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The role of environmental and industrial safety during subsoil development

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Abstract. The article examines the environmental problems of the territories of the Republic of Kazakhstan. These problems are associated with the depletion of accessible mineral resources and the growing amount of man-made waste (MMW), which increases the land area occupied by dumps and landfills as well as the negative impact on the environment. Accumulated waste is, on the one hand, the main pollutant of the environment, and on the other hand, a valuable material potentially suitable for processing and reuse in the production of widely demanded building materials. The need for processing technogenic mineral formations is dictated by the fact that they occupy vast territories, are easily dispersed by wind, and pose an increased environmental risk for mining and metallurgical regions. In this regard, the scientific foundations of integrated methodologies for the environmental assessment of MMW and their recycling in the production of building materials and products were developed. The study substantiates the possibility of using these wastes as raw materials for building products while simultaneously addressing environmental challenges in the affected territories. Methods for the disposal of man-made waste and a quantitative assessment of the prospects for introducing resource-saving technologies are presented.
Keywords: *environmental problems, the resource approach, man-made wastes, building materials, wastes.*

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1. Introduction

The mineral resource complex plays a crucial role in ensuring the economic stability and sustainable development of the Republic of Kazakhstan. The country possesses vast reserves of mineral raw materials, including both metallic and non-metallic ores, which constitute the foundation of industrial growth and export potential. However, the effective utilization of these resources requires not only geological exploration and extraction, but also a well-balanced state policy aimed at rational use, technological modernization, and environmental protection.

Based on the importance of the mineral resource complex for the national economy, the strategy for its development should be implemented throughout the country and, therefore, must be a state-level strategy. The ultimate goal of this state strategy is to identify and implement optimal solutions that would satisfy Kazakhstan's internal demand for minerals, enhance the competitiveness of its mining and metallurgical sectors, and ensure a stable and secure position in the global mineral market.

To achieve this goal, it is necessary to address a series of fundamental questions [1-3]:

1. What types of mineral resources are advisable to mine directly on the territory of the Republic of Kazakhstan?
2. What volumes of mineral extraction, and in what time frame, should be ensured?
3. Which mineral deposits, including technogenic and secondary ones, should be prioritized for exploitation?
4. What technological solutions should be implemented in the extraction and processing of minerals and mineral raw materials?
5. Which beneficiation and enrichment technologies should be applied to maximize recovery and minimize losses?
6. What human resources are required both in quantity and qualification to ensure sustainable industry development?
7. To what extent should financial resources be mobilized (public and private investment) to implement this strategy effectively?

Finding comprehensive answers to these questions is an extremely complex task. The economy of Kazakhstan relies on more than one hundred types of minerals that vary in quality, origin, technological processing, and industrial application. These factors create a wide spectrum of possible development pathways for the national system of mineral and energy supply. Therefore, there is a need for a scientifically grounded methodology that would enable the reduction of numerous possible options to a rational and economically justified set, allowing the preparation of reliable feasibility studies for mining projects and technological solutions.

An important part of this comprehensive approach is the study of waste and secondary mineral resources, which represent a significant reserve for increasing the efficiency of the mineral sector.

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Tailings from ore enrichment and man-made deposits contain valuable components that can be reused in various technological cycles, including in the production of construction materials. Research in this area not only contributes to resource conservation and circular economy principles but also reduces the environmental burden on mining regions.

The object of this study is enrichment tailings and embedded mixtures with and without additives based on them, while the subject of research is the physical and mechanical properties and hardening behavior of these embedded mixtures under natural moist conditions.

2. Materials and methods

2.1. Research materials

Scientific publications of foreign and domestic researchers in the field of using mining and metallurgical waste as secondary raw materials were analyzed. The tailings of the processing plants Achpolymetal, Donskoy GOK, Kazakhmys Corporation and the Akzhal mine of Nova-Zinc LLP were studied, and the ash and slag waste from the Almaty thermal power plant, which uses coals from the Ekibastuz deposit, was also studied.

By burning coal, thermal power plants receive thermal energy and generate electrical energy. The negative side of this process is the formation of by-products of coal combustion – fly ash and slag. The composition of the ash and slag material was determined by the quantitative ratio of the minerals included in it, which depend on the mineralogical composition of the initial part of the fuel. Ordinary samples weighing from 3-5 to 15-16 kg were taken at the ash dumps, of which group samples were subsequently compiled.

