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Mining of non-metallic mineral deposits in the context of Ukraine's reconstruction in the war and post-war periods

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Abstract

Purpose. The research purpose is to study the conditions for mining deposits of metamorphic and igneous origin to produce crushed stone products in conditions of limited electricity supply.

Methods. The research uses an integrated approach, including data analysis on quarry field spatial dimensions and the overburden rock thickness, which provides the basis for identifying deposits into basic groups. For the identified groups of deposits, taking into account the hydrological characteristics of non-metallic deposits and their parameters, patterns have been determined that characterize the change in the normative atmospheric precipitation inflow, based on the quarry field area and the change in the specific costs for water drainage depending on the studied quarry field type. Based on data on technical characteristics of mobile and semi-stationary units and aggregates, the parameters of physical-mechanical properties of granites and diorites, technical-technological solutions for the formation of complexes for processing raw materials for the production of crushed stone products are proposed.

Findings. Problems arising during mining operations under conditions of limited electricity supply, which is caused by mass attacks on Ukraine's energy infrastructure, have been revealed. A systematization of deposits of igneous and metamorphic origin for mining of rock building materials, which are the basis for the production of crushed stone products, has been developed. The rates of water inflow into the mined-out space depending on the quarry field spatial parameters and the depth of mining operations have been studied. Technological schemes of the apparatuses of a complex for processing raw materials for production of crushed stone products and the apparatuses of a complex for processing siftings are proposed.

Originality. Dependences of possible water inflow into the mined-out space of the quarry and change in energy consumption for water drainage have been determined, taking into account the accepted classification criteria, namely the quarry field spatial dimensions, the overburden rock thickness and the quarry depth.

Practical implications. The obtained data on the possible water inflow into the mined-out space of the quarry and change in energy consumption for water drainage make it possible to assess the efficiency of pumping units. The proposed technical-technological solutions on formation of complexes for processing raw materials to produce crushed stone products have been developed in accordance with the fundamental provisions of the Law of Ukraine "On approval of the National program for the development of the mineral resource base of Ukraine for the period up to 2030".

Keywords: *non-metallic deposits, minerals, raw materials, quarry, water inflow, crushing-screening plant, crushed stone*

1. Introduction

In the context of warfare and regular destruction of military and civil infrastructure facilities, there is a growing need for their rapid restoration to cover the population's critical needs for housing, water and electricity supply [1]-[3]. To date, the study of the current state of mining and processing of mineral raw materials during the russian large-scale invasion is very relevant, especially in the directions of providing building materials [4], [5]. The building materials industry uses non-metallic mineral resources [6], [7].

In the aftermath of large-scale invasions and conflicts, the reconstruction of a nation's economy becomes imperative. The branch structure of the national economy plays a pivotal role in this recovery process. Post-war periods necessitate strategic planning and optimization to channel resources effectively. In the context of the Russian invasion, understanding the dynamics of the national economy becomes crucial for efficient restoration [8]-[10].

Mineral construction raw materials are mined almost throughout Ukraine [11]-[13]. The main general building materials include all types of binders – cement, gypsum, lime; wall – bricks, gas concrete blocks, foam concrete blocks; construction fillers – sand, expanded clay, crushed stone, stone screening dust; concrete and cement admixtures. Ukraine is the world's leading country in terms of natural building stone reserves [14]-[17].

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The Ukrainian Crystalline Shield (UCS) runs across the entire territory of Ukraine from the northwest to the southeast. Its part directly outcropped to the surface is 200 km wide and about 1000 km long. It is in this zone that the main building stone deposits are concentrated. Therefore, it is natural that the industry of building material production from natural building stone has become widely developed in Ukraine. Most sand and crushed stone is mined in the Zhytomyr, Vinnytsia, Zaporizhzhia, Kirovohrad and Zakarpattia Oblasts. There are main deposits here where granite, marble, labradorite and other stones are mined. Sand, gravel and crushed stone are usually mixed with cement or bitumen to form concrete, mortar or asphalt [18]-[21].

The functioning of the building materials market is determined by two groups of needs. The first includes the need for building materials for the construction of production plants, office premises, and other material production facilities, as well as repair and reconstruction of residential, administrative, public amenities buildings, and industrial infrastructure facilities. The second group should include the population's needs in building materials for their own construction of housing and other necessary household amenities, as well as their periodic restoration [22], [23].

According to Kyiv School of Economics, as of June 2023, the total direct documented damage to Ukraine's infrastructure due to a full-scale russian invasion is estimated at $ 150.5 billion (at replacement cost) (Fig. 1).

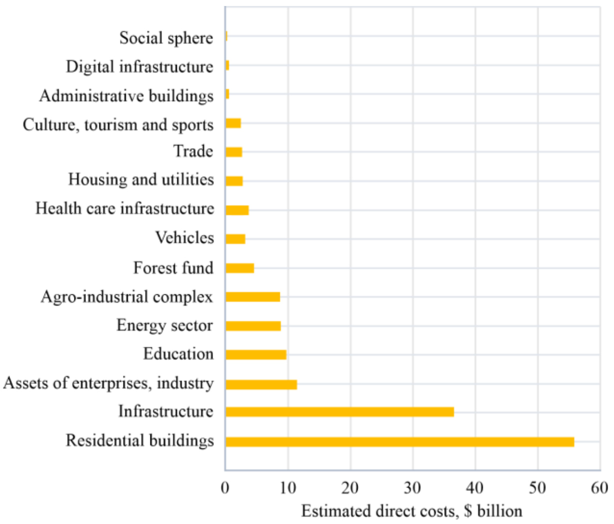

Figure 1. Schedule for assessing the damage caused to Ukraine's infrastructure (June, 2023)

Housing fund accounts for the largest share of the total direct damage – $ 55.9 billion, given the damage of about $ 1 billion from flooding and destruction of residential buildings due to the explosion of a hydroelectric power plant. According to preliminary data from regional military administrations, as of June 2023, the total number of housing facilities destroyed or damaged as a result of hostilities is about 167.2 thousand buildings, of which 147.8 thousand are private houses, 19.1 thousand are apartment buildings, and another 0.35 thousand – dormitories. As a result of the Kakhovka hydroelectric power plant explosion, almost 37 thousand residential buildings were at risk of flooding, most of which are located in Kherson Oblast.

It should be noted that before the full-scale invasion of russia, the Ukrainian market for the construction of new buildings developed very rapidly. New facilities were constantly being built in major cities and beyond. Despite this, in such conditions, in all regions of Ukraine remote from hostilities, there is some resumption of construction, while at the same time prices have risen substantially and are higher than before the war. Thus, as noted in [24], the cost of construction since the beginning of the war has already increased by 20% and may increase by 30% depending on the materials used.

