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Environmentally sound geotechnologies for leaching metals from polymetallic ore processing wastes and wastewater

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Abstract

Global challenges (increased consumption of georesources, climatic changes, limited reserves) increase the relevance of the problems of growing waste accumulation and environmentally-sound modernization of mineral extraction. In this regard, the existing approaches to the design of geotechnologies for metal mining need to be improved based on a concept of so-called circulation waste management and ecologization of technological processes. The paper is devoted to the issue of formation of conceptual bases and directions of ecologization of geotechnologies at leaching metals from polymetallic ore processing wastes and wastewater. The study presents recommendations for improving in-situ leaching of ores in blocks, allowing to determine the optimal conditions for increasing the completeness of subsoil use and reducing environmental damage. It was revealed that at metal extraction with solution circulation through brine chambers the content of Na, Cl, SO_4 and Ca ions in dialysate was low, while without circulation through brine, it significantly exceeded corresponding MPCs. This proves the fundamental feasibility of controlling natural leaching processes by enhancing the oxidizing potential of natural solvents through the addition of industrial oxidizing agents. It was found that increasing the duration of agitation leaching (both with and without mechanoactivation) leads to a uniform expansion of the local maximums of Pb yield from the pulp when the minimum NaCl concentration decreases from 11–12 to 7% at H_2SO_4 concentration of 0.6%. One of key results of the study is justifying the expansion of the use of disintegrators to realize targeted activation of tailings. The practical significance of the obtained results lies in the proved feasibility of optimizing the flow sheet of electrochemical extraction of metals from wastewater on the basis of the obtained regularities of the use of brine circulation through brine chambers. In addition, the totality of the obtained results of using a disintegrator for re-extraction of lead from geomaterials will allow developing a methodology for calculating the parameters of mechanoactivation action to increase the degree of metal recovery from the tailings of North Ossetia-Alania's (Zgidskoe, Sadonskoe, Arkhonskoe deposits) polymetallic ores beneficiation. The most promising way for further research is to substantiate methods of using underground space for complete removal of wastes (wastewater and tailings) after their multistage treatment.

Keywords

tailings, wastewater, acid leaching, mechanochemical activation, Pb recovery, geotechnologies, waste management

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ТЕХНОЛОГИЧЕСКАЯ БЕЗОПАСНОСТЬ В МИНЕРАЛЬНО-СЫРЬЕВОМ КОМПЛЕКСЕ И ОХРАНА ОКРУЖАЮЩЕЙ СРЕДЫ

Научная статья

Экологически чистые геотехнологии выщелачивания металлов из твердых и жидких отходов обогащения полиметаллического сырья

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Аннотация

Глобальные вызовы (рост потребления георесурсов, климатические изменения, ограниченность запасов) повышают актуальность проблем роста накопления отходов и экологической модернизации добычи минерального сырья. В связи с этим существующие подходы к проектированию геотехнологий добычи металлов нуждаются в совершенствовании на основе концепции циркуляционного управления отходами и экологизации технологических процессов. Статья посвящена вопросу формирования концептуальных основ и направлений экологизации геотехнологий при выщелачивании металлов из твердых и жидких отходов обогащения полиметаллического сырья. В исследовании предложены рекомендации по совершенствованию подземного выщелачивания руд в блоках, позволяющие определить оптимальные условия для повышения полноты использования недр и уменьшения ущерба окружающей среде. Выявлено, что при извлечении металлов с циркуляцией раствора через рассольные камеры содержание ионов (Na, Cl, SO_4 и Ca) в диализате было низким, а без циркуляции в рассоле существенно превышало ПДК (по Na, Cl, SO_4 и Ca). Это доказывает принципиальную возможность управления процессами подземного выщелачивания путем усиления окислительного потенциала растворителей за счет добавления промышленных окислителей. Установлено, что рост продолжительности агитационного выщелачивания (как с использованием, так и без механоактивации) приводит к равномерному расширению локальных максимумов выхода Pb из пульпы при снижении минимальной концентрации NaCl с 11–12 до 7 % при H_2SO_4 = 0,6 %. Одним из ключевых результатов исследования является обоснование расширения области использования дезинтеграторов для осуществления направленного активационного воздействия на хвосты обогащения. Практическое значение полученных результатов заключается в возможности оптимизации технологической схемы электрохимического извлечения металлов из техногенных стоков на основании полученных результатов применения циркуляции рассолов через рассольные камеры. Кроме того, совокупность полученных результатов использования дезинтегратора для повторного извлечения свинца из геоматериалов позволит разработать методику расчета параметров механоактивационного воздействия для повышения степени извлечения металлов из хвостов обогащения полиметаллического сырья РСО–Алания (Згидское, Садонское, Архонское месторождения). Наиболее перспективным направлением дальнейших исследований является обоснование путей использования подземного пространства для полного захоронения отходов (техногенных стоков и хвостов обогащения) после их многостадийной обработки.