2.2. Research methods

To determine characteristics of input materials and composition of embedded mixtures and their physical and mechanical properties, standard methods were used, and XRF and IR were used to identify their physical and chemical properties. X-ray phase analysis (XPA) was carried out on a DRON-3M X-ray installation (RF) and X-ray structural analysis was carried out with a JCXA-733 «Superprobe» microanalyzer (Japan) with software, scientific research to study waste structure using laboratory polarizing microscope Leica ICH DM2500 (Switzerland), equipped with a powerful 100 W illuminator, which allows you to comfortably work with differential interference contrast; differential thermal analyzes (DTA) were carried out on a derivatographic device MOM-1500 D (Hungary); chemical analysis and microhardness tester PMT-3 (RF). Particle size distribution analysis was carried out using Analizette 22 Micro Tec Fritsch GmbH (Germany) device.

3. Results and discussion

As all industries grow, the consumption of the resources of the Earth's interior, including mineral resources, increases, which leads to the formation of a large amount of man-made waste (MMW) production. In this regard, environmental problems are increasing. The construction materials industry is one of the few that can dispose of high-tonnage waste from other industries. Large-scale utilization of MMW can significantly expand the raw material base for the production of building materials, as well as contribute to improving the environmental situation in the regions.

At the same time, it must be considered that the scale and depth of the negative impact of mining on the environment causes great concern to society. Even poets write with excitement: «There is less and less surrounding nature, More and more environment».

It has been established that the impact of mining on the environment must be identified a priori in order to have a reserve of time to develop the most technologically and economically effective methods for eliminating and minimizing this impact.

When developing technological processes for mining production, priority should be given to those solutions that ensure the absence or minimum generation of production waste (Figure 1).

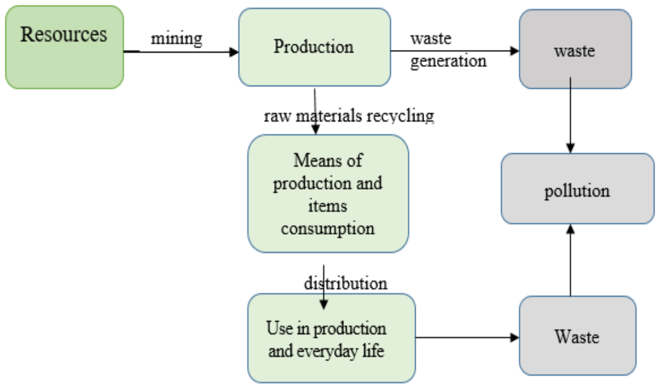

Figure 1. Conversion of subsoil resources into environmental pollution

The idea of creating waste-free (ecologized) subsoil use involves the development and implementation of methods and means of their organizational and economic support, allowing modern mining production to fit into the natural geochemical cycle, thereby turning it into a geochemically closed system. Closed green mining production is based on the following principles:

– minimum losses of matter and energy at the stages of their removal from the natural system and subsequent use in mining;

– maximum use of mining waste in other economic systems and to restore the disturbed ecological balance of the natural system.

These principles should be considered when developing the scientific basis for an environmental strategy for the development of the mineral resource base and mining industry in the Republic of Kazakhstan. All methods of mining are characterized by an impact on the biosphere, polluting almost all its elements, including the subsoil.

Subsoil is the object and operational basis of mining production and is subject to the greatest impact. Since subsoil belongs to elements of the biosphere that do not have the ability to naturally renew in the foreseeable future, their protection should include ensuring scientifically sound and economically justified completeness and complexity of use.

The impact of mining on the biosphere is manifested in various sectors of the national economy and is of great social and economic importance.

At present, it is not possible to give a comparative quantitative assessment of the impact of subsoil crawling and other types of human activities on the environment, since there is no scientific and methodological basis for such a comparison. The various private criteria used do not allow us to obtain an unambiguous answer to this question.

In Table 1, a comparative qualitative assessment of the environmental impact of certain types of industrial production is given [4]. As can be seen from this table, mining has the widest impact on the biosphere, affecting almost all its elements. We analyzed the results of various programs and projects for environmental restoration in areas of closed mines for the extraction of uranium, ore and non-metallic minerals and coal.

