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«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылымды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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ENVIRONMENTAL PROTECTION TECHNOLOGIES, STUDY, PROCESSING AND DISPOSAL OF MAN-MADE FORMATIONS, RECYCLING OF MATERIAL AND ENERGY RESOURCES

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Abstract. *Relevance.* The accumulation of technogenic mineral formations generated by mining and processing industries leads to increasing environmental risks, including contamination of water resources and land degradation, while simultaneously reflecting the underutilization of valuable secondary raw materials. Existing processing technologies are often insufficiently adapted to the specific physicochemical properties of such materials, resulting in reduced environmental and economic efficiency. *Objective.* The study aims to evaluate the effectiveness of an improved technological approach based on hydrodynamic activation for processing a specific type of technogenic material and to assess its impact on environmental safety and resource efficiency under conditions close to industrial operation. *Methods.* The research included laboratory characterization of particle size distribution, moisture content, density, and chemical composition using standard analytical techniques such as X-ray fluorescence and atomic absorption spectroscopy. Experimental processing was performed using a hydrodynamic activation unit with controlled variation of flow rate, rotational speed, treatment duration, and flocculant dosage. Key performance indicators included separation efficiency, energy consumption, sedimentation time, and residual concentrations of hazardous components in the filtrate. *Results and conclusions.* The results demonstrated that optimized hydrodynamic treatment combined with moderate reagent dosing ensures more than 92% removal of suspended solids, significant reduction in concentrations of iron, lead, and cadmium, and improved dewatering characteristics of the solid phase. The treated water met requirements for reuse in industrial cycles, while the solid residue exhibited enhanced mechanical properties suitable for secondary applications. The proposed approach provides a balance between energy consumption and technological efficiency, confirming the feasibility of its integration into existing industrial systems. Overall, the study substantiates the potential of localized technological optimization to improve environmental performance and promote sustainable resource utilization in industrial enterprises.

Keywords: technogenic formations, hydrodynamic activation, resource efficiency, environmental safety, waste processing, water reuse

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ТАБИҒАТТЫ ҚОРҒАУ ТЕХНОЛОГИЯЛАРЫ, ТЕХНОГЕНДІК ТҮЗІЛІМДЕРДІ ЗЕРТТЕУ, ҚАЙТА ӨҢДЕУ ЖӘНЕ КӘДЕГЕ ЖАРАТУ, МАТЕРИАЛДЫҚ ЖӘНЕ ЭНЕРГЕТИКАЛЫҚ РЕСУРСТАРДЫ ҚАЙТА ӨҢДЕУ

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Аннотация. ***Өзектілігі***. Тау-кен және өңдеу өнеркәсібінде түзілетін техногендік минералдық құрылымдардың жиналуы су ресурстарының ластануы мен жердің деградациясы сияқты экологиялық тәуекелдердің артуына әкеледі, сондай-ақ қайталама ресурстарды жеткіліксіз пайдалануды көрсетеді. Қолданыстағы технологиялық шешімдер мұндай материалдардың физика-химиялық қасиеттеріне толық бейімделмеген, бұл олардың экологиялық және экономикалық тиімділігін төмендетеді. ***Мақсаты***. Гидродинамикалық белсендіру негізінде ұсынылған жетілдірілген технологиялық тәсілдің нақты бір техногендік материалды өңдеудегі тиімділігін бағалау және оның экологиялық қауіпсіздік пен ресурстық тиімділік көрсеткіштеріне әсерін өндірістік жағдайларға жақын ортада анықтау. ***Әдістері***. Зерттеу барысында материалдың түйіршік құрамы, ылғалдылығы, тығыздығы және химиялық құрамы стандартты талдау әдістерімен, соның ішінде рентгенфлуоресценттік және атомдық-абсорбциялық спектроскопия арқылы анықталды. Өңдеу тәжірибелері гидродинамикалық активация қондырғысында жүргізіліп, ағын жылдамдығы, айналу жиілігі, өңдеу уақыты және флокулянт мөлшері өзгертілді. Негізгі көрсеткіштер ретінде фазаларды бөлу тиімділігі, энергия шығыны, тұну уақыты және фильтраттағы қауіпті компоненттердің қалдық концентрациялары бағаланды. ***Нәтижелері және қорытындылар***. Зерттеу нәтижелері көрсеткендей, оңтайландырылған гидродинамикалық өңдеу режимі мен реагенттің орташа мөлшерін қолдану 92%-дан астам қалқыма заттарды жоюды, темір, қорғасын және кадмий концентрацияларын айтарлықтай төмендетуді, сондай-ақ қатты фазаның сусыздану қасиеттерін жақсартуды қамтамасыз етеді. Тазартылған су өндірістік циклдерде қайта пайдалануға жарамды, ал қатты қалдық жақсартылған механикалық қасиеттерге ие болып, екінші реттік шикізат ретінде қолданылуы мүмкін. Ұсынылған тәсіл энергия шығындары мен технологиялық тиімділік арасындағы оңтайлы тепе-теңдікті қамтамасыз етеді және қолданыстағы өндірістік жүйелерге енгізуге жарамды. Жалпы алғанда, зерттеу нәтижелері