The most commonly used building material is crushed stone. Crushed stone products are mainly used for road construction, production of ready-mixed concrete and reinforced concrete products. At present, the demand for crushed stone tends to increase, especially for high-quality cube-shaped crushed stone. The need for such crushed stone is determined by the restoration of roads, airfield runways, foundations for railway construction, etc. [25]-[28]. It is worth noting the significant potential of Ukraine in the raw material base for producing such crushed stone. However, producing cube-shaped crushed stone is accompanied by significant costs related to both deposit mining and mechanical processing [29], [30]. The suitability of various types of rock for the production of crushed stone for various purposes is regulated by a number of standards, such as: "Dense natural crushed stone and gravel for building materials and products, structures and works. Technical specifications" (DSTU B V.2.7-17-95), "Non-metallic materials for crushed stone and gravel foundations and road surfaces" (DSTU B V.2.7-30-95), "Crushed stone, sand, and gravel for heavy concrete. Technical specifications" (DSTU 10268-80), etc. Directions for using crushed stone depending on fractional sizes are given in detail in Table 1 [31].

Table 1. Directions for using crushed stone depending on fractional sizes

Products	Directions for use
Fraction 0.6-2.0 mm	Ruberoid sprinkling
Fraction 1-3 mm, 2-5 mm	Filler in the production of paving slabs, self-leveling flooring, asphalt-concrete, as well as in filters for wastewater treatment facilities
Fraction 30 mm	Filler in concrete and asphalt production for building and road construction
Fraction 4-8 mm, 8-11 mm	For the upper layer of the road surfacing, in the production of reinforced concrete structures
Fraction 5-20 mm	For the production of asphalt and concrete products, which are used for the construction of residential and office complexes, for the construction and repair of roads with a high-quality surface
Crushed stone of medium fractions (20-70 mm)	For construction and repair of roads, railway tracks
Decorative crushed stone and sand of different fractions (5-10 mm, 0.5-5 mm, 0-2.5 mm) made of marble	For mosaic self-leveling flooring, decorative plasters, landscape design, as a carbonate filler in dry construction mixes, filler in decorative concrete
Rubble stone	For decorative and landscape construction, construction of building plinths, parapet fences, retaining walls

Crushed stone production in Ukraine can be classified according to the main types – granite crushed stone, gravel crushed stone, limestone crushed stone. The granite crushed stone production consists in the crushing of rocks that occur in natural rocky masses. To do this, the masses are blasted to obtain rock mass and rubble stone, which are then crushed in crushers and screened, separating them into fractions based on grain size.

Gravel crushed stone (gravel) is produced by screening quarry rock. It has a lower strength than granite crushed stone, but at the same time also lower radioactivity. Such crushed stone is used for the road construction, concrete and reinforced-concrete products. Limestone crushed stone is used primarily as a base for road foundations during road construction. As a rule, the directions for using crushed stone depend on the specialization of the enterprises using it.

The main enterprises engaged in the production of crushed stone in Ukraine are: Unigran LLC in Zhytomyr Obalst, which is part of the Unigran Holding Company, LLC Ukrainian Mining Company in Dnipropetrovsk Oblast, LLC Novosyniavskyi Crushing Plant in Khmelnytskyi Obalst, Shamrayivske LLC in Kyiv Oblast, Voznesensky granite and crushed stone LLC in Mykolaiv Obalst, etc.

According to the State Geologic and Subsoil Survey of Ukraine, in 2021, more than 73 million tons of crushed stone were produced in Ukraine. The total number of deposits producing crushed stone products is 944 (Fig. 2).

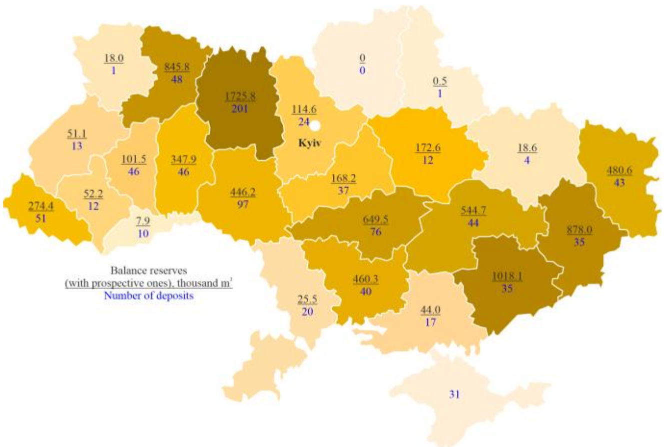

***Figure 2.** Distribution map of deposits producing crushed stone products by regions (Obalsts) of Ukraine (according to the Ukrainian Geological Survey (UGS) data)*

The analysis of the data in Figure 2 indicates that the largest number of deposits producing crushed stone products is located in Zhytomyr Obalst (201 deposits) with balance reserves of 1725.8 thousand m^3. Moreover, the largest amount of crushed stone is produced during the autumn months. For example, as of 2020, crushed stone production amounted to 7.66 million tons in September, 7.68 million tons in October, and 7.52 million tons in November (Fig. 3). This is primarily due to the intensification of works and services related to construction and repairs at the end of the budget year.

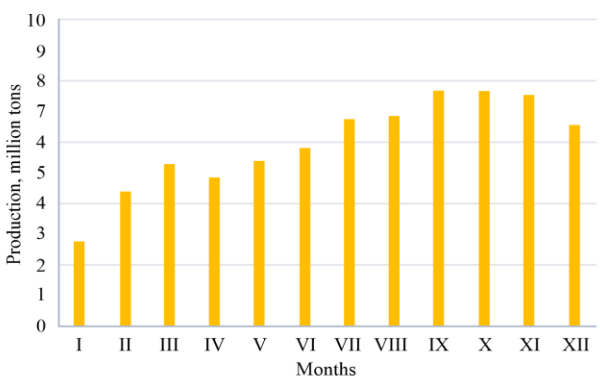

***Figure 3.** Graph of changes in crushed stone production in Ukraine*

New realities imposed on managers of enterprises involved in mining and processing of crushed stone products require the introduction of significant changes to the existing wartime development strategies. Managers of enterprises operating in these difficult circumstances need to improve management methods and tools, anticipate the efficiency of mining operations, their feasibility and, if possible, perform technical re-equipment. The main challenge faced by managers of mining enterprises in 2022 and at the beginning of 2023 is limited electricity supply, which is caused by mass attacks on Ukraine's energy infrastructure. In a number of cases, mining operations were stopped due to significant water inflows. Considering the peculiarities of quarries operating on deposits of igneous and metamorphic origin, which are the raw material base for mining building materials for the production of crushed stone products, the main factor in their stoppage is also related to the work of crushing-screening plants, the power source of which is the power grid.