Table 1. Comparative assessment of the impact of various types of industrial production on the environment

Industry	Impact of industries on elements of the biosphere						
	Airpool	Water pool		Earthly surface		Flora, fauna	Subsoil
		Superficial water	Underground water	Soil cover	Landscape		
Chemical and petrochemical	S_t	S_t	M_e	M_e	Mi	M_e	Mi
Metallurgical	S_t	S_t	Mi	M_e	Mi	M_e	O
Fuel and energy	S_t	S_t	Mi	Mi	Mi	Mi	O
Construction	Mi	Mi	Mi	M_e	M	Mi	Mi
Transport	M_e	M_e	Mi	Mi	Mi	Mi	O
Mining	M_e	S_t	S_t	S_t	S_t	M_e	S_t

*Note. O – no impact; Mi – minor impact, M_e – medium impact, S_t – strong impact

Activities that were carried out during the implementation of these programs included: inventory of areas of underground and open-air mining complexes, creation, management and visualization of a database, assessment of environmental impact, forecasts of future changes in this impact, classification and prioritization of individual and group underground and above-ground objects complexes, development of technical solutions for the liquidation or conservation of objects with subsequent technical and biological reclamation of disturbed areas, management and purification of mine and drainage waters and simultaneous environmental monitoring.

For example, mining enterprises annually extract over 200 million tons of minerals and host rocks from the depths of the Republic of Kazakhstan. The extraction and processing of such large volumes of mineral resources have a negative impact on the environment due to the generation of mining waste. Subsoil use waste is stored off-balance ore, overburden rock, intermediate waste from the process of ore preparation and hydrometallurgy, waste tailings from the flotation and sorption process, slag from the pyrometallurgy process, liquid cyanide containing waste, which is placed on internal and external dumps, tailings and ash and slag storage facilities and other storage facilities.

Mining in Kazakhstan continues to have a negative impact on environmental components. During the extraction of mineral deposits, huge amounts of hazardous waste are produced, which detonate in the dumps of mines and mines, as well as in the tailings of processing plants and hydrometallurgical plants.

Solution to environmental problems in the areas of mines and processing plants cannot be delayed. Intervention at the highest levels of government is urgently needed. Modern society is seriously concerned about solving problems of mining ecology and industrial safety, on which the well-being of the current and future generations involved in subsoil use depends [5].

Thus, subsoil use objects are the main cause of negative impacts on the environment and mining safety. Neutralization of such impacts during the modernization of the mining industry will play a positive role in the formation of a strategy for the development of the mineral resource base; it requires, on the one hand, a certain organization of production and, on the other hand, the use of a method of rational development of subsoil resources, taking into account the problems of mining ecology and industrial safety, which is positive will influence the choice of priorities for the development of the mining industry.

Negative impact of industry is expressed in the impact on specific parts of nature and on the biosphere in whole from processes of extraction and processing of natural resources. Production and consumption waste are sources of anthropogenic environmental pollution on global scale and arise as inevitable result of consumer attitudes and unacceptably low resource utilization rates [6].

For example, in the USSR, non-ferrous metallurgy consumed about 2 billion tons of rocks per year, and commercial output accounted for 1%. In the Russian Federation, one way or another, 90-95%, or from 80 billion to 120 billion tons, end up as waste. More than a billion of them are toxic. Every year, the area occupied by waste increases by 250 thousand hectares. The main suppliers of waste are the mining, chemical, metallurgical, fuel and energy industries.

Depending on the possibility of use, distinction is made between recyclable and non-recyclable waste. For the former, there is technology for processing and inclusion in economic circulation, for the latter it is currently not available. Classification of industrial waste [7] wastes are often chemically heterogeneous, complex polycomponent mixtures of substances with various chemical and physical properties, presenting toxic, chemical, biological, corrosive, fire and explosion hazards.

Number of waste classifications are known in modern scientific and technical literature N.F. Reimers [8] divides waste into industrial, agricultural, construction and municipal. M.E. Pevzner [4] considers only MMC waste and divides it into solid, liquid and gaseous. Ch. Mantell [9] identifies 6 classes of waste: agricultural, livestock, metallurgical, construction, chemical and municipal. The works of Z.A. Estemesov and T.K. Sultanbekov [10] proposed classification of urban construction waste into 13 groups.