Ключевые слова

хвосты обогащения, растворы/стоки, кислотное выщелачивание, механохимическая активация, извлечение Pb, геотехнологии, управление отходами

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Introduction

Mining enterprises around the world step up the rate of accumulation of various types of waste, causing environmental degradation due to the growth of production, gradual transition to the mining of lean and disseminated ores, as well as due to the complication of mineral deposits mining conditions [1–3]. Big data from the enterprise can be used to reduce resource consumption and optimize reserves at mines using digital twin approach [4]. Digital models of geologic mineral reserves in combination with GIS technologies allow forming digital twins of deposits, determining the design of more rational mining methods [3]. At the same time, solutions to some environmental problems can be achieved by optimizing existing technological processes, as well as improving the quality of management of natural-technogenic systems [5, 6].

Heap leaching methods, which are widely used around the world, allow metals to be extracted more profitably from various types of low-grade ores. At the same time, even the existing level of understanding of its fundamentals does not allow to fully ensure environmentally sound implementation in the pursuit of sustainable development of mineral resource base [7]. This gives rise to the problem of formation of wastewater, dry waste dumps and dust contamination. Each dusting facility is characterized by individual peculiarities, which allows the use of process models to minimize emissions into the atmosphere, but does not allow to completely solve this problem [8]. Minimizing the consequences, i.e., hydrosphere pollution, requires the development of measures that take into account a whole set of mutually determined factors [9, 10]. Tailings storage facilities (TSFs) are anthropogenic deposits composed of ore processing tailings, which participate in environmental pollution with chemical ingredients due to natural and anthropogenic leaching processes [11–14]. Thus, in our country, more than 45 billion tons of solid waste (including dusting ones) have already been stockpiled in the form of waste dumps, of which beneficiation wastes annually add about 140 million m^3/year to this figure [15].

The solution to waste problems in the recovery of polymetallic raw materials can be achieved with greening and widespread use of in-situ leaching geotechnologies. Progressive technologies of in-situ leaching in blocks are implemented in mining industry to maintain and strengthen the mineral resource bases of technologically developed countries [16, 17]. The history of implementing and development of the in-situ block leaching at nuclear industry enterprises of the USSR in Kazakhstan is described in [18]; at the same time some processes remain insufficiently studied. Thus, for Jimidon ore field, increasing the availability for processing of low-grade reserves of polymetallic raw materials can be achieved by improving the quality of breaking (blasting) and selective energy consumption in the blasting preparation of ores [19]. At mining enterprises in Russia, primarily in the nuclear industry, in-situ block leaching methods are used in mining of a large share of commercial products, for example, at Priargunsky MCC. In this case, suboptimal topology of the surface well network is used, which does not allow the use of directional drilling to minimize the number of injection wells (when they are drilled in parallel to the ore body) that leads to an increase in waste generation with low efficiency of in-situ leaching [20].

The rate of leaching processes is determined by the metal content, the thickness of the diffusion layer and the diffusion coefficient. The rate of chemical reaction is crucial for the extraction of rare earth elements in the process of in-situ leaching (which is accompanied by ion migration, which gives it an electrochemical character) with two parameters being the most important: solution resistance and charge transfer resistance [21]. In addition, the maximum recovery corresponds to a high velocity of solution movement relative to the reaction surface. In the Caucasus, most of the exploited deposits are of the quartz-polymetallic type in the quartz-keratophyre formation, e.g., Sadonskoe. It is characterized by polymetallic and pyrrhotite types of mineralization. Water is the cause of the hydrolysis process. When a certain acidity is reached, iron sulfate reacts to form iron hydroxide. Of the methods of solution purification the most commonly used is chemical, the disadvantage of which is the possibility of environmental pollution by reagents in case of emergency violation of the process conditions.