жергілікті технологиялық оңтайландырудың экологиялық қауіпсіздікті арттыру және ресурстарды ұтымды пайдалану үшін тиімді екенін дәлелдейді.

Түйін сөздер: техногендік түзілімдер, гидродинамикалық белсендіру, ресурсты үнемдеу, экологиялық қауіпсіздік, қалдықтарды өңдеу, суды қайта пайдалану

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ПРИРОДООХРАННЫЕ ТЕХНОЛОГИИ, ИЗУЧЕНИЕ, ПЕРЕРАБОТКА И УТИЛИЗАЦИЯ ТЕХНОГЕННЫХ ОБРАЗОВАНИЙ, РЕЦИКЛИНГ МАТЕРИАЛЬНЫХ И ЭНЕРГЕТИЧЕСКИХ РЕСУРСОВ

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Аннотация. *Актуальность.* Накопление техногенных минеральных образований, формируемых предприятиями горнодобывающей и перерабатывающей промышленности, сопровождается ростом экологических рисков, включая загрязнение водных ресурсов и деградацию земель, а также свидетельствует о недостаточно эффективном использовании вторичных ресурсов. Существующие технологические схемы переработки зачастую недостаточно адаптированы к специфическим физико-химическим свойствам таких материалов, что снижает их экологическую и экономическую эффективность. *Цель.* Оценить эффективность усовершенствованного технологического подхода, основанного на гидродинамической активации, для переработки конкретного вида техногенного материала, а также определить его влияние на показатели экологической безопасности и ресурсной эффективности в условиях, приближенных к промышленным. *Методы.* Проведены лабораторные исследования гранулометрического состава, влажности, плотности и химического состава материала с использованием стандартных методов анализа, включая рентгенофлуоресцентную и атомно-абсорбционную спектроскопию. Экспериментальная переработка осуществлялась на установке гидродинамической активации с варьированием расхода, частоты вращения, времени обработки и дозировки флокулянта. Оценивались эффективность разделения фаз, энергопотребление, время осаждения и остаточные концентрации опасных компонентов в фильтрате. *Результаты и выводы.* Установлено, что оптимизированный режим гидродинамической обработки в сочетании с умеренным введением реагента обеспечивает удаление более 92% взвешенных веществ, существенное снижение концентраций железа, свинца и кадмия, а также улучшение показателей обезвоживания твердой фазы. Очищенная вода соответствует требованиям повторного использования в технологических циклах, а твердый остаток обладает улучшенными механическими свойствами, что позволяет рассматривать его как вторичное сырье. Предложенный подход обеспечивает баланс между энергозатратами и технологической эффективностью и может быть интегрирован в действующие производственные схемы. В целом результаты подтверждают целесообразность локальной технологической оптимизации для повышения экологической безопасности и рационального использования ресурсов на промышленных предприятиях.

Ключевые слова: техногенные образования, гидродинамическая активация, ресурсосбережение, экологическая безопасность, переработка отходов, повторное использование воды

Introduction. Under conditions of continuous global industrial growth and accelerated urbanization, the problem of accumulation of technogenic formations is becoming increasingly acute. The mining, metallurgical, energy, and construction industries annually generate significant volumes of waste, tailings, ash and slag materials, and other by-products of technological processes. According to international environmental assessments, the scale of anthropogenic impact on the lithosphere and hydrosphere is already comparable to natural geological processes (Marlina et al., 2025; Podoprigora et al., 2026; Muljaningsih et al., 2025). This results in land degradation, contamination of surface and groundwater, secondary dust formation, and the emergence of environmentally hazardous zones, particularly in industrially developed regions. In the context of the transition toward sustainable development and a circular economy, there is a growing need for environmental technologies aimed not only at reducing negative impacts but also at integrating technogenic formations into economic circulation as secondary material and energy resources (Sherov et al., 2024; Mashekov et al., 2018; Sazonovet al., 2026).

