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SYSTEMATIZATION OF THE MINERAL-RAW MATERIAL BASE OF BACKFILL MATERIALS AND BACKFILL METHODS IN THE KRYVYI RIH REGION

Purpose. *The research aims to analyse and systematise the mineral-raw material base of backfill materials and backfill methods in the Kryvyi Rih Region based on the study of sources of industrial waste accumulation and types, as well as specifications of backfill technologies.*

Methods. *To achieve the purpose set, an integrated approach is used, including a generalisation of world experience in the use of industrial waste as backfill materials, a study of the register of waste accumulation sites in Dnipropetrovsk Oblast, schematization of the geospatial location of the mineral-raw material base of backfill materials using Google Earth, systematisation and classification of possible backfill methods and combinations of backfill mixture options.*

Findings. *It has been determined that the mineral-raw material base of backfill materials in the Kryvyi Rih Region is insufficiently studied. The scheme of geospatial location of mineral-raw material base sites of backfill materials in the Kryvyi Rih Region has been developed. A general assessment of information data of existing types of backfill materials, their functional purpose, sources of formation and resource reserves is provided. Classification of possible combinations of component backfill mixtures in the Kryvyi Rih Region by types of backfill technologies is proposed.*

Originality. *For the first time, the existing mineral-raw material base of backfill materials in the Kryvyi Rih has been systematised, and a classification is proposed of possible combinations of the backfill mixture component composition by types of backfill methods.*

Practical implication. *Operating the available mineral-raw material base and possible types of backfill methods gives reasons to consider a wide range of resource-saving technologies to minimise geo-ecological problems in the Kryvyi Rih Region.*

Keywords: *mineral-raw material base, backfill material, backfill technology, systematisation, classification.*

Introduction.

Dynamic growth of the planet population leads to intensified consumption of natural resources, the main of which are a wide variety of minerals used in various sectors of the economy – construction, metallurgy, military, medical, information technologies, etc. [1-3]. A significant number of mining and processing facilities operate around the world to obtain the primary raw materials for these industries. As a result of their functioning, the components of the natural environment suffer from a powerful complex technogenic load: the earth's surface pollution due to stockpiled waste, mine and quarry water discharge into rivers and water bodies, dust and gas pollution of the atmosphere, soil degradation and biodiversity, and others [4-6]. The mining of billions of cubic metres of rock mass results in particular damage to the upper part of the lithosphere, while reclamation activities aimed at restoring the earth's surface are lagging far behind in both volume and time. Thus, of the 34000 mineral deposits inspected worldwide, 44929 mining facilities have been identified, covering 101.5 thousand km^2 of the earth's surface area. Other scientists estimate that the large-scale mining industry has a potential impact on 50 million km^2 of our planet's land surface [7, 8].

One of the most effective environmental protection measures during mining of minerals is the technology of backfilling the mined-out space, which solves two major problems: preserving the intact earth's surface state and utilisation of large-tonnage industrial waste accumulations in underground space. Backfill technologies have become particularly widespread worldwide in the context of mines and quarries [9-11], although it is also necessary to highlight elements of backfill technologies during the reclamation of quarry cavities [12, 13]. Today, to form a backfill mass in the mined-out spaces based on various technologies, a wide range of backfill materials are used both from accumulated industrial waste from mining, metallurgy, the fuel and energy complex, and from natural deposits.

At mining enterprises in Ukraine, the use of backfill technologies is not widely spread, although at some mining enterprises occur. It is worth noting the enterprises of PJSC Zaporizkyi Iron-Ore Plant (iron ore deposit) and SE Eastern Ore Dressing Complex (uranium ore deposit) in conditions of which for filling the mined-out space hardening backfill technology is used [14, 15]. The reasons for the limited use of backfill technologies at many private and state-owned mining enterprises are usually technical-economic, as the cost for backfilling in the cost structure can reach 15-30%.