The existing mathematical methods for controlling leaching processes require a large amount of a priori information about the structure and properties of the deposit, with one of the main methods being the method of expert reviews, which does not provide sufficient reliability of the results obtained [22, 23]. The noted features of mining practice are most acutely manifested in the implementation of processes where the error can reduce the performance of a process to an unacceptable level [24, 25]. For example, if the parameters of ore breaking for leaching are wrong, the highly efficient process with chemical dissolution of metals becomes impossible to use.

The existing approaches to the design of geotechnologies for metal extraction need to be improved based on the concept of circulation waste management and greening of technological processes [26, 27]. Study [28] convincingly proved the necessity of solving the primary problems for "the transition to the circulation economy in the conditions of handling technogenic mineral formations". The drawback of realizing the author's idea of creating pathways to achieve the goal is the perception of the circulation approach as a "closed supply chain concept". While, for example, for coal mine's methane it is formulated as "conversion of waste (methane) into energy" [29, 30]. In this regard, the author's hypothesis of "circulation management of tailings" consists in: "the optimization of technological processes of leaching, mechanochemical activation of geomaterials or other methods allowing to transform beneficiation tailings into the source of additionally recoverable metals with the subsequent use of tailings in production of building materials or at facilities for burial (inert filler of underground space)".

In this regard, the **purpose** of the study is the formation of conceptual bases and directions of ecologization of geotechnologies at leaching metals from polymetallic ore processing wastes and wastewater. In this regard, the following **problems** should be solved: 1 – to analyze and classify measures to improve geotechnologies of underground metal leaching; 2 – to simulate the process of electrochemical metal extraction from wastewater; 3 – to substantiate the efficiency of metal extraction with the use of preliminary mechanochemical activation of dry tailings.

Methods

The study targets are technogenic deposits of North Ossetia-Alania (Russia). Intensive exploitation of ore deposits is accompanied by the formation of dumps of substandard ores and tailings of processing plants located in river valleys.

Quantitative values and parameters of wastewater in the conditions of the Sadonskoe ore cluster deposit are given in Table 1.

The volumes of storage of tailings from the processing plants of the North Caucasus are given in Table 2.

To assess the prospects in the field of improvement of underground geotechnologies, a retrospective review of the theory and practice of application of technological innovations at the enterprises of the Ministry of Atomic Energy and Industry of the USSR was carried out.

To solve the second problem, wastewater with electrochemically treated leaching reagents were tested. Sulfate-chloride wastewater of the Arkhonskoe deposit (North Ossetia-Alania) with predominance of sodium cations was tested at a unit in the All-Union Research Institute of Chemical Technology (Moscow). The base for determining the performance of metal leaching from natural resources is the results of leaching of ores and their processing products in percolator columns using natural reagents.

The third problem was solved on the basis of testing of Mizursky processing plant tailings. The pulp was activated by high-energy grinding in DESI-11 unit with rotor speeds of 50 and 200 Hz for 0.25 and 1 h, respectively. To form a pulp, the ground tailings samples were screened using a 2.0 mm mesh sieve and mixed with the filtrate. The modeling technique was developed by analogy with the technique considered in [31–33], and consisted in data processing based on the Savitzky-Golei filter combined with three-dimensional interpolation using the method of R.J. Renka (Robert Renka) [34–36]. The algorithms were implemented as "scripts" (using Vi IMproved software (version 9.0)) in Python (version 2.7.10). The final three-dimensional plots were built using Gnuplot software (version 5.4).

Table 1

Characterization of industrial wastewater

Deposit	Wastewater volume, m^3/h	Metal content, g/m^3
Sadonskoe	300	Lead – 5, zinc – 7
Zgidskoe	24	Lead – 5, zinc – 12
Kholstinskoe	70	Lead – 8, zinc – 25
Archonskoe	30	Lead – 65, zinc – 7
Khanikom-Kakadurskoe	150	Lead – 5, zinc – 100
Urupskoe	350	Copper – 12, zinc – 41, iron – 0.2
Tyrnyauz	400	Molybdenum – 37, tungsten – 45

Table 2

Ore processing tailings storage quantities

Tailings Storage Facility (TSF)	Quantity of beneficiation tailings, tons	Grades of Metals, %
Mizursky processing plant	3,000,000	Zinc – 0.15–0.25, lead – 0.13–0.19
Fiagdon processing plant	3,000,000	Zinc – 0.18–0.24, lead – 0.18–0.24
Electrozinc plant	3,000,000	–
Urupskoe processing plant	4,000,000	Zinc – 0.25–0.40, copper – 0.36–0.46, iron – 30–35
Tyrnyauz processing plant	120,000,000	Tungsten – 0.25–0.40, copper – 0.36–0.46, iron – 30–35%

Findings

Improvement of geotechnology of in-situ leaching of metals

Leaching of polymetallic raw materials is the process of filtration of aqueous solution through rock strata under the action of gravity, capillary forces at interphase boundaries or due to pressure gradients between injection and production (pumping-out) wells. The internal structure of a porous medium is random and its geometry can be described only approximately. In this connection, the determination of aqueous solutions flow parameters on the basis of hydraulic equations shall be approximated, with some degree of probability.