The main factor in stoppage of mining operations is either the lack of electricity or the limitation of power consumption, which is connected with mass attacks on Ukraine's energy infrastructure [32], [33]. Such a situation is especially critical for deposits that are directly adjacent to river or lake basins and have significant water inflows [34], [35]. Then the manager of the enterprise is faced with the question of whether to pump out water or put the crushing-screening plant into operation.

Implementing autonomous power supply through biosolid oxide fuel systems and optimizing asynchronous motors with variable frequency drives, augmented by an additional power source connected via a combined converter [36]-[38], can mitigate the impact of electricity shortages and enhance the resilience of mining operations against mass attacks on Ukraine's energy infrastructure.

To date, in order to understand the depth of the problem, it is important to highlight the main changes occurring in such a situation [39]. It is necessary to identify the main problems and predict ways to solve them. The direction of development of mining enterprises producing mineral raw materials in wartime in Ukraine is studied for the first time. Major research on the development of the mining industry was conducted in peacetime and did not take into account current threats that may arise suddenly. Research was mainly aimed at substantiating and solving issues related to optimizing rock mining [40] and transportation technologies [41], [42], crushing processes [43], determination of parameters for transport operations [44]-[46], research on the productivity of excavator-vehicle complexes [47], peculiarities of the natural environment anthropogenic transformation during quarrying [48], monitoring of surface subsidence [49]-[54], reclamation measures to restore disturbed areas [51]-[53] and efficient transportation methods to maximize the efficiency and consistency of mining processes [55]-[57]. Therefore, research related to water inflows into the mined-out space of the quarry, which makes it possible to predict the operating performance of a pumping unit and plan its shutdown schedules with the possibility of maximum loading of crushing-screening plants, is of particular relevance. According to NPAOP 0.00-1.24-10, in the event of flooding of the deposit, appropriate drainage measures should be developed and implemented to ensure the safety of operations, as well as draw up an emergency response plan to prevent flooding of the lower horizons of the quarry.

There have been practically no research on hydrogeological peculiarities, namely water inflows into the quarry mined-out space for deposits of igneous and metamorphic origin. This is primarily due to the fact that these quarries are not very deep, currently ranging from 20 to 150 m, and on average no more than 75 m. In works [58]-[60], which studied in detail the issue of groundwater inflow in non-metallic deposits of Ukraine, it is noted that the maximum permissible water inflow during mining the granite quarries is determined by a combination of various factors and, first of all, by the production capacity of the quarry, and should not exceed the value accepted for a large quarry of 2250 m^3/hour at the production capacity of the enterprise 2500 thousand m^3/year.

An increase in groundwater (with increasing depth) and surface water inflow (with increasing quarry field spatial dimensions) entails an increase in the costs for dewatering and drainage, and is one of the key parameters in determining the feasibility of mining operations at these deposits [61]. Analyzing these studies, it can be concluded that the issues of hydrogeological peculiarities, namely water inflows into the mined-out space of the quarry, are devoted to deposits of sedimentary origin [62], [63], brown coal sections [64] and iron ore deposits mined through deep quarries with a depth of over 400 m [65].

Today, the recent increase in consumption of high-quality crushed stone and stricter quality requirements for product quality pose new challenges for managers of mining companies. At present, during martial law, achieving project targets for mineral raw material extraction is an extremely difficult task [66]-[69]. It is possible to solve this problem by introducing state-of-the-art crushing plants at crushed stone enterprises and modernizing the entire technological chain – from drilling-blasting operations in the quarry to the very last screening stage. Modern technical solutions make it possible to create machines more adapted to the specific operating conditions on sites, thereby simplifying technological schemes. One of the promising directions for increasing the efficiency of crushed stone production is the use of mobile crushing-screening plants [70].

The research purpose is to study the conditions for mining deposits of metamorphic and igneous origin to produce crushed stone products in conditions of limited electricity supply. To achieve the purpose set, this research will conduct an analysis during mining the deposits of igneous and metamorphic origin with their subsequent systematization into groups with the identification of typical (basic) deposits; study the changes in energy consumption due to the atmospheric precipitation and groundwater inflow; propose technological-technical solutions for the possible re-equipment of crushing-screening plants by commissioning mobile and semi-stationary units and aggregates for effective water drainage control.

2. Methods

Detailed analysis of geological-hydrological characteristics of non-metallic deposits of mineral raw materials for the manufacture of building products (building materials) is performed using the example of 117 non-metallic deposits of igneous and metamorphic origin in the Prydniprovsk region, systematized into groups with the identification of typical (basic) deposits. The above systematisation identifies three main groups of quarries by deposit area: large, medium and small, and three main types that differ in average thickness of overburden rocks: low-thickness, medium-thickness and thick. Also, these deposits are directly adjacent to the basin of Ukraine's main artery – the Dnipro River with its numerous tributaries. Such deposits are in the most unfavorable conditions for water inflows into the mined-out space.

2.1. Determination of water inflow into the mined-out space of a quarry

The substantiation of the possible groundwater and atmospheric water inflow into the mined-out space of a quarry is performed taking into account the exploration and increase of useful mineral reserves to the maximum depth without spacing the quarry walls beyond the boundaries of estimated reserve contour by area and intra-quarry stockpiling of overburden rocks [71]-[73]. This ensures the development of resource-saving technologies for mining the deposits of igneous and metamorphic origin.

The methodology for substantiating the possible water inflow into the mined-out space of a quarry consists of theoretically determining the rates of water inflow into the mined-out space, selecting pumping equipment based on the analysis of graphic characteristics of pumps according to the passport, and numerically determining the electricity consumed for water drainage.

In advancing the methodology for substantiating potential water inflow into a quarry's mined-out space, incorporating innovative materials such as polymer concrete and fiber concrete for the manufacturing of gear cases and pumps proves essential, with a focus on studying the efficacy of fiber-reinforced concrete in casting housing parts of pumps to enhance durability and resistance [74], [75]. Furthermore, employing supervised machine learning techniques for analyzing the compressive strength of steel fiber-reinforced concrete can optimize the selection of materials, contributing to the overall efficiency and sustainability of the water drainage system in mining operations [76].