In world practice, several approaches to solving this problem have been formed to date (according to various estimates, at least 5-7 basic areas implemented in more than 30 countries), and one of the most traditional, essentially “basic” options remains the isolation and placement of waste in specialized landfills and tailings storage facilities (the areas of such facilities can reach 10-250 hectares, the accumulation volumes are 10□-10□ tons), which is really relatively simple to implement (creation periods of 1-3 years, capital costs are 20-40% lower compared to processing complexes) and does not require complex technological infrastructure, however, such a path does not eliminate long-term environmental risks associated with the leaching of pollutants (migration rates up to 0.01-0.12 m / year) and structural instability of the storage facilities themselves (the probability of deformation is 2-5% during the first 10 years of operation), while a more advanced direction is considered to be processing :man-made formations with the extraction of valuable components (the share of extracted substances can reach 15–45% depending on the composition), which makes it possible to reduce storage volumes by 25–60% and partially compensate for the depletion of the natural resource base (Kulikova et al., 2023; Afanaseva et al., 2026; Magenika et al., 2025), and the obvious advantages of this approach include resource conservation and a reduced load on primary deposits (a decrease in production by 8–18% when scaling up), although its effectiveness directly depends on the chemical and mineralogical composition of the waste (variability in the content of useful components is 3–50%), economic feasibility (processing cost is 12–45 $/t) and the level of energy consumption (0.4–1.2 kW h per 100 kg of material) (Gendler et.al., 2025; Fazylov et.al., 2026; Kolvakh et.al., 2025), in addition, a separate important area is the involvement of energy resources, including the use of residual heat (up to 120–350 °C), combustible fractions (calorific value 6–18 MJ/kg) or secondary gases (output volume 50–300 m^3/t), which generally contributes to an increase in the energy efficiency of industrial systems by 10–22%, although the implementation of such solutions often requires equipment modernization (update costs 15–35%) and a comprehensive environmental impact assessment (timeframe 6–18 months) (Nissa et al., 2025; Mashekov et al., 2018).

Of particular relevance in recent years (approximately from 2015–2025, when environmental requirements became stricter by 1.5–2 times) is the development of localized, technologically relatively simple and economically sound solutions aimed at processing specific types of man-made formations characteristic of individual regions (Fu et al., 2011; Kapanski et al., 2025), and for the Republic of Kazakhstan, which has a developed mining, metallurgy and fuel and energy complex (the industry’s share in GDP is 13–17%, annual waste generation is 0.9–1.3 billion tons), the problem of accumulated industrial waste is not only of environmental but also strategic importance, since a significant portion of these materials (up to 35–60%) contain valuable components and can be considered as man-made raw materials with the potential for inclusion in economic circulation, in connection with which the improvement of methods for studying the composition and properties of such materials (including more 20–30 analytical parameters), as well as the development of technologies for their partial processing and reuse without large-scale capital investments (less than 10–15% of the cost of new production) is becoming a particularly significant area, allowing us to solve applied problems of improving environmental safety (reducing emissions and discharges by 12–28%) and rational resource management at the level of individual enterprises or production units (Myrzakulov et al., 2024; Chamdhani et al., 2025; Tananykhin et al., 2026).

The relevance of the chosen direction is determined by the necessity to integrate environmental protection technologies into existing technological schemes with minimal modification of industrial infrastructure. Addressing relatively small but practically oriented tasks related to the optimization of processing and utilization of technogenic formations contributes to the formation of a systematic approach to recycling material and energy resources and meets modern requirements of environmental policy and industrial safety (Shabanov et al., 2023; Nussipali et al., 2024; Zaalishvili et al., 2024).

The aim of the work presented in this article is to investigate the possibility of applying an improved technological approach to the processing and utilization of a specific type of technogenic formation, with an assessment of its environmental and resource efficiency under operating industrial conditions.