The main parameters of the filtration process are viscosity, permeability, velocity, and pressure of a liquid [37, 38]. A liquid moving in a porous medium is a non-Newtonian one, for which the relation describing the rate of strain change as a function of stress is described by the rheological law:

$$\tau_{xy} = \tau_0 + \mu \frac{\partial u_x}{\partial y}, \tag{1}$$

where μ is dynamic viscosity; τ_0 is initial shear stress; u_x is flow velocity in the direction being square with OX axis.

In a porous medium, a non-Newtonian liquid satisfies the equation of motion and the continuity equation in the absence of inflows and discharges:

$$\begin{gathered} \rho \frac{\partial \bar{V}}{\partial t} = -\nabla \bar{p} + \nabla(\bar{\tau} - \rho \bar{V}' \bar{V}'), \\ \frac{\partial(\rho m)}{\partial t} + \nabla(\rho \bar{V}) = 0, \end{gathered} \tag{2}$$

where ρ is density of medium; m is porosity; $\bar{V}$ is the velocity vector; $\bar{p}$ is pressure distribution; $\bar{\tau}$ is stress tensor.

The permeability of an ore-bearing formation differs depending on its density, but under the conditions of chaotic variation of filtration characteristics at each point of a formation it is possible to assume its state to be homogeneously permeable. If the filtration characteristics of a formation, porosity and permeability, vary from point to point, the formation is heterogeneous.

In a mathematical model of potential flow, the total formation flow rate is the sum of the flow rates of all layers (composing the formation). For simplification, a heterogeneous formation is modeled as a quasi-uniform formation with averaged formation permeability

$$k_{av} = \sum_i \frac{k_i h_i}{h}, \tag{3}$$

where k_i is permeability of the i-th layer; h_i is thickness of the i-th layer; h is thickness of the whole formation.

In generalized form, the model of diffusion of solution for leaching of metals from ores can be represented by the Fokker-Planck equation:

$$\frac{\partial W}{\partial t} = \left[\begin{gathered} -\sum_{i=1}^{3} \frac{\partial}{\partial x_i} D_i^1(x_1, x_2, x_3) + \\ + \sum_{i=1}^{3} \sum_{j=1}^{3} \frac{\partial}{\partial x_i \partial x_j} D_{ij}^2(x_1, x_2, x_3) \end{gathered} \right] W, \tag{4}$$

where $W(\bar{V}, t)$ is velocity probability density function; D^1 is flow drift vector; D^2 is diffusion tensor.

The presence of particles coarser than 5 mm in a layer adjacent to a solid phase increases the intensity of metal particles transport in the extracted liquid.

The optimal leaching method is the one that ensures the transit of metals into a mobile state with minimal ore preparation costs and provides permeability of the crushed ore for leaching solutions. Mineral extraction technologies, including leaching methods, and their individual components are evaluated by the criterion of the completeness of metal extraction from ores [39, 40]. It follows from the review of studies [41] that measures to improve in-situ leaching of ores in blocks (with controlled permeability of the blocks for leaching solutions) can be systematized (Table 3).

Simulation of efficiency of metal recovery from wastewater

The method of electrochemical softening of concentrated solutions through electrodialysis desalination consists in using the phenomenon of selectivity of ion-exchange membranes: cation-exchange membranes pass positive ions, while anion-exchange membranes pass negative ions.

Membrane electrolysis provides reagent-free softening of natural solutions and concentrating of minor elements. Electrodialysis and activation in diaphragm electrolyzers with decomposition of salt systems into acid and alkali and neutralization of solutions are rather promising. The disadvantage of the method is the deposition of hardly soluble compounds in brine chambers.