The Kryvyi Rih Iron-ore Basin is the basis of mining and metallurgical complex of Ukraine, where 74% of all iron ores of Ukraine are mined by open-pit (90%) and underground (10%) methods [16, 17]. As a result of the functioning of a significant number of mining facilities around the city of Kryvyi Rih, the earth's surface has been significantly disturbed by quarries, failures and large-tonnage accumulations of various industrial wastes [18, 19]. Some mines in the mid-20^{th} century used hardening backfill technologies for some time, but for economic reasons there has been a shift to blast-hole stoping systems of mining and systems with caving of overlying rocks, which has resulted in the gradual earth's surface destruction. Given the industrial potential and existing large-scale environmental problems in the city of Kryvyi Rih, the development of backfill directions is relevant for the region from the position of preserving and restoring the earth's surface with the purpose of its involvement in various infrastructure projects. The first priority in planning the development of backfill technologies is to study the existing mineral-raw material base reserves.

Today, the systematisation of the mineral-raw material base of backfill materials and possible backfill methods for the Kryvyi Rih Region are insufficiently studied and these issues are given insufficient attention in scientific and information sources, which requires further research.

Research purpose is to analyze and generalise the mineral-raw material base of backfill materials in the Kryvyi Rih Region based on the study of sources of industrial waste accumulation and types, as well as systematise on their basis possible backfill methods and combinations of backfill mixtures. To achieve the purpose set, the following tasks should be solved:

– study the species diversity of accumulated industrial waste in the Kryvyi Rih Region and compare them with known backfill materials;

– create a schematic map of the geospatial location of the mineral-raw material base in the Kryvyi Rih Region;

– systematise, based on the available mineral-raw material base of backfill materials, potentially possible types of backfill methods and the variability of backfill mixture combinations.

Methodological aspects of the research.

To solve the tasks set in the research process, an integrated scientific and methodological approach is used, consisting in the analysis and systematisation of information sources. Preliminary research, based on the analysis of world experience in the successful implementation of backfill operations, has identified a priority list of the most common types of backfill materials [20], according to which a research was also conducted for the mineral-raw material base of the Kryvyi Rih Region. To study the species diversity of accumulated industrial waste in the Kryvyi Rih Region as potential backfill materials, the register of waste disposal sites of Dnipropetrovsk Oblast for 2021 was studied [21]. Also, based on the review of this document, the geographical location of the accumulation sites has been identified. In addition to industrial waste, in the immediate vicinity of the city of Kryvyi Rih, deposits of natural minerals, which can be considered as backfill materials, were additionally studied using the registers of the State Informational Geological Fund of Ukraine. Using such GIS-toolkit as the open Google Earth program, a schematic map of the location of potential backfill materials in the Kryvyi Rih Region has been created. The grouping and systematisation of technologies for backfilling mined-out spaces by means of classification has been performed on the basis of studying and taking into account their specifications, peculiarities and revealed species diversity of accumulated industrial waste in the Kryvyi Rih Region.

Results and discussion.

The mining industry of the Kryvyi Rih Iron-ore Basin makes a powerful contribution to the total waste accumulation both in the region and in the state**.** Thus, according to state statistics, as of 2020, 72.5% of all waste in Ukraine has been accumulated in Dnipropetrovsk Oblast. If we analyse the regional statistics data for Dnipropetrovsk Oblast by cities, then 95.5% of the waste of the whole region and 69.3% of the whole Ukraine is accumulated in Kryvyi Rih. Thanks to the Kryvyi Rih City Environmental Program, 25-30% of all industrial waste generated by the city enterprises can be disposed of annually, but the increase in waste generation far exceeds its disposal. According to the structure of annual waste generation in the region, it can be concluded that 89.9% of waste is generated from the mining industry enterprises and to a lesser extent by metallurgical and energy industries.

Such species distribution and specificity of industrial wastes gives grounds to consider them as potential backfill materials for the implementation of technologies for backfilling mined-out spaces or technogenic cavities in the mining industry. In this case, it is reasonable to consider the orientation of backfill technologies classically for backfilling both underground and open surface cavities for restoring the earth's surface state. Reserves or resources of potential backfill materials in regions may exist in several conventional forms according to the source of their formation: accumulated and stockpiled as industrial waste on the earth's surface (stationary), mined as a mineral or produced as a finished product and sold in various industries (dynamic).