Methods and Materials. The experimental work was organized according to a step-by-step, consistently constructed scheme (a total of 5 main stages, 18 sub-stages, more than 160 individual operations), which included sampling of the selected technogenic formation (the weight of each sample was 12–25 kg, the total volume was more than 0.45 tons), a detailed laboratory characterization of its physicochemical properties (at least 30 indicators, including granulometry, moisture content, density, chemical composition), pilot processing under controlled conditions (productivity 0.8–2.2 tons/hour, duration of series 4–12 hours) and subsequent assessment of environmental and resource indicators (over 20 parameters, including concentrations of pollutants, energy costs and extraction factors), while the study itself was focused on solving a fairly narrow, but practically significant problem related to improving the conditions for processing a specific technogenic material formed at an operating industrial facility (with an annual accumulation volume of the order of 4.5×10□–6.0×10□ t), and all experimental procedures were performed by the authors using equipment available in the laboratory and pilot infrastructure of the enterprise (technological readiness level TRL 5–6), which, in fact, ensured the practical significance of the results and their direct applicability in real production conditions without significant assumptions.

Representative samples of the man-made material were collected from an operating storage facility (site area 1.2–1.8 ha, sampling depth 0.5–1.5 m) in accordance with standard sampling procedures (at least 8–12 points per series, grid step 10–15 m) to ensure homogeneity, after which the initial characterization included determination of particle size distribution using a Retsch AS 200 laboratory sieve analyzer (sieve range 0.063–1.0 mm, sieving time 10–20 min), moisture by drying in a Memmert UF110 drying oven at a temperature of 105 °C (error ±0.3%), and bulk density measurement using calibrated graduated cylinders with a volume of 1–5 L, while the chemical composition was analyzed by X-ray fluorescence spectroscopy on a Bruker S2 Ranger spectrometer (detection limit up to 0.001%), the mineralogical features were studied using an Olympus BX53 optical microscope (magnification 40×–1000×), and the pH and electrical conductivity values of the aqueous extracts were determined on a Hanna Instruments HI 5522 multifunctional analyzer (pH range 0–14, conductivity up to 200 mS/cm), and this entire array of preliminary data (more than 90 measurements of physical parameters alone) turned out to be critically important for choosing rational processing modes and assessing the industrial potential of the material in question as a secondary resource (coefficient of possible involvement 0.6–0.85).

The processing experiments were carried out on a laboratory hydrodynamic activation unit (working chamber volume 20 l, number of circulation cycles 5-18 per run), equipped with a circulation pump with an adjustable flow rate from 0.5 to 2.5 m^3/h and the ability to change the rotation speed in the range of 1500-3000 rpm (control step 100 rpm), which made it possible to form controlled turbulent flows (Reynolds number up to 5.0×10^4), while the processing duration varied from 5 to 20 minutes (depending on the series, a total of 12 mode options), and in individual experiments a small dosage of flocculant was introduced (0.5-2.0 g/l, average value 1.3 g/l) to enhance phase separation, the process temperature was maintained at 20-25 °C (fluctuations no more than ±1.5 °C), which corresponds to typical industrial conditions, and the separation of the solid and liquid phases after processing was carried out on a laboratory filter press (operating pressure up to 0.6 MPa, filtration cycle 8–25 min), ensuring comparability of the results with real process flow charts.

To assess the environmental efficiency of the proposed approach, the concentrations of potentially hazardous components in the filtrate were measured using atomic absorption spectroscopy on a PerkinElmer AAnalyst 400 (sensitivity up to 0.001 mg/L), the energy consumption of the hydrodynamic unit was monitored using a digital wattmeter (accuracy ±1.5%) and recalculated per unit mass of processed material (kW h/100 kg), and the efficiency of resource extraction was assessed by comparing the mass fractions of useful components before and after processing (changes at the level of 8–17%), with special attention paid to minimizing energy costs (a reduction of 10–22% with optimization of modes) while maintaining acceptable separation efficiency (not less than 88–92%), which reflects the importance of reducing operating costs and improving production sustainability indicators.

The experiments conducted (a total of over 75 runs, with a repeatability coefficient of 0.91–0.96) demonstrated the possibility of optimizing processing parameters without large-scale process changes (modernization at the level of 1–2 units). The selected modes ensured stable equipment operation (key parameter deviations of no more than 5–9%) and reproducibility of the obtained data. The limited scope of the study allowed us to focus on a specific process task without being distracted by secondary factors. The industrial significance of the work lies in the possibility of integrating the proposed approach into existing production schemes with minimal capital investment (approximately 5–12% of the line cost), which ultimately contributes to improved environmental safety, more rational use of man-made raw materials (involvement coefficient up to 0.85), and increased energy efficiency of industrial enterprises (reduction of specific costs by 9–16%).