In this work, to understand mechanism of occurrence, control, and management, as well as to eliminate shortcomings noted above, classification of production and consumption waste was made according to physical condition, by sources, chemical and morphological composition, as well as by industries and regions (Figure 2).

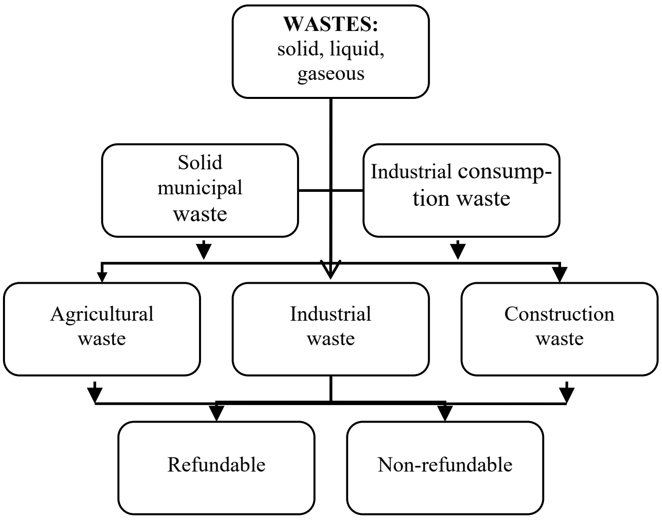

Figure 2. Classification of waste by characteristics physical condition and education

The main causes of waste generation in the mineral resource sector are multifactorial and systemic in nature [11]. They can be summarized as follows:

– irrational management practices, which have become the norm for many enterprises that continue to operate with outdated production and processing technologies;

– an obsolete regulatory framework, which does not correspond to the modern requirements of environmental protection and circular economy principles;

– ineffective supervision and control by central and local environmental and health authorities, as well as by other sectoral government bodies responsible for monitoring waste management practices;

These factors collectively hinder the transition to sustainable resource management and lead to the accumulation of large volumes of industrial and mineral processing waste, creating both environmental and economic challenges for the country. The absence of a specialized law that would comprehensively regulate relations in the field of waste generation, utilization, and disposal. Most cities with a population of over 100 thousand inhabitants, especially megacities like Almaty, are experiencing an environmental crisis due to production and consumption waste.

The high concentration of population in megacities leads to increase in anthropogenic load on environment, which consists in increasing the production and consumption of various energy values. This leads to environmental pollution and disruption of ecology of the urban landscape. Disposal of waste generated by the city to landfills leads to pollution and irrational use of land, the atmosphere, surface and ground waters, increased transportation costs and irretrievable loss of valuable materials and substances.

The solution to this problem is currently urgent due to the manifold increase in the volume of solid waste. In this regard, the end of the twentieth century was marked by the holding of several International Environmental Congresses in the following countries: Brazil, Canada, Japan, Portugal, Sweden, and Russia. Several laws and codes have been adopted in Kazakhstan, which confirms the global nature of environmental problems associated with the lithosphere, atmosphere, hydrosphere and biosphere. The scientific foundations and practical recommendations for environmentally sound management of industrial waste are formulated in the works of scientists from Kazakhstan and abroad [12-17].

However, despite certain achievements in this area, the problems of waste burial, storage, neutralization, and disposal remain among the most critical environmental challenges. Insufficient attention is still paid to the processing and reuse of mining, construction, and municipal waste. Over many decades, the mining and metallurgical complex of the Republic of Kazakhstan has accumulated vast amounts of overburden materials, enrichment tailings, and metallurgical slags. As a result, millions of tons of harmful substances are annually released into the atmosphere, while hundreds of millions of cubic meters of contaminated wastewater are discharged into natural water bodies.

The accumulation of such waste not only leads to the degradation of landscapes and soil contamination but also poses risks to groundwater quality, biodiversity, and public health. Furthermore, the inefficient management of industrial waste represents a significant economic loss, as many of these materials contain valuable components that could be recycled or reused within the framework of a circular economy. Addressing this issue requires the development of innovative technologies for waste utilization, including the creation of construction materials and binder mixtures based on tailings and other by-products of mineral processing. (Figure 3).

(a)

(b) (c)

Figure 3. General view of industrial waste: (a) – overburden dumps formed during open-pit mining; (b) – accumulation of ore beneficiation tailings near processing facilities; (c) – storage of metallurgical slag and coarse waste materials at industrial sites.