The parameters of metal recovery from a solution are determined for options with the solution circulation through brine chambers and without the circulation. Natural solutions are fed into the desalting chamber, and pure water is fed into the acid/alkali generation chamber. After that, the reagents required for the generation of alkali and acid (selected for the implementation of the technological cycle) are fed into the chambers. As the proportions of magnesium, calcium ions, and acids increases, the efficiency of the investigated process deteriorates due to a decrease in the quality of membrane contact with brine

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due to the adhesion of carbonate precipitates and magnesium oxide. Energy consumption for removal of 1 kg of salt is 0.6 kW (at residual concentrations of Zn = 0.3–0.4 mg/dm^3 and Pb = 0.06–0.08 mg/dm^3, respectively).

To implement the author's approach, a series of tests was carried out for different schemes of brine (solution) circulation. The obtained performance data for these schemes are presented in Table 4 and Figs. 1, 2.

It follows from the surface analysis presented in Fig. 1, that the option of the electrochemical method with brine circulation through brine chambers is the most efficient way to leach metals from industrial wastewater. Extraction of metals from brines is carried out in sorption and washing columns up to 4 m high and 1–1.5 m in diameter. Consumption of reagents per 1000 m^3 of solution: cationite (anionite), 0.8 kg; regenerating reagent, 100–150 kg.

It follows from the analysis of the concentrations presented in Fig. 3, that the values for Na, Ca, Cl, and SO_4 significantly exceed the MPCs (Na – 6,089, Ca – 650, Cl – 4,600, and SO_4 – 153 mg/dm^3).

Table 3

Measures to improve in-situ leaching of ores in blocks

Process	Essence of the process	Effect of implementation
1	2	3
Rock blasting and crushing	Advanced horizontal undercutting by blastholes (by a value of the thickness of a vertical layer)	Rationalization of compensation space formation, optimization of the ore grain size to be shrinked
	Blasting by layer with variable line of least resistance	
	Approximation of a layer shape to the vertical projection of the release shape	
Spraying with reagent solutions	Wells with casing and positioning of fine-grained layer in broken ore	Regular spraying by reagent solutions within the shrinked ore and in time
	Hydraulic rock fracturing	
Collection of solutions	Capturing solution leaks with electro-vacuum units	Optimization of reagent consumption
	Drainage by perforated pipes to a unit bottom	
	Creation of impervious screens made of polymeric materials	Minimizing environmental damage
Process intensification	Use of liquid explosives in blastholes for ore blasting	Displacement of leached ore pieces with destruction of colmataged zones
	Ore movement when breaking new layers on it	
	High-pressure compressed air pulse action	Increase in permeability through removing joint fillers and destruction of clay films Increasing the rate and completeness of metal recovery
	Ultrasound action during electromagnetic treatment of solutions with passing them through electric field	
	Action by pulsating electric current with low-frequency pulses	
Combining the extraction of different grade ores	Excavation of balance ores for conventional processing, shrinkage of a portion of balance and off-balance ores and leaching	Comprehensive improvement of deposit development performance

Table 4

Performance of metal recovery from solutions at different types of solution circulation

Component	N	Initial solution (wastewater)	Performance of metal recovery from solutions (brines)	
			with brine circulation through brine chambers	without circulation
			in dialysate	
Model options		1	2	3
Pb	1	2.2±0.3	0.1±0.02	0.08±0.02
Zn	2	40±1.2	0.4±0.05	0.3±0.03
Mg	3	70±1.9	10±2	8±1,1
Ca	4	200±6	30±1.2	40±1.7
Na	5	450±15	72±1.5	90±1.3
SO_4	6	580±20	100±11	95±4
Cl	7	900±5	114±19	105±5

