface topography. The microstructure of samples was examined using scanning electron microscopy (SEM), a technique in which the surface is scanned with a focused electron beam. This providing highly detailed images of the sample surface topography with significant magnifications (Fig. 3).

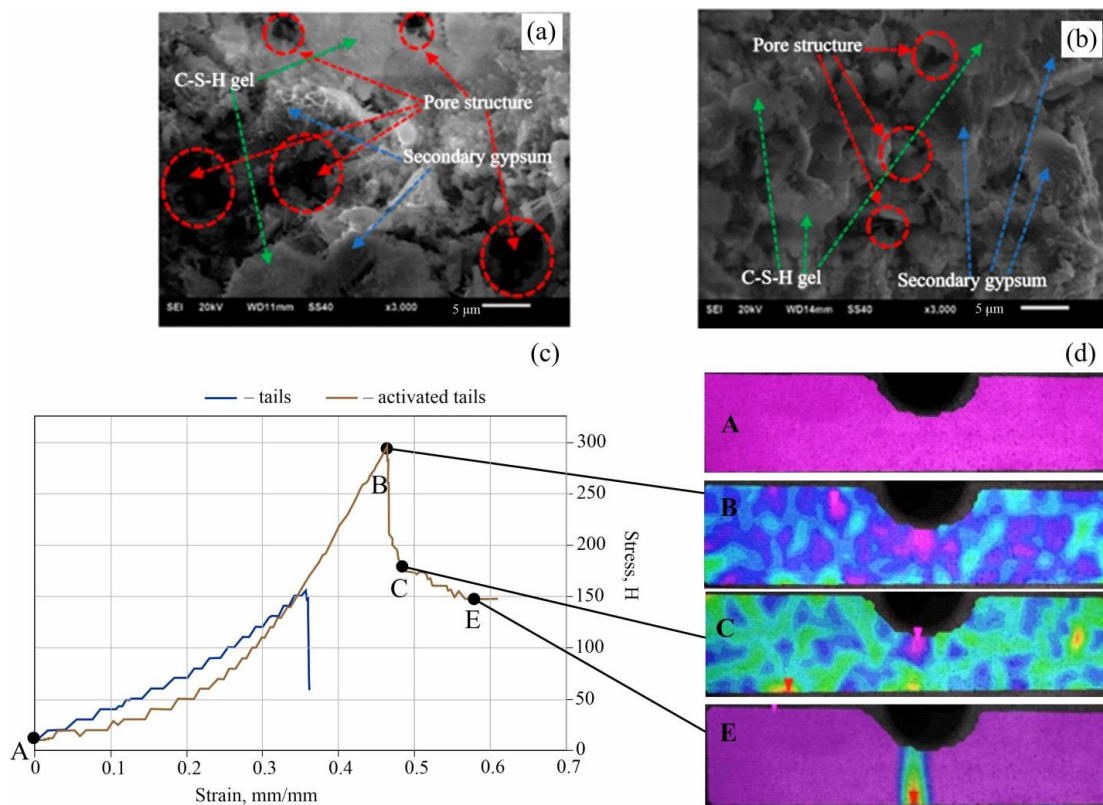


Fig. 3. Microstructural analysis of monoliths based on activated enrichment tailings: a) digital images of samples with non-activated enrichment tailings; b) digital images of samples with activated enrichment tailings; c) results of the optical method of correlation of moving digital images during tensile testing of samples; d) results of testing of samples during three-point bending.

To identify the main patterns of the influence of activation action on the dynamics of long-term strength of monoliths, microstructural studies of samples were carried out. Analysis of the results shown in Fig. 3a,b reveals that the matrix of the cured filling composite is a multiphase solid-liquid-gas system. The presented images clearly indicate that the distribution of matrix elements and the formation of pore space depend significantly on the grinding fineness of the beneficiation tailings. In both cases, at the early stages of hardening, the formation of hydration products is quite active, resulting in the development of a calcium silicate hydrate gel phase (C–S–H gels), commonly known as tobermorite gels ($\text{CaO} \cdot \text{SiO}_2 \cdot \text{H}_2\text{O}$). However, gels formed in composites containing non-activated tailings produce a less dense structure with larger pore spaces (Fig. 3a), in contrast to composites with activated tailings (Fig. 3b). The results of three-point bending tests of monoliths showed that the backfill mass based on activated waste (with some addition of plasticizer) has a significantly higher tensile strength (more than 75%) compared to monoliths based on non-activated enrichment waste. In contrast, the sample formulated with activated tailings demonstrated partial recovery of resistance after reaching the peak load (point B in Figure 3c), as shown by the ascending segment BC in Figure 3c. The results of measurements using the three-dimensional digital image correlation method made it possible to identify the features of the spatial variability of contour deformations, which are shown in Fig. 3d.