Scale of the impact of industrial waste on environment is comparable to geological processes. Large-tonnage industrial wastes are accumulations of waste from the mining, metallurgical, energy and chemical industries containing useful components or minerals. The bulk of mining waste in Kazakhstan is generated in mining enterprises (73%), processing plants (25%) and metallurgical plants (2%). According to modern estimates, the enterprises of the mining complex of Kazakhstan have accumulated over 50 billion tons of industrial waste and occupy vast territories (more than 200 km^2 of area). Every year the amount of industrial waste increases by approximately 1,5 billion tons, and at the same time, the level of use of solid waste is currently low. The total reserves and areas occupied by tailings dumps within the regions are given in Table 2.

Table 2. Processing waste by regions of Kazakhstan

Regions	Quantity	Reserves, thousand tons	Area km^2
Akmola	11	76834.50	12.30
Aktobe	8	30675.30	6.30
Almaty	5	47914.90	2.99
East Kazakhstan	39	887914.57	19.57
Zhambulskaya	6	44188.93	1.58
Karaganda	37	2809342.13	89.20
Kostanayskaya	4	611101.70	27.45
Pavlodar	2	8770.86	1.23
South Kazakhstan	5	142355.30	3.52

Moreover, the largest reserves are concentrated in tailings dumps. The need to involve enrichment tailings in production is dictated by the following circumstances:

– service life of tailings dumps is limited; the filling of many has already been completed or will end in the coming years;

– tailings occupy vast territories and, because they are finely dispersed and easily blown away material, are source of increased environmental risk for regions where mining and processing complexes operate.

Since enrichment waste is finely ground product that does not require additional grinding before use, this reduces economic costs. In addition, the process of ore enrichment ensures the homogeneity of the material both in chemical and mineralogical composition. The total reserves of mining and processing waste of some large mining enterprises in Kazakhstan are given in Table 3.

Table 3. Reserves of technogenic waste at large mining enterprises

Name of the enterprise	Reserves, thousand tons	
	Technogenic dumps	CP dumps
JSC "Achpolitmetal"	–	142570.1
Belogorsky GOK	24406.0	10067.8
Donskoy GOK	81447.7	38280.4
Kazakhmys LLP	973114.7	1674691.5
Zhairemsky GOK	6354.8	3188.8
Tekeli Mining and Processing Plant	15723.9	40360.5
JSC "Kazzinc"	–	373147.1
Zhezdinsky GOK	89.7	3173.2
JSC "Kostanay Minerals"	–	2038.3

According to the bodies of State Control and Supervision of Natural Resources, the share of waste used in the republic is currently 18-20%. It remains extremely low compared to world practice. In Western Europe (France, Germany, Italy, England) this figure is up to 58%, in North America (USA, Canada) – up to 63%, in Japan – up to 87%, China – up to 37% [18].

Accumulated waste is, on the one hand, the main pollutant of environment, and on the other hand, it represents valuable products that are potentially suitable for processing and reuse to obtain popular building materials.

The need for development (processing) of technogenic mineral formations is dictated by the fact that they occupy vast territories, easily blown away material, and are a source of increased environmental risk for the mining and metals industry regions. The constant increase in the volumes of various types of waste generated in the mining and processing industries and their storage in storage facilities and the experience of using such objects in industry allows us to consider them as sources for obtaining secondary raw materials and building materials.

Technologies development for production of building materials based on technogenic waste, contributing to development of industrial and innovative potential of state, careful attitude towards natural resources and the environment, should be considered as the most important scientific and practical task, the solution of which is directly related to environmental safety when disposing of billions of tons of waste in industrial regions [19, 20].

4. Conclusions

The conducted research confirms that waste generated by mining and metallurgical complexes (MMC) and thermal power plants (CHP) can serve as a valuable secondary raw material for various industries, particularly for the production of construction materials. These technogenic formations, traditionally considered an environmental burden, actually represent a significant reserve of useful components suitable for reuse. Their rational involvement in industrial circulation not only reduces the area occupied by dumps and tailings but also prevents the accumulation of new waste, contributing to the transition toward waste-free and environmentally sustainable production.