The water inflow into the mined-out space (Q_w) is determined by the expression [77]:

$$Q_w = Q_g + Q_p , \quad (1)$$

where:

Q_g – average daily water inflow due to groundwater in fractured zones of crystalline rocks, m^3/day;

Q_p – normative water inflow from atmospheric precipitation, m^3/day.

$$Q_g = S_{s.q} \cdot q , \quad (2)$$

where:

$S_{s.q}$ – the outcropped area of the quarry walls from which water flows into the mined-out space, m^2;

q – rock filtration coefficient, m/day.

$$S_{q.w} = \sum_{i=1}^{n} S_i = S_{q.w}^{I} + S_{q.w}^{II} ; \quad (3)$$

$$S_{q.w} = \left[\left(L_q - H_d \cdot ctg\alpha_r^I \right) H_d + \left(B_q - H_d \cdot ctg\alpha_r^I \right) H_d \right] \times \times 2 + \left[\left(L_r - H_r \cdot ctg\alpha_r^{II} \right) H_r + \left(B_r - H_r \cdot ctg\alpha_r^{II} \right) H_r \right] \cdot 2 , \quad (4)$$

where:

$S_{q.w}^{I}$ – the area of outcropped quarry walls of approved reserves, m^2;

$S_{q.w}^{II}$ – the area of outcropped quarry walls of added reserves, m²;

L_q – quarry length, m;

H_d – depth of internal dump formation, m;

$ctg\alpha_r^I$ – the resulting wall slope angle when mining the approved reserves, deg;

B_q – a quarry width, m;

L_r – a quarry length with extension of reserve, m;

H_r – the depth of added reserves, m;

B_r – a width of extension of reserves, m;

$ctg\alpha_r^{II}$ – the resulting wall slope angle when mining the added reserves, deg.

$$Q_p = S_q \cdot P_y , \quad (5)$$

S_q – the quarry surface area, m²;

P_y – the average daily amount of precipitation falling per calendar year, mm/day.

Electricity consumption (Z) for drainage is calculated by the Formula [78]:

$$Z = C_e \cdot \frac{N_p \cdot N_e \cdot P_p \cdot K_e \cdot T_d \cdot \dfrac{A \cdot S_q + S_o \cdot q}{Q_c \cdot T_o}}{\eta_c} , \quad (6)$$

where:

C_e – cost of 1 kWh, UAH;

N_p – the number of pumps in operating mode;

N_e – number of engines on the pump;

P_p – pump power, kW;

K_e – pump load factor;

T_d – the number of working days per year;

A – average daily precipitation, m;

S_q – quarry field area, m²;

S_o – area of mineral deposit outcrop from which groundwater is released, m²;

q – the volume of water entering the quarry from one square meter, m³/m²;

Q_c – pump capacity, m³/hour;

T_o – operating time of the pump per day, hours;

η_c – network efficiency coefficient.

Thus, considering the exploration and addition of reserves to the maximum depth without spacing the quarry walls, this approach ensures the development of resource-saving technologies for mining the deposits of igneous and metamorphic origin. Theoretical determination of rates of water inflow into the mined-out space, selecting pumping equipment and determination of numerical electricity consumption on water drainage allows effective management of the quarry water regime. An important stage in developing a strategy for the optimal use of resources and ensuring the sustainability of the ongoing mining processes is the use of expressions for determining water inflow and calculating electricity consumption.

2.2. Mining-geological research object conditions

The studied deposits are represented by the rocks of the Konsko-Verkhovtsevska series of the ultrametamorphic formation, confined to the rocks of the upper suite of the Aul series of Archean age, intrusive formation, rocks of the weathering crust and rocks of the Quaternary system. The area of studied deposits is a low-lying, slightly undulating, rather unevenly dissected plain. The lowest surface elevations are observed along the Dnipro River valley and its tributaries. The deposit minerals (disturbed by weathering and fresh rocks) are part of the Crystalline Massif with an uneven surface. The average daily annual inflow is 250-1500 m³, which depends significantly on the hydrogeological conditions, mining depth, and location (distance to the coastline) [77]. The crystalline rock water saturation is determined by the degree of fracturing and the fracture state. The groundwater mirror lies below the crystalline rock roof, groundwater is non-pressure.

The aquifer thickness ranges within 30-75 m, the average thickness in the mined part of the deposits is 50-60 m. The filtration rate of crystalline rocks and their weathering crust ranges within 0.17-0.001 m/day. For gravel and crushed stone, according to experimental data from hydrogeological studies, it varies from 0.1 to 5-10 m/day.

2.3. Technical re-equipment of crushing-screening plants

The basis of technical-technological improvements of crushing-screening plants is the commissioning mobile and semi-stationary units and aggregates. The authors of the research use as a basis the following equipment:

1. To mechanise work:

– a wheel loader LiuGong 856H (bucket 3.5 m³) or analogue;

– automobile transport KrAZ-6510, KrAZ-65055, MAN, DAF, Scania, IVECO (load-carrying capacity of up to 40 tons).

2. For a complex producing crushed stone products:

– hopper-feeder DRO-604;

– jaw crusher DRO-609A;

– cone crusher Triman TMC-3;

– screening machine GIL-42, TEREX Horizon 6203;

– belt conveyors L = 10-20 m, B = 600-1200 mm;

3. For the siftings processing complex:

– hopper with feeder LP-800;

– washing screening machine GIL-21;

– drain screening machine HVCH-31 (single-deck, two-sieve);

– belt conveyors L = 7-20 m, B = 600-800 mm;

– hydrocyclone HC-250.

The input raw materials for the plant producing crushed stone products should be solid non-metallic minerals of various origins, which, due to their laboratory-confirmed physical-mechanical properties and parameters, are suitable for the production of crushed stone products according to the direction of application (Tables 2 and 3).

Table 2. Parameters of physical-mechanical properties of granites

Parameters	Fresh granites			Affected by weathering		
	min	max	average	min	max	average
Volumetric weight, t/m³	2.59	2.70	2.62	2.58	2.63	2.61
Specific weight, t/m³	2.62	2.75	2.65	2.63	2.68	2.65
Water absorption, %	0.18	0.52	0.31	0.19	0.80	0.41
Porosity, %	0.00	2.96	1.22	0.38	2.61	1.51
Ultimate compressive strength, kg/cm²						
– dry samples	1289	2080	1606	953	1644	1363
– water-saturated samples	1207	2115	1470	808	1189	1070
– after 50 cycles of freezing	1080	1523	1275	–	1437	–
Frost resistance (weight loss)	0.003	0.045	0.03	0.011	0.05	0.038

Table 3. Parameters of physical-mechanical properties of diorites

Parameters	Fresh granites			Affected by weathering		
	min	max	average	min	max	average
Volumetric weight, t/m^3	2.77	2.92	2.84	2.80	2.90	2.85
Specific weight, t/m^3	2.83	2.96	2.88	2.82	2.95	2.89
Water absorption, %	0.08	0.67	0.24	0.12	0.69	0.21
Porosity, %	0.70	2.37	1.38	0.68	2.42	1.38
Ultimate compressive strength, kg/cm^2						
– dry samples	1095	–	1561	1015	1367	1168
– water-saturated samples	1209	2047	1473	923	1183	1072
– after 50 cycles of freezing	1066	–	1297	828	1291	1089
Frost resistance (weight loss)	0.060	0.130	0.089	0.060	0.130	0.100

The linear dimensions of the input raw materials are limited by the technical characteristics of the first production unit of the plant and amounted to: 0-680 mm for the raw material processing complex producing crushed stone products; 0-20 mm for a plant processing siftings.