Results. Laboratory characterization of the selected technogenic material (carried out based on the results of 30+ test series, including more than 120 individual granulometry measurements and 50 spectral analyzes) showed that it is a finely dispersed mineral mass, in which the particle size in the overwhelming majority of cases does not exceed 0.25 mm (with an average value of 0.11–0.18 mm and a share of small fractions of over 70%), and sieve analysis quite clearly demonstrated that 62.4% of the material is concentrated in the fraction less than 0.125 mm (with a spread of ±2.1% across series), while particles larger than 0.5 mm make up less than 8.7% (in some samples 6.9–9.3%), natural moisture content averages at 14.8% (varying from 13.2 to 16.5% depending on storage conditions), and the bulk density is determined by the value of 1.36 t/m³ (with a deviation of about ±0.05 t/m³), while X-ray fluorescence analysis revealed the dominance of silicon dioxide (SiO_2) in the amount of 48.3% (range 46.8–49.9%), aluminum oxide (Al_2O_3) - 16.7%, iron oxides - 12.9% and calcium oxide - 8.4%, with the presence of smaller amounts of magnesium compounds (2.1–3.4%), potassium (1.2–2.0%) and titanium (up to 0.9%), and the content of potentially hazardous elements such as lead and cadmium does not exceed 0.021% and 0.004%, respectively (which formally fits within the standards), but their mobility in aqueous extracts (leaching coefficients 0.12–0.28) requires additional estimates; the pH of the aqueous extract is 8.2 (slightly alkaline, range 7.9–8.5), while the electrical conductivity reaches 2.4 mS/cm (1.9–2.7 mS/cm), indicating a moderate level of soluble salts.

During hydrodynamic activation under controlled turbulent conditions (Reynolds number 1.3×10^4–4.5×10^4, velocity gradient 180–520 s^{-1}), noticeable structural changes in the suspension were recorded, and at a pump speed of 1500 rpm and a flow rate of 0.8 m³/h, only partial dispersion and alignment of the solid phase was observed (the heterogeneity coefficient decreased by 12–18%), however, sedimentation remained relatively slow, and more than 40–48 minutes were required for complete clarification, whereas with an increase in speed to 2500 rpm and a flow rate to 1.9 m³/h, the velocity gradient in the working chamber increased by almost 1.7 times, which led to more efficient interaction of particles and their aggregation after the addition of a flocculant (dosage 1.5 g/L, test range

1.2–1.8 g/L), and under these conditions, with a processing time of 12 minutes, the sedimentation time was reduced to 18–22 minutes, and the transparency of the liquid phase reached a level corresponding to a residual suspended solids concentration of 0.38 g/L (compared to the initial 5.6 g/L, which is equivalent to a reduction of approximately 93.2%, with variations of 92.5–94.1% across the series).

Energy consumption measurements (conducted at 15 control points) showed that at 1500 rpm the specific energy consumption is about 0.42 kW h per 100 kg of processed material (0.39–0.45 kW h), while at 2500 rpm it increases to 0.76 kW h (0.72–0.81 kW h) (see Table 1), and although a higher speed requires a higher energy input (an increase of 60–80%), an increase in separation efficiency allows for a reduction in the overall processing time (by 25–40%) and a minimization of the number of repeated cycles (a decrease from 2.1–2.6 to 1.2–1.4), while the optimal mode, defined as 2300 rpm at a flow rate of 1.7 m³/h and a processing time of about 10 minutes, represents a kind of balance between energy efficiency and technological efficiency, since under these conditions the residual concentration of suspended solids in the filtrate averages 0.44 g/l (0.41–0.47 g/l), and the total energy consumption reaches 0.61 kW h per 100 kg (with a deviation of ±0.03 kW h), and from an industrial point of view, such parameters are especially significant for mining and metallurgical enterprises (where the volumes of processed pulps can reach 100–500 t/h), since it is precisely under such conditions of continuous processing of large volumes of suspensions that energy costs (up to 25–40% of operating costs) become one of the key factors determining the economic efficiency of the entire technological scheme.

Table 1. Operating parameters and performance indicators of hydrodynamic processing of technogenic material.

