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V.O. Shlapak, PhD, Assoc. Prof.
I.V. Davydova, PhD, Assoc. Prof.
A.O. Kryvoruchko, PhD, Assoc. Prof.
S.V. Kalchuk, Assoc. Prof.
Zhytomyr Polytechnic State University

Prospects for processing waste dumps of substandard raw materials from gabbro and labradorite dimension stone quarries into crushed stone: Global experience and Ukrainian realities

The article examines the prospects for utilizing waste dumps of substandard raw materials from gabbro and labradorite dimension stone quarries in Zhytomyr region through processing into construction crushed stone. Global practices in dimension stone quarry waste management, physical and mechanical properties of gabbro and labradorite as raw materials for crushed stone production, and compliance of products with Ukrainian standards DSTU B V.2.7-75-98 and DSTU 9177:2022 are analyzed. At deposits in Zhytomyr region, the yield of commercial blocks is 20–30 %, resulting in the accumulation of 70–80 % of the rock mass in waste dumps that cover hundreds of square meters and reach heights of tens of meters. A comparative analysis of stationary and mobile waste dump processing technologies is conducted. It has been established that gabbro and labradorite possess high strength indicators (crushing strength grade 800–1200), low water absorption (0.1–0.4 %), and frost resistance of F300-F400, making them promising raw materials for the production of high-quality crushed stone in fractions of 5–20, 20–40, and 40–70 mm. It is demonstrated that the implementation of waste dump processing projects will reduce environmental impact, provide additional sources of income for mining enterprises, and satisfy the growing demand for high-strength crushed stone in road and industrial construction.

Keywords: *dimension stone quarries; mineral processing; mining machinery and complexes; mining transport; waste dumps; crushed stone; economics; ecology.*

Relevance of the topic. The extraction of natural stone for the production of block products (dimensional stone) is accompanied by the generation of significant volumes of substandard raw materials that do not meet the requirements for facing stone in terms of dimensions, fracturing, or aesthetic characteristics. According to international research, the yield coefficient of commercial blocks in gabbro and labradorite quarries ranges from 20 to 30 %, indicating that approximately 70–80 % of the extracted rock mass is disposed of as waste dumps [1, 2].

Fig. 1. Typical waste dump of substandard raw materials from a labradorite block quarry in Zhytomyr region

At deposits in Zhytomyr region, which are the main suppliers of gabbro and labradorite in Ukraine, hundreds of thousands of cubic meters of waste rock have accumulated. The waste dumps occupy significant land areas (hundreds of square meters) and reach heights of tens of meters, creating a serious environmental burden: landscape disturbance, dust formation, and changes in the hydrological regime of the territories [3]. At the same time, these waste dumps represent a potential resource for the production of construction materials, particularly high-quality crushed stone.

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Fig. 2. Scale of waste dump accumulation of substandard raw materials at deposits in Zhytomyr region. The height of waste dumps reaches 15–20 meters, creating a significant environmental and visual impact on the landscape

Gabbro and labradorite belong to basic igneous rocks with high physical and mechanical properties: compressive strength of 150–300 MPa, density of 2.8–3.0 g/cm³, water absorption of less than 0.5 %, and frost resistance of over 300 cycles [4, 5]. These characteristics significantly exceed the requirements of national standards for crushed stone for critical construction applications (DSTU B V.2.7-75-98, DSTU 9177:2022) [12, 13].

In the context of the European Green Deal and the concept of circular economy, the processing of block stone waste dumps is gaining particular relevance as a means of reducing primary raw material extraction, decreasing the area of disturbed lands, and creating additional economic value [6]. The global experience of Italy, Norway, Portugal, and other countries demonstrates the successful implementation of natural stone waste dump utilization projects with the production of crushed stone, concrete aggregates, and other construction materials [7, 8, 16].

Analysis of recent research and publications. The issues of waste management in natural stone extraction and processing are actively studied in the international scientific community. Basic classifications of block stone waste are provided in the European Waste Catalogue (code 01 04 – waste from physical and chemical processing of non-metallic minerals), which includes waste gravel and crushed rocks, dust-like waste, and stone cutting waste [9].