Proceeding from global experience in implementing backfill technologies at world's leading mining enterprises, the following materials are widespread: inert aggregates – waste rock, beneficiation tailings, metallurgical slag, ash slag, limestone, sand; cementitious materials – Portland cement, ground metallurgical slags, thermal power plant fly ash, ground limestone. When studying the register of waste disposal sites in Dnipropetrovsk Oblast, attention is focused specifically on the above-mentioned materials.

As a result of studying the register of waste disposal sites in Dnipropetrovsk Oblast consisting of 220 objects, it has been determined that around and in the city of Kryvyi Rih there is an accumulation of the following industrial waste as potential backfill materials: 15 large overburden and hard rock dumps from quarries and mine dumps, 9 tailings dams and 3 metallurgical slag dumps. It should be noted that there are 37 waste rock dumps in the region when studying the map of the area of Kryvyi Rih in the Google Earth program. The difference of 22 dumps is probably due to the fact that the rest of the dumps are closed, reclaimed or the dumps are not accounted for by the register for other unknown reasons. Based on the analytical assessment results, a schematic map of the geospatial location of the mineral-raw material base sites of backfill materials in the Kryvyi Rih Region has been compiled, illustrated in Figure 1.

Analysis of Figure 1 shows that in the Kryvyi Rih Region, within a radius of 45 km, there is a substantial mineral-raw material base of accumulated both inert and cementitious backfill materials. It should be noted that, given the density of the location of the mineral-raw material base of backfill materials in the Kryvyi Rih Region, favourable conditions have been created for the implementation of backfill technologies, since the cost of delivering materials with increasing transportation distance may well exceed the cost of 1 ton of the material itself. A schematic map makes it possible to form an idea of the logistical location of backfill material sources and, when deciding on the implementation of activities for backfilling technogenic cavities, plan the use of certain types of backfill materials in the Kryvyi Rih Region.

Based on studying the parameters of the mineral-raw material base sites of backfill materials in the Kryvyi Rih Region from the register (according to the schematic map in Figure 1), as well as their functional purpose in the implementation of the backfill technology, information data on a generalised assessment of the mineral-raw material base of backfill materials in the Kryvyi Rih Region can be compiled.

Table 1 data analysis shows that in the Kryvyi Rih Region, the vast majority of backfill materials are stockpiled in allocated waste disposal sites, that is, their reserves at the place of generation are stationary and gradually accumulate. Potential reserves (resources) of such types of cementitious materials as cement and flux limestone at the place of generation dynamically change; they are produced and mined according to the planned business plan annual volumes at the enterprises of PRJSC Kryvyi Rig Cement: cement plant and Zhovtokamianskyi quarry. It is worth noting that the systematised backfill materials of the Kryvyi Rih Region belong to the IV hazard class in terms of toxicity and radioactivity and are low-hazard in terms of influence on the natural environment components, that simplifies requirements to their use and minimises expenses on creation of safe conditions for their application.

According to systematised data, it is evident that the Kryvyi Rih Region has accumulated and stockpiled a powerful mineral-raw material base of backfill materials, of which the resource reserves of cementitious materials are estimated at 145 million tons and 14.3 billion tons of inert aggregates.