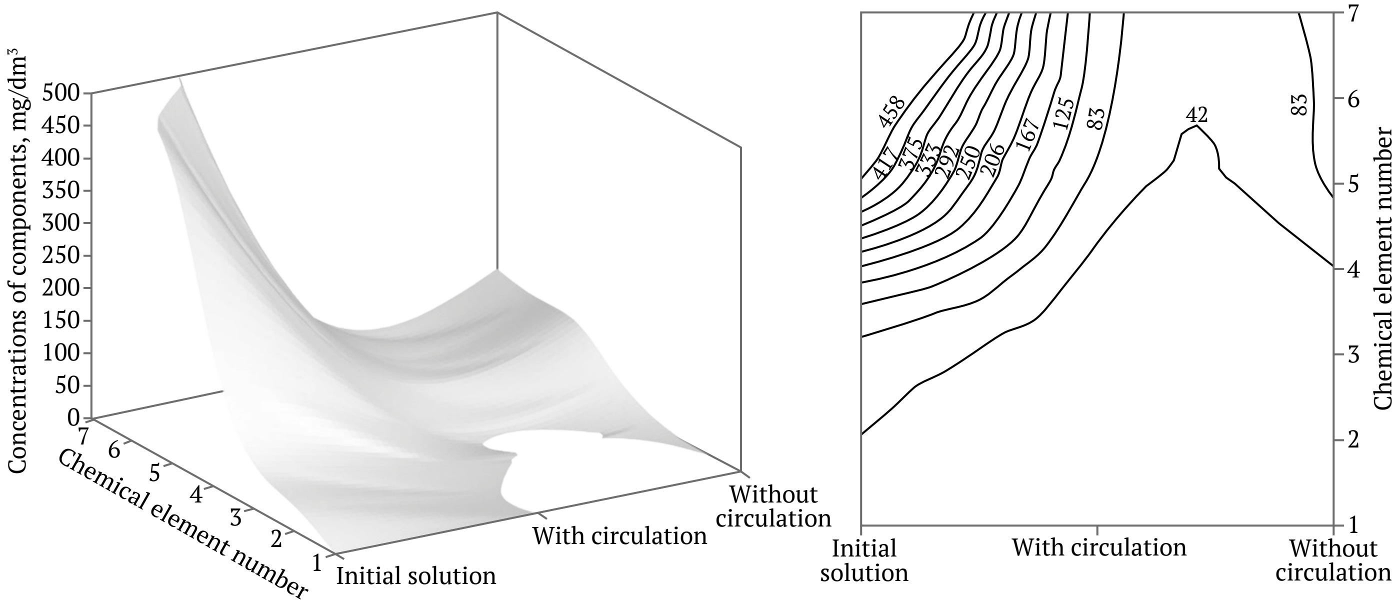

Fig. 1. Efficiency of chemical elements extraction at different parameters of electrochemical method

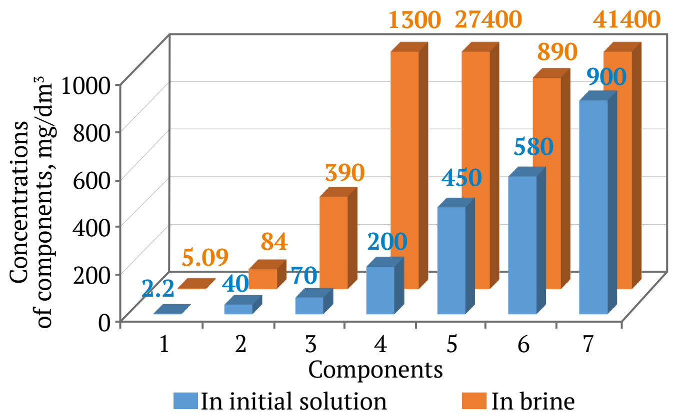

Fig. 2. Concentration of chemical elements in brines without circulation in comparison with initial solution

Metal recovery with preliminary mechanochemical activation of dry tailings

Since mechanoactivation is effectively used to convert tailings into a binding component of a backfill material [42], it was decided to use the geomaterials activation effect to increase the yield of lead from tailings. Geomaterials were pre-milled in a laboratory ball mill, screened using a 4.0 mm mesh sieve and subjected to mechanoactivation (dry) in a DESI-11 disintegrator. The rotor speeds were 50 and 200 Hz. The testing program included the use of sulfuric acid and sodium chloride in different proportions. The acid concentration varied in the range including 20, 90 and 160 g/l, and that of sodium chloride, 2, 6, and 10 g/l. The preparation of the liquid fraction of the pulp implied preliminary preparation of chemical reagents (in separate flasks) in the proportions specified in the methodology of the test. All calculations were performed to obtain one liter of leaching solution with selected solid to liquid fraction ratio (S/L) values of 1/4.1, 1/7 and 1/10, respectively. After obtaining the activated solid fraction of the geomaterial, it was mixed with the liquid solution in a specified S/L fraction ratio to obtain a pulp. Agitation leaching was then carried out in laboratory columns.