The technological benefit of such an approach lies in the implementation of modern waste-processing methods within the framework of Kazakhstan’s national program for industrial and innovative development. Economically, it allows for the production of additional building materials and related products, expanding the raw material base of the construction industry. From a social perspective, this process stimulates the creation of new jobs in regions adjacent to mining and metallurgical enterprises, improves working conditions, and enhances environmental safety.

The environmental effect is particularly significant: it manifests in the reduction of land areas allocated for dumps, the restoration of disturbed ecosystems, and the mitigation of harmful emissions and discharges. Thus, the integrated recycling of man-made waste contributes simultaneously to resource efficiency, economic diversification, and the improvement of the ecological situation in industrial regions of Kazakhstan.

Author contributions

Conceptualization: MMB, MBN; Data curation: TBN, DMK; Formal analysis: TBN, DMK; Funding acquisition: YIK, MBN; Investigation: YIK, MBN; Methodology: MMB, MBN, TBN; Project administration: MMB, YIK; Resources: MBN, TBN; Software: DMK; Supervision: MMB, MBN; Validation: MBN, TBN; Visualization: MBN, DMK; Writing – original draft: MMB, MBN; Writing – review & editing: MBN, TBN. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Жер қойнауын игерудегі экологиялық және өнеркәсіптік қауіпсіздіктің рөлі

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Аңдатпа. Мақала Қазақстан Республикасы аумақтарының экологиялық проблемаларын қарастырады. Олар техногендік қалдықтар (ТҚҚ) санының ұлғаюымен, үйінділер мен полигондар алып жатқан аумақтардың өсуімен, сондай-ақ қоршаған ортаға теріс әсерімен бірге жердің минералды ресурстарының қолда бар қорларының азаюымен байланысты. Жинақталған қалдықтар, бір жағынан, қоршаған ортаны ластаушы болып табылады, ал екінші жағынан, сұранысқа ие құрылыс материалдарын алу үшін қайта өңдеуге және қайта пайдалануға болатын құнды өнімдер болып табылады. Техногендік минералды түзілімдерді игеру (қайта өңдеу) қажеттілігі олардың кең аумақтарды алып жатқандығына, желдің оңай үрленуіне және тау-кен және металлургия өнеркәсібі аймақтары үшін экологиялық қауіптің жоғарылау көзі болып табылатындығына байланысты. Осыған байланысты мақалада техногендік қалдықтарды экологиялық бағалаудың және оларды құрылыс материалдары мен бұйымдарын өндіруде қайта өңдеудің кешенді әдістемесінің ғылыми негіздері әзірленді, аумақтардың экологиялық мәселелерін бір мезгілде шеше отырып, аталған қалдықтарды оларды өндіру үшін шикізат ретінде пайдалану мүмкіндігі негізделді. Техногендік қалдықтарды кәдеге жарату әдістері және ресурс үнемдеуші технологияларды енгізу перспективаларын сандық бағалау ұсынылған.

Негізгі сөздер: *аумақтардың экологиялық проблемалары, ресурстық тәсіл, техногендік қалдықтарды кәдеге жарату, құрылыс материалдары мен бұйымдары, қалдықтардың көлемі.*

Роль экологической и промышленной безопасности при освоении недр

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Аннотация. Статья рассматривает экологические проблемы территорий Республики Казахстан. Они связаны с сокращением доступных запасов минеральных ресурсов Земли при одновременном увеличении количества техногенных отходов (ТГО), ростом площадей, занимаемых отвалыми и полигонами, а также отрицательным воздействием на окружающую среду. Накопленные отходы, с одной стороны, являются основным загрязнителем окружающей среды, а с другой — представляют собой ценные продукты, потенциально пригодные для переработки и повторного использования для получения востребованных строительных материалов. Необходимость разработки (переработки) техногенных минеральных образований диктуется тем, что они занимают обширные территории, легко раздуваются ветром и являются источником повышенного экологического риска для регионов горнодобывающей и металлургической промышленности. В этой связи в статье разработаны научные основы комплексной методики экологической оценки техногенных отходов и их переработки в производстве строительных материалов и изделий, обоснована возможность использования указанных отходов в качестве сырья для их производства при одновременном решении экологических проблем территорий. Представлены методы утилизации техногенных отходов и количественная оценка перспектив внедрения ресурсосберегающих технологий.

Ключевые слова: *экологические проблемы, ресурсный подход, утилизация техногенных отходов, строительные материалы, отходы.*

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