3. Results and discussion

3.1. Substantiation of water inflow in the mined-out space of quarries producing hard-rock building materials

The main factor influencing the water inflow rates from atmospheric precipitation and groundwater into the quarry is the quarry field area and the outcropped area of the quarry walls, from which water enters the mined-out space. To obtain a general picture of possible water inflows, non-metallic deposits of igneous and metamorphic origin of the Prydniprovsk region are systematized into groups, identifying typical (basic) deposits (Table 1).

The above systematisation identifies three main groups of quarries by deposit area: large, medium and small, and three main types that differ in average thickness of overburden rocks: low-thickness, medium-thickness and thick (Table 4).

Table 4. Systematization of quarries by spatial dimensions and overburden rock thickness

Group by spatial dimensions		Type by overburden rock thickness		Average quarry field area, ha	Outcropped area of the quarry walls from which water flows into the mined-out space, m^2
I	Large area	1	Low-thickness	92.7	913955
		2	Medium-thickness	86.8	784772
		3	Thick	92.2	680222
II	Medium area	4	Low-thickness	30.8	305054
		5	Medium-thickness	31.5	317936
		6	Thick	33.4	287867
III	Small area	7	Low-thickness	13.4	141126
		8	Medium-thickness	14.6	142787
		9	Thick	15.3	137720

According to data in [79], the average amount of precipitation per year ranges from 250 to 2200 mm/year, and averages 550-600 mm/year. As for the steppe zone, where non-metallic deposits of hard-rock minerals are most widespread, this parameter is 450-500 mm/year. Thus, the normal water inflow from atmospheric precipitation, depending on the quarry field area, is (Fig. 4).

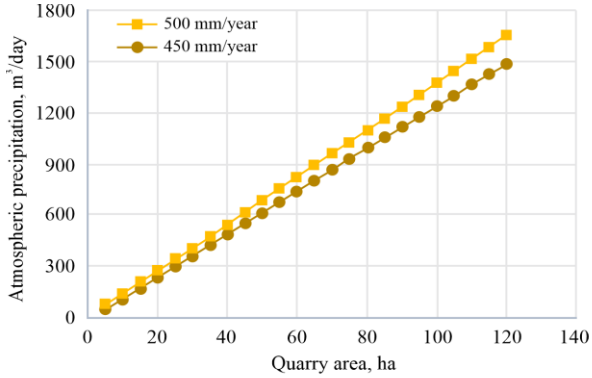

Figure 4. Dependency graph of the normative atmospheric precipitation inflow on the quarry field area

Analyzing the obtained results, it can be concluded that the dependence of the normative atmospheric precipitation inflow on the quarry field area varies according to equation $Q_p = 12.67\ S_q - 7 \cdot 10^{-13}$. The resulting regression equation can be used to determine the amount of atmospheric precipitation at typical quarries with the approximation accuracy $R = 0.997$. Rates of water inflow from atmospheric precipitation at typical quarries are presented in Table 1.

As noted earlier, q is the rock filtration rate, which for rocks of igneous and metamorphic origin with an undisturbed texture (practically impermeable or waterproof rocks) is 0.001 m/day, and for rocks with capillary fracturing (poorly permeable rocks) it can be 0.001-0.01 m/day. The practice of mining deposits of igneous and metamorphic origin shows that in zones of tectonic faults and weathering crust this rate can reach 0.025-0.17 m/day [80]-[82]. Parameters for calculating the average daily water inflow due to groundwater at typical quarries are given in Table 2. Table 3 shows the total volume of water entering the quarry. As a result of the research, a graph of a change in the average daily groundwater inflow depending on the depth of deposit mining at typical quarries has been obtained (Fig. 5). As can be seen from the results obtained, the largest water inflow is from groundwater with a sharp increase in the quarry depth to 130 m.

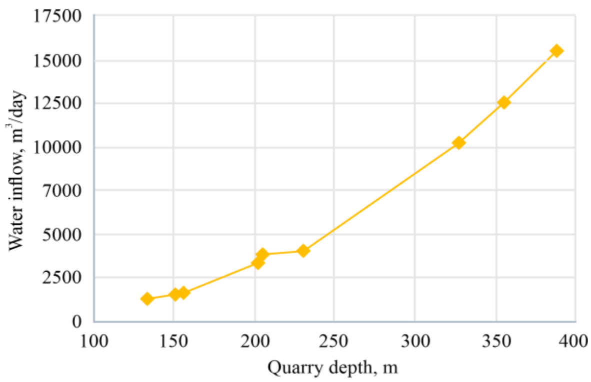

Figure 5. Graph of changes in the average daily groundwater inflow depending on the quarry mining depth at typical quarries

The specified parameters of groundwater inflow (Fig. 5) are approximated in the form of the following analytical dependence: $Q_g = 0.0002 H_q^3 + 0.007 H_q^2 + 12.66 H_q - 1029.5$. The resulting regression equation can be used to determine the amount of average daily groundwater inflow at the base quarries with the approximation accuracy $R = 0.9984$. The error in calculating the expected water inflow does not exceed 1%.

Analyzing the obtained data, showing the change in the average daily water inflow into the quarry from atmospheric precipitation and from groundwater, estimating the hourly water inflow for each type of quarry, the authors of the research have selected the necessary pumping station that will pump out the volume of water from the maximum quarry depth. The type of pump station is selected according to the passport (graphic characteristics of the pumps), the results are shown in the Table 5. The calculation results of the patterns of change in energy consumption for water drainage depending on the quarry depth have the dependence shown in Figure 6.