Weight concentrations of leaching solution components in the final pulp, %, were determined by the following formula (using sulfuric acid as an example):

$$m_p(H_2SO_4) = \frac{m_L(H_2SO_4)}{M_p} \times 100, \qquad (5)$$

where M_p is weight of pulp, consisting of the weight of solution (varying depending on the ratio of the concentrations of the reagents in 1 liter) and a constant weight of a subsample of solid dry waste, equal to 50 g; $m_L(H_2SO_4)$ is weight of sulfuric acid in the liquid fraction of the pulp at different concentrations of the acid and sodium chloride in it, g.

Lead concentration in the pulp was determined by standard method using atomic absorption spectrometer “KVANT-AFA” (KORTEK LLC). *Q–Q* plots (quantile-quantile plots – goodness-of-fit criterion of model construction) were plotted in Microsoft Excel 2010 software. The lead extraction performance at preliminary activation of the tailings and leaching time of 0.25 h (option I), as well as at preliminary activation of tailings by dry method in the disintegrator and leaching time of 1 h (option II) are presented in Table 5 and Fig. 3.

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It follows from the analysis of Fig. 3, a, that the activation effect at υ = 50 Hz and leaching duration of 0.25 h causes an increase in the beneficiation performance at H_2SO_4 (concentration) = 0.8–0.9% and NaCl = 11.5–14%. In addition, a pronounced second maximum is traced: Pb = 28% at H2SO4 = 0.32–0.45% and NaCl = 5–7.6%. Increasing the leaching time from 0.25 to 1 h and υ to 200 Hz leads to an increase in the absolute values and the area of the second zone of local maximum, which significantly changes the idea of the process (Fig. 3, *b*). At H2SO4 = 0.9%, increasing the concentration of NaCl from 1 to 14% leads to a monotonic increase in lead yield from 4% to more than 40% (concentration of NaCl = 13.5%). The area of the local maximum is limited to the region from 0.5 to 0.7% of H_2SO_4 and from 7 to 14% of NaCl. The goodness-of-fit criterion for verifying the quality of the four three-dimensional *Q*–*Q* models is the graph shown in Fig. 4.

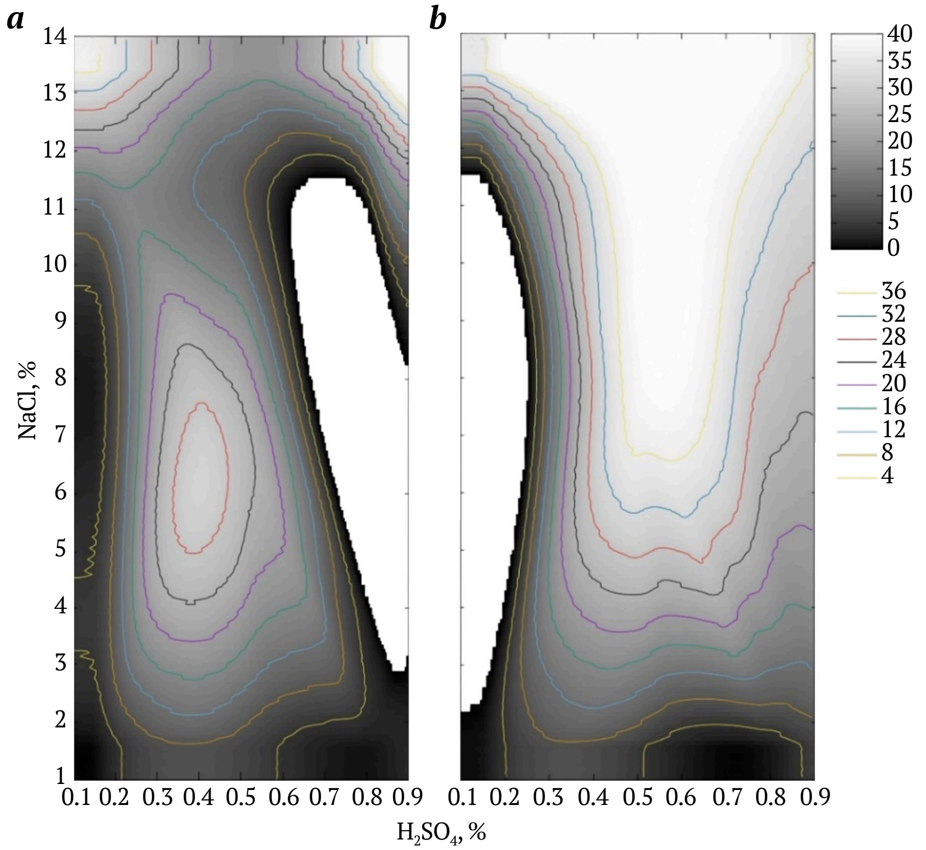

Fig. 3. Distribution of lead yield from Mizursky mill tailings:
a – leaching of Pb from pre-activated tailings υ = 50 Hz, duration of 0.25 h (option II);
b – leaching of Pb from pre-activated tailings υ = 200 Hz, duration of 1 h (option IV)