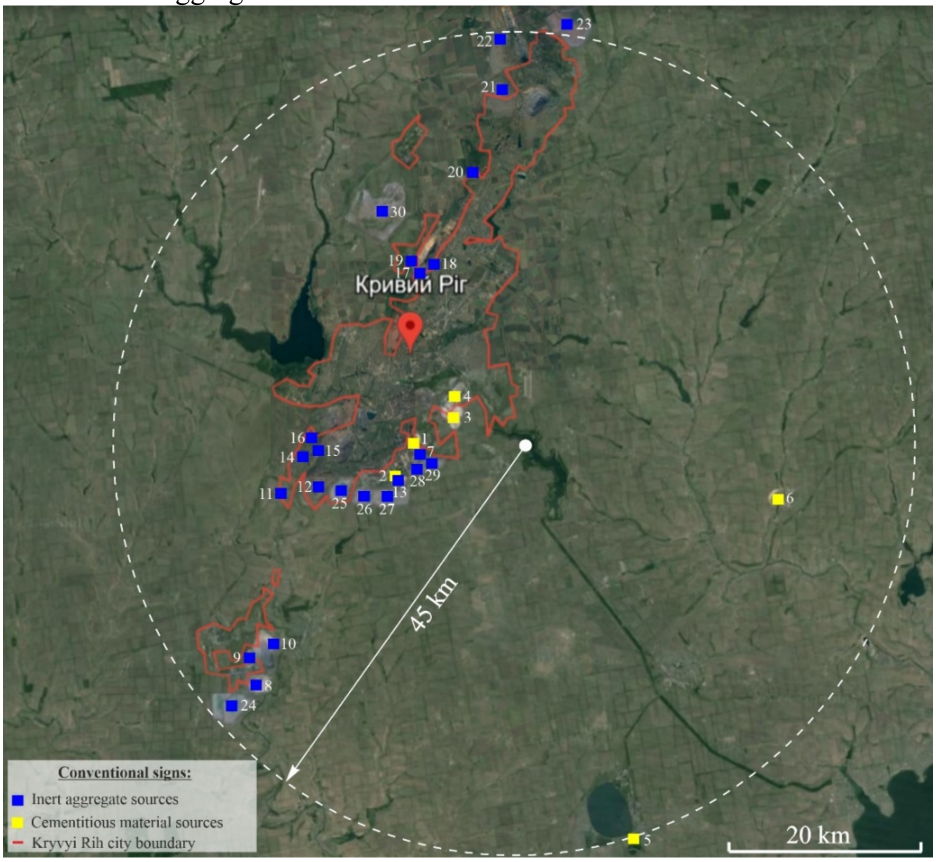

Fig. 1. Schematic map of the location of the mineral-raw material base sites of backfill materials in the Kryvyi Rih Region

Table 1. Mineral-raw material base of backfill materials in the Kryvyi Rih Region

No. (Fig. 1)	Backfill material	Functional purpose	Source of formation	Number of sites	Hazard class	Volume (resource), million tons
1-2	Blast-furnace slag	Cementitious material	Metallurgical production dumps	2	IV	13.5
3	Blast-furnace waste slag	Cementitious material/ Inert aggregate	Metallurgical production dump	1	IV	61.0
4	Cement	Cementitious material	Cement plant	1	IV	1.75 million tons/year
5	Fly ash	Cementitious material	Thermal power plant ash and slag dump	1	IV	70.0
6	Flux limestone	Cementitious material	Quarry mining	1	IV	0.88 million tons/year
7	Steelmaking slag	Inert aggregate	Metallurgical production dump	1	IV	90.0
8-22	Mine rock	Inert aggregate	Overburden and mine rock dumps	15	IV	10000.0
23-31	Beneficiation tailings	Inert aggregate	Tailings dams of mining-processing plants	8	IV	4300.0

In addition, the region mines and produces about 2.6 million tons/year of flux limestone and cement, which can also be considered as cementitious substances in backfill technologies. Such ratio of the resource base of cementitious and inert materials is favourable, since in the backfill mixture composition, the main share by mass is inert aggregate, which is the rigid basis of the backfill mass and the content of which can reach 70-100%, depending on the accepted backfill method.

Therefore, given the sufficient and varied mineral-raw material base of backfill materials in the Kryvyi Rih Region, there are prospects for the use of various technologies for backfilling technogenic cavities, formed by complex open-pit and underground mining of iron ores. The indicated distribution of backfill material types in the region makes it possible to systematise possible options for backfill technologies (loose, injection, hardening and paste backfilling) in the Kryvyi Rih Region that can be used to solve various geotechnical and environmental problems.