Table 5. Selection of the type of pumping unit for typical quarries

Quarry group	Quarry type	Quarry depth, m	Total water inflow, m^3/hour	Pump type	Pump power, kW	Required pump number, units
I	1	388	697	TsNS 850-420	1250	1
	2	355	569	TsNS 300-360	425	2
	3	327	483	TsNS 180-340	225	3
II	4	230	188	TsNS 105-245	110	2
	5	205	176	TsNS 180-212	140	1
	6	203	161	TsNS 180-212	140	1
III	7	156	75	TsNS 60-198	65	1
	8	153	73	TsNS 60-198	65	1
	9	134	66	TsNS 60-165	55	1

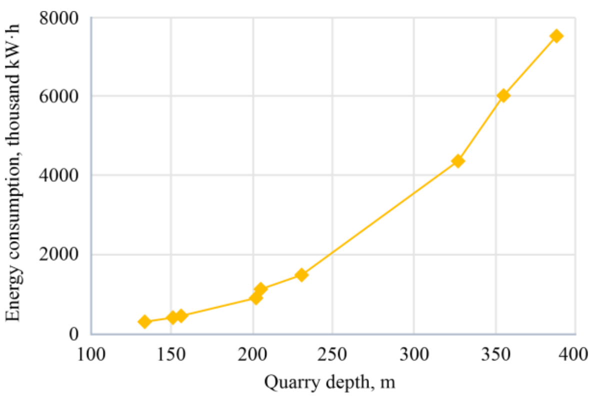

Figure 6. Patterns of changes in energy consumption for drainage depending on the quarry depth

The electricity spent for water drainage is calculated by Formula (6), the calculation results are shown in Figure 7 (the cost of 1 kW is considered within 2019-2023 for mining enterprises).

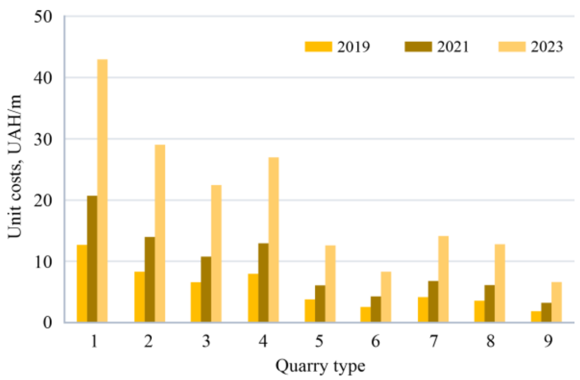

Figure 7. Changes in unit cost parameters for dewatering at typical quarries

Analyzing the obtained results shown in Figures 6 and 7, it can be concluded that with an increased depth of mining the field, there is an increase in the rates of water inflow into the mined-out space, which is reflected by a sharp increase in the quarry depth to 130 m. The dynamics of change in the unit costs for groundwater and atmospheric water drainage from a quarry has a proportional growth with an increase in the cost of energy resources for mining enterprises and has a significant growth in recent years, which has led to an increase in the share of water drainage costs in the total cost of mining building materials and to a decrease in the enterprise profitability.

3.2. Technical-technological solutions on formation of complexes for processing raw materials to produce crushed stone products

The whole picture of the technical support of complexes for processing of mineral raw materials is usually presented in working projects, access to which, in most cases, is limited. Therefore, the authors of the research highlight the basic interrelation schemes for the apparatuses of a complex on processing raw materials to produce crushed stone products and processing of siftings. This will allow a wide range of mining engineers or mining company managers to preliminarily assess the feasibility of re-equipping crushing-screening plants and determine their operating efficiency. And with limited energy consumption, it is rational to plan their operation. The yield of finished products by particle size classes depends on physical-mechanical properties and granulometric composition of the input raw materials. The line productivity is calculated for the standard granulometric composition of the input raw materials for classes d = 0-680 mm. The productivity and efficiency of equipment (screening) depends on the moisture content of the input raw materials. Figure 8 shows a technological scheme for the apparatuses of the raw material processing complex to produce crushed stone products.

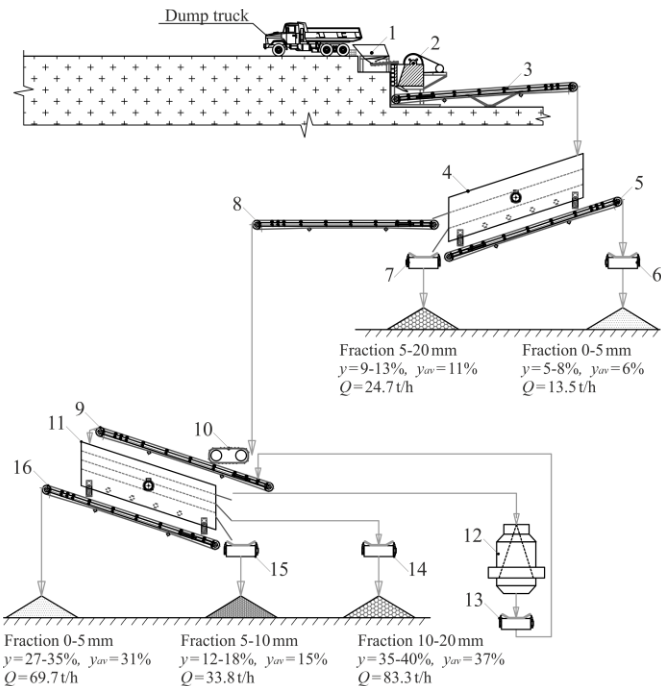

Figure 8. Technological scheme for the apparatuses of the raw material processing complex to produce crushed stone products (input raw materials "raw materials for the manufacture of crushed stone products": Q = 225 tons/hour or 85m³/hour; D = 0-680 mm)

Input raw materials from the rock mass are loaded by a LiuGong 856H front wheel loader or its analogue *1* into KrAZ-6510, KrAZ-65055, MAN, DAF, Scania, IVECO or their analogues with a load-carrying capacity of up to 40 tons *2*, which produce delivery of input raw materials to the loading site of the crushing- screening plant.

Input raw materials with a particle size of up to 680 mm are loaded into a receiving hopper with a capacity of V_h = 20 m^3 using dump trucks. Then, using the DRO-604 plate feeder *1*, all input raw materials are sent to the first crushing stage, namely to the DRO-609A jaw crusher *2*. The DRO-609A jaw crusher *2* is configured in such a way that the discharge slot maximum size is 125 mm, due to which the maximum crushed material size is 155 mm. All input raw materials are unloaded onto the LK-1 belt conveyor *3* and reloaded into the GIL-42 screening machine *4* in order to remove small particle size classes of 0-5 mm and 5-20 mm at the first screening stage. The GIL-42 screening machine *4* is equipped with sieves with the following hole sizes: on the upper tier 22 x 22 mm, and on the lower tier 5×15 mm. Thus, all granite raw materials with a particle size of 0-155 mm undergo the first screening stage according to the 20 and 5 mm particle size classes.