Evaluation of decarbonization efficiency in underground construction of backfill strips. At the second stage, a classical two-dimensional problem was solved (methane emission dynamics at different distances from the face) – the formation of a model of the dynamics of methane emission into degassing wells, both for the entire range of values and for a discrete set of intervals of distance to the face of the longwall shown in the Fig. 4.

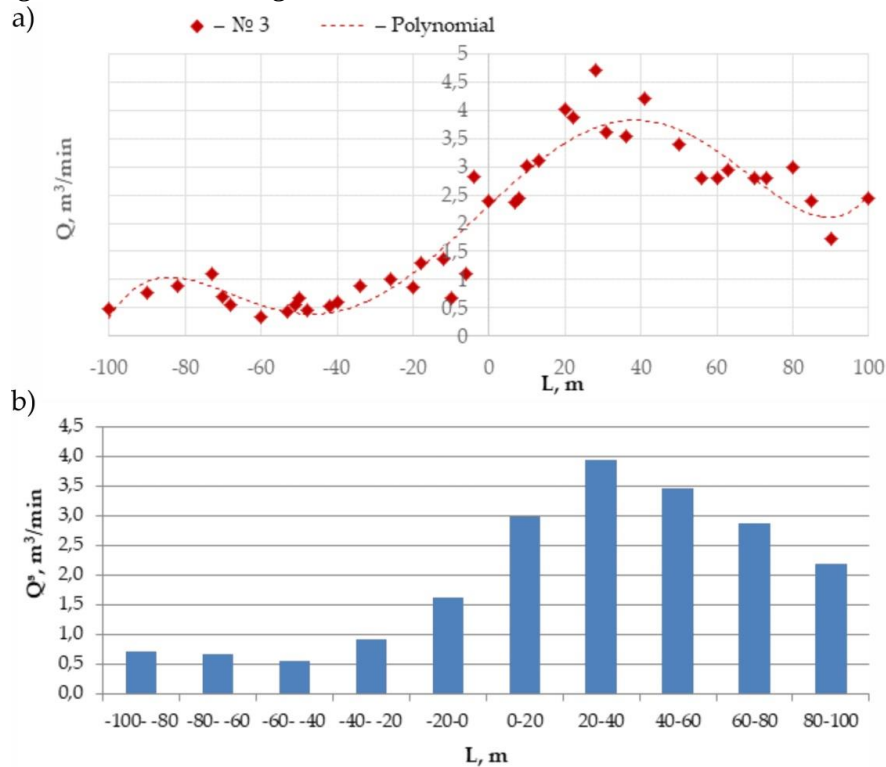


Fig. 4. Variation in the level of coal mine methane emission (Q) at different distances (L) between degassing borehole mouths and the advancing longwall face: a) – with continuous changes in L ; b) – using average Q values calculated over discrete intervals of L .

As a result of the analysis of Fig. 4.a), it was established that the function of the change gas flow consumption from distance to the working face, with a continuous change in L , has the following form ($R^2 = 0.89$):

$$CH_4 = 1E - 09L^5 + 4E - 09L^4 - 1E - 05L^3 + 0,0001L^2 + 0,0636L + 2,315. \quad (5)$$

As a result of solving the three-dimensional problem statement (Fig. 5.), a polynomial dependence of methane concentration on the distance from the working face line was established with decreasing distance to the beginning of panel ($R^2 = 0,93$). The domain of definition of points (the orthogonality interval of the approximating polynomials) corresponds to $S = S'$ for all $S' \in [0, \pi]$ and $L = L'$ for all $L' \in [0, \pi]$:

$$\begin{aligned} CH_4 = & 68,3 - 6,6 \cos(S) + 12,5 \cos(L) + 15,2 \cos(2S) - 43,3 \cos(S) \cos(L) + 30,8 \cos(2L) - \\ & - 23,7 \cos(3S) + 21,7 \cos(2S) \cos(L) - 3,79 \cos(S) \cos(2L) - 12,59 \cos(3L) + 3,69 \cos(4S) - \\ & - 31,28 \cos(3S) \cos(L) + 17,4 \cos(2S) \cos(2L) - 14,2 \cos(S) \cos(3L) - 14,4 \cos(4L) - \\ & - 0,29 \cos(5S) + 10,8 \cos(4S) \cos(L) + 1,1 \cos(3S) \cos(2L) - 8,0 \cos(2S) \cos(3L) + \\ & + 10,5 \cos(S) \cos(4L) - 4,6 \cos(5L) + 4,06 \cos(6S) - 12,5 \cos(5S) \cos(L) - \\ & - 8,3 \cos(4S) \cos(2L) + 2,5 \cos(3S) \cos(3L) - 0,4 \cos(2S) \cos(4L) + 10,2 \cos(S) + \\ & + \cos(5L) - 0,8 \cos(6L) - 3,6 \cos(7S) + 6,6 \cos(6S) \cos(L) - 8,5 \cos(5S) \cos(2L) - \\ & - 8,5 \cos(4S) \cos(3L) + 1,2 \cos(3S) \cos(4L) - 0,5 \cos(2S) \cos(5L) + 3,5 \cos(S) \cos(6L) - \\ & - 3,8 \cos(7L) + 0,4 \cos(8S) - 5,8 \cos(7S) \cos(L) - 4,7 \cos(6S) \cos(2L) + \\ & + 6,9 \cos(5S) \cos(3L) + 7,1 \cos(4S) \cos(4L) - 6,4 \cos(3S) \cos(5L) + \\ & + 5,5 \cos(2S) \cos(6L) - 3,8 \cos(S) \cos(7L) - 3,4 \cos(8L) - 2,6 \cos(9S) + \\ & + 4,5 \cos(8S) \cos(L) - 1,2 \cos(7S) \cos(2L) - 0,2 \cos(6S) \cos(3L) + 4,4 \cos(5S) \cos(4L) - \\ & - 0,8 \cos(4S) \cos(5L) - 2,3 \cos(3S) \cos(6L) + 1,0 \cos(2S) \cos(7L) + 0,6 \cos(S) \cos(8L) - \\ & - 3,9 \cos(9L) + 1,1 \cos(10S) - 3,9 \cos(9S) \cos(L) - 0,6 \cos(8S) \cos(2L) + \\ & + 1,1 \cos(7S) \cos(3L) + 3,5 \cos(6S) \cos(4L) - 4,6 \cos(5S) \cos(5L) + \\ & + 1,6 \cos(4S) \cos(6L) + 1,3 \cos(3S) \cos(7L) + 1,3 \cos(2S) \cos(8L) + \\ & + 3,1 \cos(S) \cos(9L) - 1,8 \cos(10L). \end{aligned} \quad (6)$$

there: CH_4 – the methane concentration, %; L – the distance between degassing borehole mouths and the advancing longwall face, m; S – the distance from face to beginning of panel, m.

From the analysis of the linear trend shown in Fig. 5a, it follows that the quality of the obtained model is satisfactory.