Table 5

Effect of pre-mechanoactivation of tailings by dry method

N of test	$m_P(H_2SO_4)$, weight concentration of sulfuric acid in pulp	m_P(NaCl), weight concentration of sodium chloride in pulp	Test option	
	%	%	I	II
1	0.16	1.58	0.81	1.43
2	0.79	1.58	0.95	0.86
3	0.15	11.79	17.62	3.33
...	...	...	...	...
12	0.83	13.36	38.1	38.1
13	0.54	1.80	6.04	5.21
14	0.50	13.38	17.56	50.88

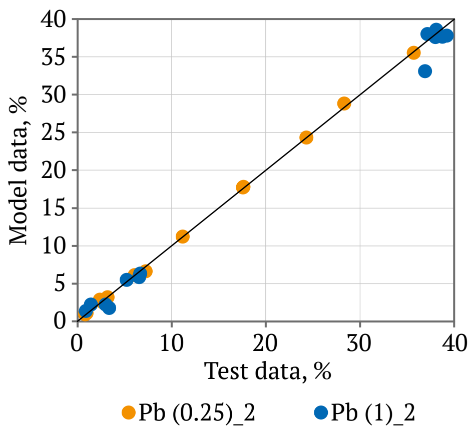

Fig. 4. *Q*–*Q* for the two model options

It follows from the analysis of the response surfaces that on the whole the obtained data are consistent with the results of studies [43, 44] on chalcopyrite processing in a fine grinding mill, where the growth of H2SO4 concentration was higher by 30%. Leaching of Cu from ore with sulfuric acid [39] confirms the increase in epy process productivity with the increase of rotor speed in the disintegrator from 50 to 200 Hz. Studies [45, 46] also confirm the effectiveness of DESI-15 for mechano-activation of geomaterials.

Practical application

The practical significance of the obtained results lies in substantiating the feasibility of optimizing the flow sheet of electrochemical extraction of metals from wastewater on the basis of the obtained regularities of the use of brine circulation through brine chambers. In addition, the totality of the obtained results of using a disintegrator for re-extraction of lead from geomaterials will allow developing a methodology for calculating the parameters of mechanoactivation to increase the degree of metal recovery from the tailings of North Ossetia-Alania's (Zgidskoe, Sadonskoe, Arkhonskoe deposits) polymetallic ores beneficiation.

Areas of further research

Further research should be focused on the specific changes in the parameters of existing geotechnologies not only in terms of greening of individual components or technological processes. In this regard, the most promising area for further research is to substantiate methods of using underground space for complete removal of wastes (wastewater and tailings) after their multistage treatment.

Conclusion

The main area of transformation of natural resources use paradigm should be the circulation management of mining and processing waste. The recession in mining production with decommissioning of existing rich ore and exploitable deposits can be mitigated with the development of in-situ leaching process with involving substandard reserves in exploitation. The proposed recommendations for improving in-situ leaching of ores in blocks make it possible to determine the optimal conditions for increasing the completeness of subsoil use and reducing environmental damage.

Environmental degradation caused by liquid wastes of in-situ leaching of ores can be minimized by technological means. The method of electrodialysis and activation in diaphragm electrolyzers is promising for treatment of mine wastewater. It was revealed that at metal extraction with solution circulation through brine chambers the concentrations of Na, Cl, SO_4 and Ca in dialysate was low, while without circulation through brine, they significantly exceeded MPCs (for Na, Cl, SO_4 and Ca). This proves the fundamental feasibility of controlling natural leaching processes by enhancing the oxidizing potential of natural solvents through the addition of industrial oxidizing agents.

Tailings storage facilities are man-made deposits within which natural leaching takes place. One of the key results of the study is the justification for expanding the scope of use of disintegrators in purposeful mechanical-chemical-activation action. Increasing the duration of agitation leaching (both with and without the use of mechanoactivation) leads to a uniform expansion of the local peaks of Pb yield from the pulp while the minimum NaCl concentration decreases from 11–12 to 7% at H_2SO_4 concentration of 0.6%.

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