The 0-5 mm under-sieve product is unloaded onto the short LK-2 belt conveyor *5* and reloaded onto the LK-3 product belt conveyor *6*. From the conveyor *6*, the 0-5 mm product is unloaded into the 0-5mm fraction cone crusher. The medium-sized product of 5-20 mm is unloaded on the LK-4 product belt conveyor *7* and unloaded into the 5-20 mm fraction cone crusher. The 20-155 mm over-sieve product is unloaded onto the intermediate belt conveyors LK-5 *8* and LK-6 *9* and sent to the second stage of screening and crushing. Before being fed to the Terex Horizon 6203 inertial screening machine *11*, the 20-155 mm product, due to the LK-6 belt conveyor *9*, passes under the MP-2S magnetic separator *10*. The purpose of the MP-2S magnetic separator *10* is to separate iron particles (bolts, nuts, scrap metal, etc.), which, if they enter the cone crusher, can cause it to fail. These iron particles are separately added to the magnetic fraction. Another 20-155 mm non-magnetic product is fed to a Terex Horizon 6203 inertial screening machine *11*, equipped with sieves with the following hole sizes: on the upper tier 22×22 mm, on the middle tier 10×10 mm and on the lower tier 5×5 mm. The 20-155 mm over-sieve product is sent to the Triman TMC-3 cone crusher *12*. The Triman TMC-3 cone crusher *12* is configured in such a way that the discharge slot maximum size is 22 mm, due to which the maximum crushed material size is 35 mm.

All granite raw material is unloaded onto the LK-7 belt conveyor *13* and reloaded onto the LK-6 belt conveyor *9*, which is directed to the Terex Horizon 6203 screening machine *11*. Thus, the 20-35 mm particle size class is recycled until it is crushed to sizes less than 20 mm. Three product belt conveyors LK-8 *14*, LK-9 *15* and LK-10 *16* come out of the Terex Horizon 6203 inertial screening machine *11*. Accordingly, the commercial product of 10-20 mm is unloaded onto the LK-8 belt conveyor *14*, which is unloaded into the 10-20 mm fraction cone crusher. The commercial product of 5-10 mm is unloaded onto the LK-9 belt conveyor *15*, which is unloaded into the 5-10 mm fraction cone crusher. The commercial product of 0-5 mm is unloaded onto the LK-10 belt conveyor *16*, which is unloaded onto the 0-5 mm fraction cone crusher.

In conditions of increasing production volumes, of course, the amount of stored siftings also increases. Figure 9 shows a technological scheme for the apparatuses of the siftings processing complex.

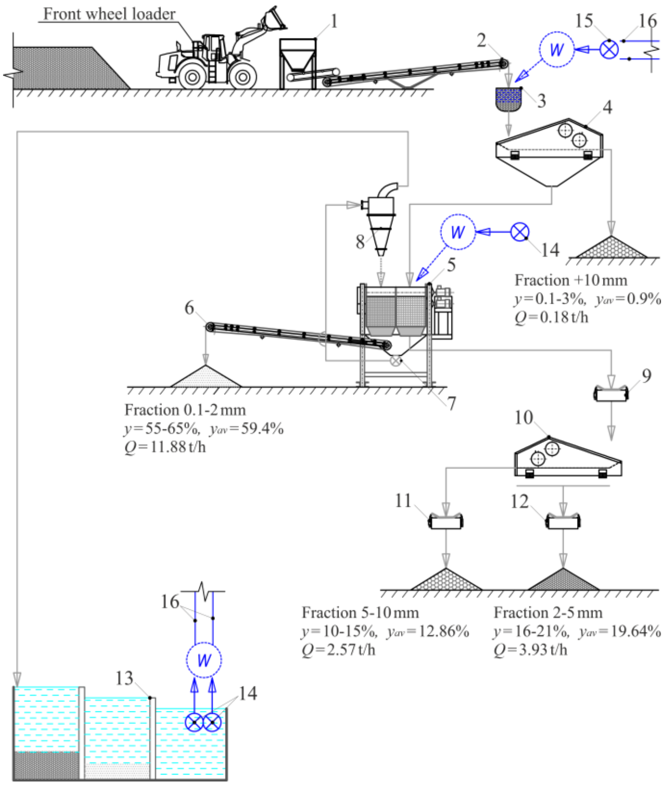

Figure 9. Technological scheme for the apparatuses of the siftings processing complex (input raw material "siftings": Q = 20 tons/hour; D = 0-680 mm

The input raw material of the complex is 0-20 mm granite siftings. Using a front wheel loader with a capacity of 20 tons/hour, the siftings is supplied to a receiving hopper with a capacity of 10 m^3, from where it is reloaded by a belt hopper with feeder LP-800 *1* onto the LK-1 belt conveyor *2*. From the LK-1 belt conveyor *2*, the material is unloaded to the preliminary preparation tank *3*, where it is mixed with water supplied under pressure to obtain a pulp with the specified characteristics T : P = 1:1.2. After mixing in the preliminary preparation tank *3*, the pulp is unloaded by gravity into the GIL-21 inertial washing screening machine *4*. On the GIL-21 inertial washing screening machine, control wet classification of siftings according to the particle size class of 10 mm and separation from the siftings of granite with size larger than 10 mm occurs, which is dewatered and unloaded into a +10 mm product cone. The particle size class -10 + 0 mm, together with water, is overloaded by gravity into the HVCH-31 inertial high-frequency drain screening machine *5*. The HVCH-31 drain screening machine is designed in such a way that the deck is divided in half in the direction of the raw material flow and is equipped with sieves with different holes to solve technological tasks. Therefore, the pulp with raw materials enters the part of the deck equipped with sieves with 2 mm holes, where, using water supplied under pressure, it is separated into an over-sieve product of 2-10 mm and a under-sieve product of 0-2 mm. The over-sieve product of 2-10 mm is unloaded onto the LK-3 belt conveyor *9* and sent to the GIL-21 inertial washing screening machine *10*. In the GIL-21 screening machine *10*, which is equipped with sieves with a hole size of 5 mm, the 2-10 mm product is separated into two commercial products: the over-sieve product of 5-10 mm and the under-sieve product of 2-5 mm. Accordingly, a commercial product of 5-10 mm is unloaded onto the LK-4 belt conveyor

11, which is unloaded in the 5-10 mm fraction cone crusher, and a commercial product of 2-5 mm is unloaded onto the LK-6 belt conveyor *12*, which is unloaded into the 2-5 mm fraction cone crusher.