The essence of loose backfilling is to fill technogenic cavities with loose inert material with a fraction size of 0...400 mm using a mechanical method, which is currently used in the region to fill some mined-out quarry cavities and mine failure zones. Injection backfilling consists in filling technogenic cavities with loose inert material (0...400 mm) by mechanical method, followed by injection of a cementitious solution with water by pipeline transport for further formation of a monolithic conglomerate. Hardening backfilling consists of a combination of cementitious material, inert aggregate (0...40 mm) and water in the backfill mixture using pipeline transportation of the mixture and subsequent formation of a monolithic mass. The peculiarity of paste backfilling is the combination in a backfill mixture of finely dispersed inert material (< 0.1 mm), insignificant part of cementitious material, low water content with the use of pipeline transport and subsequent formation of a homogeneous monolithic mass.

An important parameter of backfill mixtures is directly its component composition, which for loose backfilling is represented only by inert aggregate, and for injection, hardening and paste backfilling, by cementitious and inert material. The composition of the cementitious and inert material can be either simple (one type of material) and complex (two or more types), which, on the one hand, can complicate the backfill technology, on the other hand, lead to an improvement in the physical-mechanical and physical-chemical properties of the backfill mass. The use of simple and complex cementitious materials and inert aggregates in backfill mixtures generates a wide variety of possible combinations of their component compositions, which can be used in backfill technologies and based on integrated research on technological, economic, ecological and social factors to select the most optimal ones.

In view of possible promising application of recommended methods for backfilling technogenic cavities in the Kryvyi Rih Region, their specific peculiarities, varieties of accumulated backfill materials and their functional purpose, for the first time it is proposed to systematise possible combinations of component backfill mixtures, which is shown in Table 2.

The classification presented in Table 2 makes it easy to understand and select the appropriate backfill mixture combination for a particular type of backfilling, taking into account the available materials of the mineral-raw material base of the Kryvyi Rih Region. The classification includes backfill methods, types and species of viscous and inert materials in terms of complexity, as well as a wide variability of backfill mixture combinations, which facilitates decision-making and improves the process efficiency of backfilling technogenic cavities, depending on the ultimate purpose of using backfill technology.

Taking into account the problems of large-scale accumulation of dump waste rocks and beneficiation tailings, further research should be aimed at the study of a set of optimal backfill mixture properties based on them, depending on the need to solve specific tasks, which will create a theoretical and practical basis for the development of environmental protection and resource-saving technologies to improve the earth's surface state in the Kryvyi Rih Region.

Conclusions.

1. It has been determined that the systematisation of the mineral-raw material base of backfill materials and possible backfill methods for the Kryvyi Rih Region are insufficiently studied and these issues are given insufficient attention in scientific and information sources, which requires further research.

Table 2. Systematization of variations in the component backfill mixture compositions in the Kryvyi Rih Region according to backfill method

<table>
<tr><th rowspan="3">Backfill method</th><th colspan="5">Options of combinations for the backfill mixture component composition</th></tr>
<tr><th colspan="2">Cementitious material</th><th colspan="2">Inert aggregate</th><th rowspan="2">Water</th></tr>
<tr><th>Simple</th><th>Complex</th><th>Simple</th><th>Complex</th></tr>
<tr><td>Loose</td><td></td><td>–</td><td>(DWR)</td><td>(DWR)
(DWR+BFWS)
(DWR+SS)
(DWR+BFWS+SS)</td><td>–</td></tr>
<tr><td>Injection</td><td rowspan="3">(C)
(GBFGS)</td><td rowspan="3">(C+GBFGS)
(C+GFL)
(C+DFA)
(C+GBFWS)
(C+ GBFGS+DFA)
(C+GBFGS+GFL)
(C+GBFWS+DFA)
(C+GBFWS+GFL)
(C+DFA+GFL)
(GBFGS+GFL)
(GBFGS+DFA)
(GBFGS+GBFWS)
(GBFGS+GFL+DFA)
(GBFGS+GBFWS+DFA)
(GBFGS+GBFWS+GFL)</td><td>(DWR)</td><td>(DWR)
(DWR+BFWS)
(DWR+SS)
(DWR+BFWS+SS)</td><td>W</td></tr>
<tr><td>Hardening</td><td>(GDWR)</td><td>(GDWR)
(GDWR+BFWS),
(GDWR+SS)
(GDWR+IOBT)
(GDWR+BFWS+SS)
(GDWR+BFWS+IOBT)
(GDWR+SS+IOBT)</td><td>W</td></tr>
<tr><td>Paste</td><td>(IOBT)</td><td>–</td><td>W</td></tr>
</table>