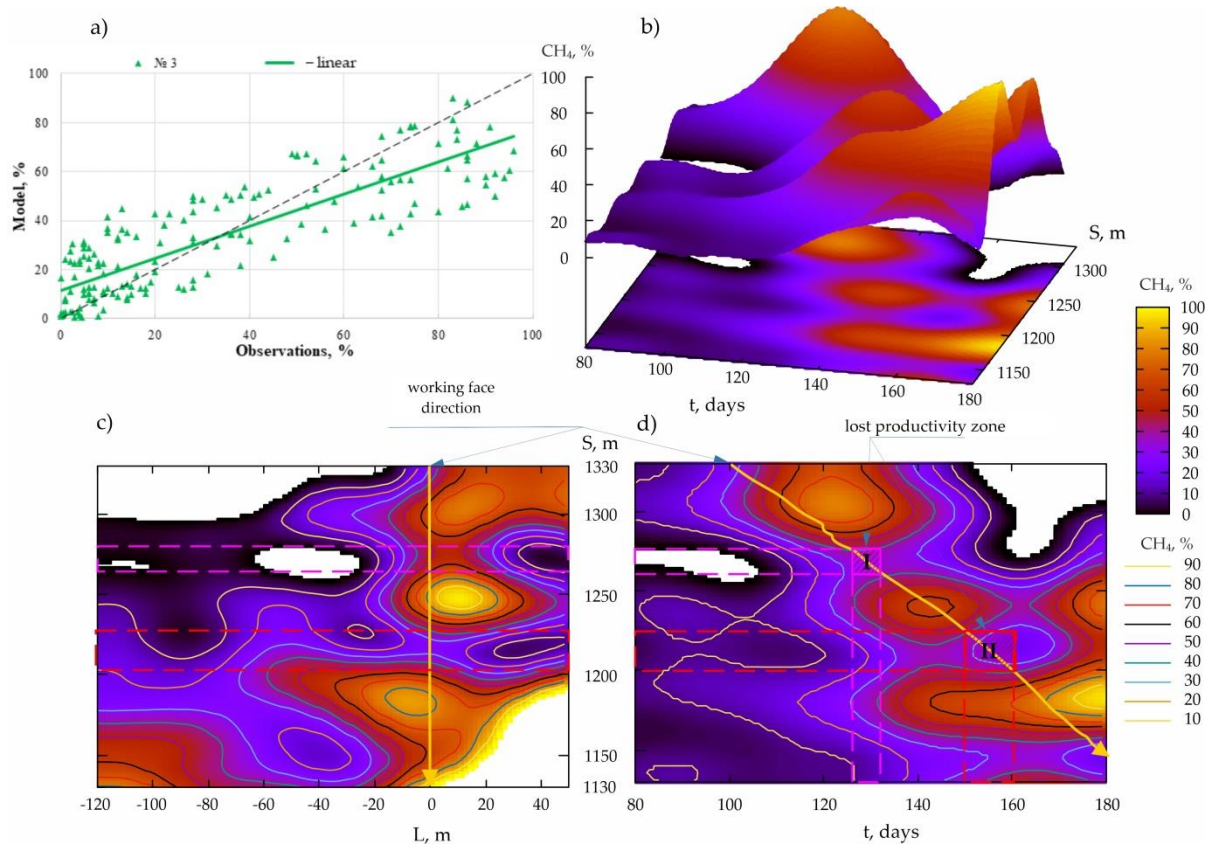


Fig. 5. Spatio-temporal dynamics of gas flows during drainage of an undermining massif by underground boreholes: a) – Q-Q diagram for assessing the model quality $CH_4 = f(t; S)$; b) – type of response function for $CH_4 = f(t; S)$; c) – projection of regression $CH_4 = f(L; S)$ onto plane L-S; d) – projection of regression $CH_4 = f(t; S)$ onto plane t-S; I and II – regions (zones) of localization of extrema of the function in which the operating mode of the degassing network was unsatisfactory (gas was released into the atmosphere instead of boreholes).

Analysis of Fig. 5c indicates that, as the face line (yellow arrow) moves from the minimum roof span and maximum S, and as borehole shafts appear ahead of the face (negative L values, from -10 to -15m), the methane content in the aero gas mixture (accordingly and net gas flow) reaches minimum values. At distances behind the face ranging from L = 0 to 20m, methane extraction volumes increases sharply; this process is expected to vary with any changes in S. In our case, several “dark spots” – zones of minimal methane capture productivity – are observed, associated with the deterioration or failure of certain boreholes due to adverse rock pressure conditions.

When examining this process over time (Fig. 5d), it becomes evident that when the face movement line turns at a specific angle (proportional to the advance rate of the working face), these zones (highlighted by dotted lines) define clear boundaries of the “level drop zone”. Parameters of this zone allow for accurate calculation of actual volumes of anthropogenic methane emissions (losses of alternative energy resources), which can lead to unreliable operation of panel degassing network. To calculate the volumes of coal mine methane lost due to poor well performance, the parameters of zones I and II were summarized in Table 1.

Table 1. Slag classification.

Pickets (S. m)	Zone I (t = 126-132 days)			Zone II (t = 150-160 days)		
	L, m	Q ^s , m³/min	ΣQ', m³	L, m	Q ^s , m³/min	ΣQ', m³
1280	20-40	3.94	39715	80-100	2.19	31536
1260	0-20	2.99	30119	60-80	2.87	41328
1230	-20	0.92	9240	20-40	3.94	56736
1210	-20	0.55	5494	0-20	2.99	43027
Common for zone I			84 568	Common for zone II		172 627

As a result of calculations, the total volume of losses, only for wells of this type and only for the studied period of panel development, exceeded 257 195m³.