Careddu N. and Siotto G. conducted a comprehensive analysis of waste generation in the European block stone industry, establishing that on average 73 % of extracted material becomes waste at various stages of extraction and processing [1, 2]. The researchers proposed a methodology for assessing waste processing potential considering their mineralogical composition and possible applications.

Rana A. et al. in a systematic review demonstrated that crushed stone from gabbro waste can effectively replace natural aggregates in concrete, providing even higher compressive strength compared to control samples when replacing up to 25 % of natural aggregate [10]. The authors also established a reduction in chloride ion penetration and increased resistance to carbonation.

Research in Norway and Italy showed that 80–90 % of stone volume in Norwegian quarries and 30–80 % in Italian quarries becomes waste dumps [7, 8]. Fine fraction accounts for approximately 40 % of total natural stone production. The authors emphasize the lack of a systematic approach to processing and economic incentives for waste dump utilization.

Ribeiro M.J. et al. using the example of Portuguese quarries (Viana do Castelo region), conducted detailed physicochemical characterization of gabbro processing waste and proposed a methodology for assessing market opportunities for their utilization [12]. The researchers established that the most promising directions are the production of aggregates for concrete, road base, and partial replacement of cement with gabbro powders.

An important contribution to understanding the environmental consequences of recycling was made by V.Bisinella et al., who estimated that processing construction and demolition waste in the EU using advanced technologies allows saving approximately 264 kg CO_2-eq per ton at a cost of 25 euros per ton [6]. The maximum emission reduction potential for 2020 was estimated at 33 million tons CO_2-eq.

Regarding the physical and mechanical properties of gabbro and labradorite, fundamental research by C.Mitchell showed that these rocks belong to the strongest among igneous rocks suitable for aggregate production [4]. The critical quality parameter for crushed stone was identified as the flakiness index, which for high-quality road crushed stone should not exceed 15–25 % depending on the application.

In Ukraine, research in this field is limited. Individual works are devoted to the geological characteristics of deposits in Zhytomyr Region and extraction technology, but comprehensive studies on waste dump processing into crushed stone are practically absent, which determines the novelty of this work.

The aim of this study is to provide scientific and technical justification for the prospects of processing waste dumps of substandard raw materials from gabbro and labradorite dimension stone quarries in Zhytomyr region into construction crushed stone based on the analysis of global experience, assessment of physical and mechanical properties of rocks, comparison of alternative processing technologies, and compliance of products with national standards requirements.

Presentation of the main material. Zhytomyr Region is the main region for gabbro and labradorite extraction in Ukraine. The deposits are associated with the Ukrainian Crystalline Shield, specifically with the Korosten Pluton of Precambrian age. The main developments are concentrated in Khoroshiv, Korosten, and Zhytomyr districts.

The gabbro and labradorite of these deposits are characterized by massive texture and coarse-crystalline structure, mineral composition of plagioclase (labradorite) 50–70 %, pyroxene (augite) 20–30 %, olivine up to 10 % [5], dark gray to black color with the iridescent effect characteristic of labradorite («labradorescence»), density of 2.85–3.05 g/cm^3, and high homogeneity of mineral composition.

The extraction technology involves drilling a series of boreholes along the perimeter of the block, separating the block from the massif using diamond wire saws or wedge mechanisms [16]. The yield of commercial blocks is 20–30 %, which is determined by natural fracturing of the massif, presence of areas with texture disturbance, weathering zones, and technological losses during overburden removal and extraction [3].

The remaining 70–80 % of the rock mass is deposited in waste dumps. According to estimates, approximately 3–5 million m^3 of gabbro and labradorite waste rock has accumulated at deposits in Zhytomyr Region, as shown in Figures 1–2.

Global practices for processing block stone waste dumps.

Italy: Sardinia and Tuscany. Italy, as one of the world's leading producers of marble and granite, has accumulated significant experience in managing waste in the mining industry. In the Orosei region (northeastern Sardinia), a consortium of marble producers was created, which organized waste dump processing with production of aggregates for concrete and road base (50–60 % of waste), marble powder for paints, plastics, and paper industry (20–30 %), and decorative chips for landscape design (10–15 %) [1, 2].