The under-sieve product of 0-2 mm, together with water, is sent to a sump with a capacity of 5 m^3, equipped with the PK-63/22 slurry pump *7*, from where it is sent under pressure to the HC-250 hydrocyclone *8*. The HC-250 hydrocyclone is an apparatus for gravitational separation of pulp 0-2 mm according to the separation class d_{av} = 0.1 mm. The sandy part of the pulp with a particle size of 0.1-2 mm is unloaded onto a part of the deck of the HVCH-31 inertial high-frequency drain screening machine, equipped with sieves with 0.6 mm holes, where it is partially dewatered. The dewatered product of 0.1-2 mm is unloaded onto the LK-2 belt conveyor (position *6*), which is unloaded onto the 0.1-2 mm fraction cone crusher. Water with small sand particles of 0.1-0.6 mm is partially returned to the sump with a capacity of 5 m^3, which is equipped with the PK-63/22 slurry pump *7*, from where it undergoes additional separation on the HC-250 hydrocyclone *8*. The particle size class of 0-0.1 mm is directed under pressure through a pipe to the cascade tank-clarifier *13*. The cascade tank-clarifier is divided into 3 parts for the purpose of accelerated gravitational clarification of circulating water. Most of the 0-0.1 mm particle size class settles in the first part, a smaller part is directed to the second part of the tank, and almost no particles of material with a particle size of 0.05 mm get into the third part. The required amount of clarified technical water is returned under pressure by Pedrollo F 40/200A *14* and SP65-50/7.5 *15* water pumps to the technological scheme of the siftings processing complex.

Based on the research conducted, it is possible to determine the prospects for further research in the direction of improving technologies and methods for mining non-metallic mineral deposits in conditions of a military conflict. The focus on developing innovative methods for ensuring the efficiency of mining processes in the absence of electricity supply and limited resources reflects the relevance of subsequent research. Particular attention should be paid to technological solutions for water drainage and energy saving, as well as improving management systems for mining facilities in conditions of instability. Prospects also include assessing the sustainability and permanence of mining facilities, developing new technologies for processing raw materials to produce crushed stone products, and strategies for rehabilitating mining enterprises. Global integration of world experience and consideration of energy-efficient planning methods are becoming important aspects for maximizing the efficiency and sustainability of mining processes in the face of wartime and post-war challenges.

4. Conclusions

In war conditions, providing the population with housing is an important socio-economic function. The course towards the growth of housing construction, constant capital repairs to restore civil and industrial infrastructure have a positive impact on the overall economic situation. It should be noted that Ukraine has great prospects for expanding the mineral-raw material base of stone building materials. Despite the war, mining companies continue to operate and pay special attention to new technologies, mastering advanced equipment for mining production.

In 2022-2023, a number of mining companies did not achieve their project targets. The main reason for this situation is the lack of electricity supply, which has led to the cessation of mining operations due to disruption of water drainage regimes and the stoppage of crushing-screening plants. This determines the relevance of conducting research in the direction of substantiating possible water inflows into the mined-out space of quarries of igneous and metamorphic origin, producing hard-rock building materials, and the feasibility of re-equipping crushing-screening plants with mobile and semi-stationary units, which are more efficient in terms of their energy consumption parameters.

Based on the research results of 117 deposits of hard-rock non-metallic minerals, systematized taking into account the qualification criteria, three groups have been identified by deposit area (large, medium and small) and three by the overburden rock thickness (low-thickness, medium-thickness and thick). Given the accepted classification criteria, 9 basic (typical) deposits have been selected as the main objects for research. Dependences of possible water inflow into the mined-out space of the quarry on the quarry field spatial parameters and the depth of mining operations have been determined, as well as an analysis of the dynamics of changes in the specific costs for water drainage has been conducted, which shows a significant increase in losses with the increase in the cost of energy resources. The research data confirm the need to revise the energy distribution between the key segments of the enterprise's operations, and in some cases it is necessary to replace pumps with more efficient ones.

Increasing consumption of high-quality crushed stone and stricter requirements for its quality are forcing product manufacturers to take innovative technological improvements in the work of enterprises to produce this products through technical re-equipment. The authors of the research propose technological schemes for the apparatuses of the raw material processing complex to produce crushed stone products and apparatuses of the siftings processing complex. This makes it possible to predict the efficiency of mining enterprises producing crushed stone products, while assessing their quality characteristics.

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Розробка нерудних родовищ корисних копалин у контексті відбудови України у воєнний та повоєнний періоди

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Мета. Дослідження умов відпрацювання родовищ метаморфічного та магматичного походження з отримання щебеневої продукції в умовах обмеженого енергопостачання.

Методика. У роботі використано комплексний підхід, який включає аналіз даних щодо просторових розмірів кар'єрних полів та потужностей порід розкриву, що слугувало основою для виділення родовищ у базові групи. Для виділених груп родовищ із урахуванням гідрологічних характеристик нерудних родовищ та їх параметрів встановлено закономірності, що характеризують зміну нормативного притоку атмосферних опадів залежно від площі кар'єрного поля та зміну показників питомих витрат на водовідлив залежно від типу досліджуваного кар'єрного поля. На основі даних щодо технічних характеристик вузлів і агрегатів мобільного та напівстаціонарного виконання, показників фізико-механічних властивостей гранітів та діоритів запропоновано техніко-технологічні рішення з формування комплексів з переробки сировини для отримання щебеневої продукції.

Результати. Виявлені проблеми, що виникають при веденні гірничих робіт в умовах обмеженого енергопостачання, що пов'язано з масовими атаками по енергетичній інфраструктурі України. Розроблена систематизація родовищ магматичного та метаморфічного походження з видобутку скельних будівельних матеріалів, що є основою для виробництва щебеневої продукції. Досліджено параметри водоприпливу у вироблений простір від просторових параметрів кар'єрного поля та глибини ведення видобувних робіт. Запропоновані технологічні схеми апаратів комплексу з переробки сировини для отримання щебеневої продукції та апаратів комплексу з переробки відсіву.

Наукова новизна. Встановлено залежності можливого водоприпливу у вироблений простір кар'єру та зміни енерговитрат на водовідлив з урахуванням прийнятих класифікаційних критеріїв, а саме просторових розмірів кар'єрних полів, потужностей порід розкриву та глибини кар'єру.

Практична значимість. Отримані дані щодо можливого водоприпливу у вироблений простір кар'єру та зміни енерговитрат на водовідлив дозволяють оцінити ефективність роботи насосних установок. Запропоновані техніко-технологічні рішення з формування комплексів з переробки сировини для отримання щебеневої продукції розроблені відповідно до принципових положень Закону України «Про затвердження Загальнодержавної програми розвитку мінерально-сировинної бази України на період до 2030 року», основним положенням якого є цінність і не відновлюваність мінерально-сировинних ресурсів, що зумовлює необхідність їх раціонального та ощадливого використання з впровадженням інтенсивних методів видобутку та переробки.

Ключові слова: *нерудні родовища, корисні копалини, мінеральна сировина, кар'єр, водоприплив, дробильно-сортувальний комплекс, щебінь*