In the microstructure of the samples with a larger fractional composition of beneficiation tailings (without activation) (Fig. 3a), the formation of scattered matrices of calcium hydrosilicate gels (C-S-H gels) or tobermorite gels (e.g., CaO•SiO₂•H₂O) is observed. The hydration products in these samples did not form strong adhesion, which is confirmed by the presence of cracks between hydration phases (or specify: e.g., particles) and a large volume of pore space within the microstructure. Thus, a single strong structural matrix of the filling composite was not formed.

The analysis indicates that the number of voids in the matrix of the filling composite decreases when using activated (i.e., finer fractional composition) beneficiation tailings in the filling composite formulation. This improves the quality of filling the voids (pores) with hydration products and the formation of stable adhesion between them, which contributes to the formation of a stronger matrix structure. Similar results to ours were obtained in the works [37-39].

The most significant result of the three-point bending test is the detection of temporary loss of resistance in samples with activated tailings after the formation of a primary crack (matrix failure) and its subsequent recovery. The nature of the formation of a brittle-plastic matrix of the filling composite with activated tailings should be studied in following studies.

During curing, secondary hydration products are formed (secondary gypsum, ettringite, and C-S-H gels) characteristic of matrices containing both activated and non-activated beneficiation tailings. Activation of beneficiation tailings allows accelerating the formation of hydration products in the matrix of the filling composite, and the formation of ettringite (aft) with the chemical formula Ca₆Al₂(SO₄)₃(OH)₁₂•26H₂O is observed in the samples. In the microstructural images of samples containing activated beneficiation tailings (Fig. 5b), a more even distribution of the formed hydration products is observed, which uniformly fills the initial voids. This made it possible to create a single strong matrix. In this context, further research on the effect of adding steel fibers to increase the strength of the fill, including taking into account seismicity, is quite promising [40-41]. The nature of the distribution of gas flows in our study confirms the correctness of the approach to modeling stress changes as a function of relative mining distance of the working face for the roof in the *m*₃ coal seam caused by mining [42].

According to Fig. 4a of this study, when the face advance distance is less than or equal to 20m, the stress state is similar to the initial, pre-mining condition. Its further increase to the formation of a stress concentration area. Furthermore, measurements in the goaf indicate that the stress after relief is markedly lower than the initial stress, and these locations are identified as "high-strength pressure relief infiltration areas". In our case, this explains the formation of the zone of maximum methane emission (highlighted in yellow in the lower right corner of Fig. 5c) within the goaf, resulting from the initial development of high-strength pressure-relief zones. We hypothesize the stress-relieved zone forms an elliptical paraboloid of the fissure [43]. This is consistent with the observation that after the main roof caved, the 80% methane isogas (blu curve) gradually expands the area of the local maximum in goaf when mining the panel in reverse order from S = 1200 to 1130m.

Although our study has limitations (considered limited in time – less than 240 days and no more than 200 m of the main roof span), the observed nonlinear pattern of methane concentration distribution as the roof span increases is similar to the stress change mechanisms in [44-46]. Unlike comparable methods, our approach quantifies methane losses resulting from local drainage network failures.

4. CONCLUSIONS

Existing level and parameters of underground geotechnologies have significant growth potential in the area of reducing emissions of climate-active gases, issues related to ensuring the decarbonization of underground construction are becoming relevant. Due to this, one of the innovative strategies founded on circular economy principles consists of using activated tailings as a component of the backfill, which ensures the sustainability of degassing wells and reduces coal mine methane emissions. The circularity of georesources is ensured by reducing methane losses and subsequently converting this “waste” into electricity. This is a promising avenue for ensuring sustainable mining by reducing emissions of climate-active gases.

As a result of the research, it was established:

- geomaterial activation improves the mechanical properties of the backfill mass created from it. This increases the uniaxial compressive strength of the mined-out backfill monoliths from 2.54 to 4.56 MPa. Furthermore, the dependences in both cases are logarithmic. Microstructural analysis confirms that tailings activation leads to the formation of a denser matrix structure. Apparently, this structure has a smaller pore space, which improves the bond between the composite components, resulting in greater strength;
- when a massif was undermined reducing the distance from the beginning of the panel or increasing the roof span to 200 m in the distance range L from –40 to 0 m (in front of the face), the methane concentration increased nonlinearly to local maximum = 70-80% ($S = 1267-1240$ m), which is replaced by a local minimum according to the polynomial dependence to 20-30% (complete collapse of the panel drainage network). For this reason, quantified losses (emissions of mine methane in atmosphere) for the wells under study during the panel development phase exceeded 257 195 m³.

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