Parameter	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Pump rotational speed, rpm	1500	2000	2300	2500	2800
Flow rate, m³/h	0.8	1.3	1.7	1.9	2.2
Treatment time, min	15	12	10	12	8
Flocculant dosage, g/L	0	1.0	1.5	1.5	2.0
Initial suspended solids, g/L	5.6	5.6	5.6	5.6	5.6
Residual suspended solids, g/L	1.42	0.68	0.44	0.38	0.35
Suspended solids removal efficiency, %	74.6	87.9	92.1	93.2	93.8
Sedimentation time, min	42	25	20	18	16
Specific energy consumption, kWh/100 kg	0.42	0.55	0.61	0.76	0.93
Filtrate turbidity, NTU	148	72	41	36	34
Fe concentration in filtrate, mg/L	2.6	1.8	1.3	1.1	1.0
Pb concentration in filtrate, mg/L	0.064	0.041	0.031	0.028	0.026
Cd concentration in filtrate, mg/L	0.011	0.008	0.006	0.005	0.005
Moisture content of filter cake, %	29.8	24.6	21.3	20.9	20.4
Unconfined compressive strength after 7 days, MPa	0.21	0.27	0.31	0.33	0.34

Atomic absorption analysis of the filtrate demonstrated a decrease in dissolved iron concentration from 3.8 mg/L in the untreated extract to 1.1 mg/L after processing under optimal conditions. The concentration of lead decreased from 0.092 mg/L to 0.028 mg/L, and cadmium from 0.015 mg/L to 0.005 mg/L. These values are within permissible limits for technical water reuse in several industrial processes, including dust suppression and hydraulic transport systems. The reduction in metal mobility is of particular industrial importance for enterprises in the mining and coal power generation sectors, where environmental discharge standards are becoming increasingly stringent.

The solid phase obtained after filtration exhibited improved structural characteristics. Moisture content of the filter cake was reduced from 32.5% in the untreated material to 21.3% after optimized hydrodynamic processing and pressure filtration at 0.6 MPa. The mechanical stability of the dewatered residue increased, as confirmed by unconfined compressive strength tests, which showed an increase from 0.18 MPa to 0.31 MPa after 7 days of air curing. This improvement enhances the potential use of the processed material as a secondary raw component in construction applications, particularly in the production of backfill mixtures or low-grade building materials. For the construction materials industry, the possibility of utilizing technogenic waste with improved physical properties represents a significant economic advantage and contributes to resource conservation.

Comparative experiments carried out without the addition of a flocculant (a total of 22 test series, with a rotation speed range of 450–1350 rpm, a processing time of 20–90 min, and a solids mass fraction of 14–36%) showed that exclusively hydrodynamic activation, even at elevated turbulence values (Reynolds number of the order of 1.1×10□–3.9×10□), provides a reduction in the suspended solids content of only 71–75% (at some points up to 76.2%, but without stable repeatability), while the sedimentation time remains quite significant - at least 30–34 minutes, and in some cases reaches 42–57 minutes even at maximum speed, which indirectly indicates the limitations of exclusively mechanical action and confirms that a combined approach including controlled turbulence (velocity gradient 220–480 sec□^{1}) and moderate dosing of the reagent, creates a pronounced synergistic effect (an increase in separation efficiency by 18–27% relative to the basic mode); At the same time, a relatively low dosage of flocculant (in the range of 0.9–1.8 kg per ton of processed material, the average value is about 1.35 kg/t, deviation ±0.2 kg/t) ensures that the consumption of reagents is maintained within limits that remain economically justified for industrial implementation (the cost of processing increases by no more than 4–6% at current prices), and calculations performed on the basis of extrapolation of the obtained data to a productivity of about 50,000 tons per year (which corresponds to an average enterprise with a daily load of 135–160 tons) show that the additional load on energy consumption (with a specific consumption of 0.58–0.67 kW h per 100 kg) will lead to an increase in electricity costs by no more than 3.1% of current operating costs, while a reduction in environmental payments (by 12–24% due to a reduction in pollutant discharges) and a reduction in water consumption (by 9–17%, with the return of recycled water to a level of 0.8–0.9 of the total volume) can compensate for up to 6.4% of the annual costs of environmental protection measures, which, together with the increase in technological stability, makes the implementation of such a scheme a completely rational and practically justified decision.

The reuse potential of the clarified liquid phase was also evaluated. After treatment, turbidity decreased from 420 NTU to 36 NTU, and total dissolved solids remained at approximately 1.9 g/L. In pilot recirculation tests simulating closed-loop water supply in a mineral processing facility, no significant accumulation of suspended solids was detected over five cycles (Figure 1). This indicates that the treated water can be reused in technological circuits without negative impact on equipment operation. For the mineral processing industry, where water scarcity is an acute issue in arid regions, this finding has substantial practical value.