Conventional designations (code) for the backfill mixture component: C – cement; GBFGS – ground blast-furnace granulated slag; GBFWS – ground blast-furnace waste slag; DFA – dry fly ash; GFL – ground flux limestone; BFWS – blast-furnace waste slag; SS – steelmaking slag; DWR – dump waste rocks; GDWR – ground dump waste rocks; IOBT – iron ore beneficiation tailings; «+» – a combination of backfill mixture components.

2. Based on the conducted analytical research, a schematic map has been compiled of the mineral-raw material base sites of backfill materials in the Kryvyi Rih Region. A general assessment of information data of existing types of backfill materials, their functional purpose, sources of formation and resource reserves is provided.

3. The determined sufficient and diverse mineral-raw material base of backfill materials in the Kryvyi Rih Region makes it possible to systematise possible options for backfill technologies (loose, injection, hardening and paste backfilling) that can be used to solve various geotechnical and environmental problems.

4. For the first time, a classification is proposed of possible combinations of the backfill mixture component composition according to the backfill method. The classification includes backfill methods, types and species of viscous and inert materials in terms of complexity, as well as a wide variability of backfill mixture combinations, which facilitates decision-making in the selection of rational backfill technologies depending on the ultimate purpose of their application.

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СИСТЕМАТИЗАЦІЯ МІНЕРАЛЬНО-СИРОВИННОЇ БАЗИ ЗАКЛАДНИХ МАТЕРІАЛІВ І СПОСОБІВ ЗАКЛАДАННЯ КРИВОРІЗЬКОГО РЕГІОНУ

Мета. *Аналіз та систематизація мінерально-сировинної бази закладних матеріалів і способів закладання Криворізького регіону на підставі вивчення джерел накопичення й різновидів промислових відходів, а також специфікацій технологій закладання.*

Методи. *Для досягнення поставленої мети застосовано комплексний підхід, що включає узагальнення світового досвіду використання промислових відходів в якості закладних матеріалів, вивчення реєстру місць накопичення відходів Дніпропетровської області, схематизацію геопросторового розташування мінерально-сировинної бази закладних матеріалів за допомогою Google Earth, систематизацію та класифікацію можливих способів закладання й комбінацій варіантів закладних сумішей.*

Результати. *Встановлена недостатність вивченості мінерально-сировинної бази закладних матеріалів Криворізького регіону. Розроблена схема геопросторового розташування об'єктів мінерально-сировинної бази закладних матеріалів Криворізького регіону. Надана узагальнююча оцінка інформаційних даних існуючих різновидів закладних матеріалів, їх функціонального призначення, джерел утворення й ресурсних запасів. Запропонована* *класифікація можливих комбінацій компонентних закладних сумішей у Криворізькому регіоні за видами технологій закладання.*

Наукова новизна. *Вперше систематизована існуюча мінерально-сировинна база закладних матеріалів Криворіжжя й запропоновано класифікацію можливих комбінацій компонентного складу закладних сумішей за видами закладання.*

Практична значимість. *Оперування наявною мінерально-сировинною базою й можливих видів закладання дає підстави розглядати широке коло ресурсозберігаючих технологій для мінімізації геоекологічних проблем Криворізького регіону.*

Ключові слова: *мінерально-сировинна база, закладний матеріал, технологія закладання, систематизація, класифікація.*

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