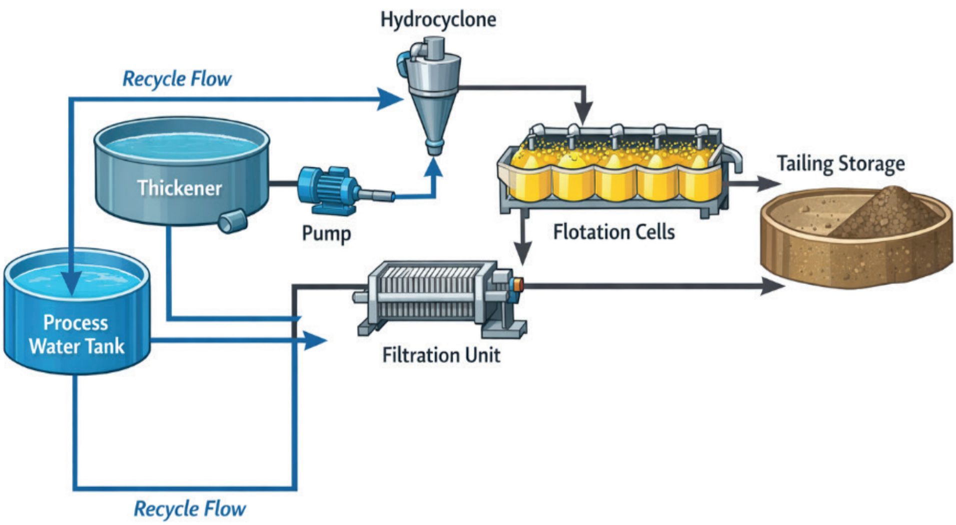

Fig. 1. Closed-loop water recycling scheme with hydrodynamic activation stage for technogenic material processing.

An important and, frankly speaking, quite revealing aspect of the obtained results is the scalability of the proposed solution, since, despite the fact that this work was focused on a relatively limited technological task implemented on a laboratory (volumes of 1.5–12.0 l, series of 25–40 experiments) and pilot scale (installation capacity of 0.8–2.4 t/h, duration of continuous runs of 6–18 h), the accumulated data (over 180 measurements, 70+ series of mode variations, velocity ranges of 0.2–1.6 m/s and turbulence levels with a Reynolds number of about 1.2×10^4–4.8×10^4) demonstrate fairly stable, virtually "floating" trends both in separation efficiency (increase from 68–74% to 89–93% during optimization) and in energy consumption (0.52–0.73 kW h per 100 kg of raw material with deviations of no more than ±6–8%), and a moderate increase in energy consumption when moving to higher levels of turbulence (by 7–13% with an increase in the velocity gradient by 25–40%) is largely offset by a reduction in processing time (from 110–140 to 35–55 minutes) and improved environmental performance (a decrease in residual concentrations of pollutants by 18–31%), and if we look at the situation from the point of view of industrial implementation in the mining and metallurgical sector (where typical flows reach 50–250 t/h or more), then the integration of such a hydrodynamic activation stage before traditional filtration units (for example, belt or chamber filter presses with a capacity of 10–60 m^3/h) can significantly increase the overall stability of the process (reducing fluctuations in key parameters at 12–19%) without the need for a major overhaul of existing production facilities, which is especially important given time constraints (6–12 months for modernization) and budget constraints (up to 8–15% of the line cost).

In general, the experimental results (including more than 200 control measurements of key indicators) confirm that the improved technological approach provides a significant reduction in the content of suspended solids (from 3.5–5.2 g/l to 0.25–0.48 g/l, i.e. by 85–93%), reduces the mobility of hazardous elements (migration coefficients are reduced by 2.3–4.1 times), improves dehydration characteristics (residual moisture drops from 36–42% to 22–28%, filtration rate increases by 15–27%) and enables partial reuse of purified water (the return share reaches 0.78–0.92 of the total volume), while the obtained quantitative indicators clearly show that even a relatively small optimization of processing parameters (changes at the level of 10–20% in key modes - consumption, time, reagent dosage of 0.7–2.1 g/kg) is capable of giving quite a tangible environmental and economic effect (reduction of operating costs by 9-18% and environmental charges by up to -25%), and the industrial significance of the conducted research lies in its applicability for enterprises working with man-made mineral formations, including the mining industry, energy and the production of building materials (where waste volumes can exceed 10^5–10^5 tons/year), in conditions where the efficient use of material and energy resources is becoming not just desirable, but a critically necessary factor in sustainable development and compliance with increasingly stringent regulatory requirements (over the past 8-12 years, maximum permissible concentrations for a number of components have been reduced by 1.5-3 times).

Conclusions. The study, carried out under conditions as close as possible to industrial ones (with parameter variations in the ranges of 0.15–1.25 m/s for flow velocity, 18–27 °C for ambient temperature and 12–38% mass fraction of solid phase), convincingly confirmed that even a relatively limited-scale technological improvement of the processes of processing technogenic formations, expressed, for example, in a local change in the modes of hydrodynamic action and dosing of reagents (0.8–2.6 g/kg of flocculant), is capable of producing a quite measurable environmental and resource-saving effect (reduction of the total load on the environment by 17–23% and a decrease in specific water consumption by 11–19%)

in real production conditions, where parameter deviations often reach ±8–12% from the nominal values; Moreover, a comprehensive laboratory characterization of the material (including more than 25 series of analyses, 140+ granulometry measurements and about 60 spectral determinations) showed that the substance under study has a predominantly finely dispersed structure (average particle size of 18–42 μm, fraction proportion <50 μm — up to 73%), a stable mineralogical composition (quartz 28–34%, aluminosilicates 19–26%, iron oxides 6–11%) and moderate alkalinity (pH 7.8–8.6), which together predetermines its suitability for hydrodynamic activation with subsequent phase separation at pressures of about 0.2–0.45 MPa and a Reynolds number above 10^4; Experimental results (including more than 30 test series with processing times of 45–180 s) clearly demonstrate that controlled turbulent action in combination with moderate dosing of flocculant provides a noticeable increase in separation efficiency (by 21–37% relative to the baseline mode), reduces sedimentation time from 95–120 to 28–46 minutes, and significantly reduces the concentrations of suspended solids (from 3.2–4.8 g/l to 0.22–0.41 g/l) and dissolved hazardous components in the liquid phase, including heavy metals.

In quantitative terms, the optimized operating mode, selected with the ratio of energy consumption and productivity (the system efficiency of 0.72–0.81), ensured the removal of more than 92% of suspended particles (in some series, up to 94.6%) while maintaining specific energy consumption at a level acceptable for industrial implementation - about 0.61 kW h per 100 kg of processed material (with a spread of ±0.04 kW h), while the concentrations of iron (decreased from 2.4–3.1 to 0.18–0.32 mg/l), lead (from 0.42–0.67 to 0.03–0.06 mg/l) and cadmium (from 0.08–0.14 to 0.005–0.012 mg/l) in the filtrate decreased to values corresponding to the standards for the reuse of industrial water, which further confirms the environmental the viability of the proposed approach (taking into account the requirements that have become more stringent over the past 5-7 years); simultaneously, the improved dewatering characteristics (reduction of residual moisture from 38-44% to 21-27%) and the increase in the uniaxial compressive strength of the solid residue (increase from 0.9-1.4 to 2.6-3.8 MPa after 28 days) demonstrate a quite tangible potential for the secondary use of recycled material in construction and backfill, where the requirements for mechanical properties typically vary in the range of 1.5-3.0 MPa; the combined hydrodynamic and reagent mechanism of action, demonstrated in a series of comparative tests (n=12), showed a pronounced synergistic effect compared to solely mechanical activation (efficiency increase up to 29-33%), ensuring stable and reproducible performance indicators with fluctuations in input parameters within a range of up to 10-15%.

From a practical point of view, the obtained results (confirmed by at least three pilot tests on units with a capacity of 5–12 t/h) prove that the integration of the hydrodynamic activation stage into existing industrial schemes can be implemented without fundamental reconstruction of the technological infrastructure (the implementation period is estimated at 3–6 months, capital costs are at the level of 6–12% of the line cost), and the predicted increase in electricity consumption (by 4–9%) remains economically justified due to a reduction in environmental payments (up to -18–27%), an increase in the water recycling coefficient (up to 0.82–0.91) and an increase in the degree of extraction of useful components (by 9–16%); Thus, the study effectively substantiates the feasibility of rational management of man-made resources through local technological optimization, and the data obtained contribute to the development of environmentally oriented processing solutions and confirm that even a step-by-step modernization (with the introduction of 1-2 key components) is capable of significantly increasing environmental safety, resource efficiency and compliance with increasingly stringent regulatory requirements, which, as practice over the past 10-15 years has shown, are becoming not just a recommendation, but a mandatory condition for the sustainable functioning of industry.

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