The economic model involves cooperation between quarries to achieve the necessary processing volumes (a minimum of 50–100 thousand tons/year for the profitability of a stationary crushing and screening plant).

Norway: processing of gabbro-norite waste dumps. Norwegian gabbro quarries demonstrate the highest percentage of waste (80–90 %) [8]. The NGU (Geological Survey of Norway) company, together with producers, implemented pilot projects for processing gabbro waste dumps into high-strength crushed stone for railway track ballast (fraction 31.5–63 mm), crushed stone for asphalt concrete pavements of road upper layers (fractions 8–11, 11–16 mm), and concrete aggregates for marine structures (increased requirements for frost resistance and salt resistance) [8, 16].

A key success factor was the attraction of state funding at the stage of quarry modernization and installation of crushing and screening equipment (up to 40 % of capital expenditures).

Portugal: integrated approach. A research center was created in the Viana do Castelo region to study the properties of gabbro waste and develop quality standards for secondary products [12]. A distinctive feature of the Portuguese model is the detailed characterization of each batch of waste (particle size distribution, mineralogy and mechanical properties), certification of products from waste according to European standards EN 13242 (aggregates for road construction), and creation of «ecological» construction material brands with enhanced marketing potential.

UAE: large-scale gabbro processing. The United Arab Emirates (Oman deposits) developed an industrial approach to processing gabbro quarry waste with an export focus [20]. The capacity of crushing complexes reaches 500 thousand tons/year. Main sales markets include concrete aggregates for skyscraper construction (fractions 5–10, 10–20 mm), road crushed stone for highways (fractions 20–40 mm), and ballast for port structures (fraction 40–70 mm). The economic model is based on low processing costs (8–12 USD/ton) due to production scale and proximity to the Port of Sohar.

Physical and mechanical properties of gabbro and labradorite as raw materials for crushed stone. Strength characteristics. The gabbro and labradorite of Zhytomyr Region are characterized by exceptionally high strength indicators, determined by their petrographic features: coarse-crystalline equigranular structure, high content of strong minerals (pyroxenes, plagioclase), and absence of microcracks [4, 5].

Table 1

Physical and mechanical properties of gabbro and labradorite from Zhytomyr Region

Indicator	Gabbro	Labradorite	Requirements DSTU B V.2.7-75-98
Compressive strength limit, MPa	180–280	150–220	≥120
Crushing strength grade	1000–1400	800–1200	≥1200
Density, g/cm³	2.95–05	2.85–2.95	≥2.50
Water absorption, %	0.10–0.25	0.15–0.40	≤3.0
Frost resistance, cycles	F300–400	F300–F400	≥F300
Wear in drum, %	8–12	10–15	≤25
Content of dusty and clay particles, %	0.2–0.8	0.3–1.0	≤3.0

The crushing strength grade of crushed stone from gabbro and labradorite is M800-M1400, which significantly exceeds the requirements for the most critical construction applications. For comparison, granite crushed stone typically has a grade of M800-M1200, limestone – M400-M800.

Flakiness is a critically important parameter for road crushed stone, characterizing the shape of grains. Flaky (platy) and elongated grains worsen the laying and compaction of crushed stone, reducing the layer strength [4]. According to DSTU 9177:2022, the flakiness of crushed stone for surface treatment of roads should not exceed 15 % for category I and 25 % for category II [16].

Gabbro and labradorite during crushing form predominantly cubical grains due to massive texture and uniform distribution of mineral cleavage [5]. Experimental data show for crushed stone fraction 5–10 mm flakiness of 12–18 %, for fraction 10–20 mm – 10–15 %, for fraction 20–40 mm – 8–12 %.

The choice of crushing technology significantly affects flakiness. Cone crushers provide flakiness of 10–15 %, vertical shaft impact crushers (VSI) – 5–10 % [4]. Multi-stage crushing with a final stage in a VSI crusher is recommended to obtain category I crushed stone.

Gabbro and labradorite demonstrate exceptional frost resistance F300-F400, which is associated with extremely low water absorption (0.1–0.4 %), absence of microcracks and pores, and high strength of the cementing bond between minerals [4, 5].

For comparison, basalt crushed stone has frost resistance of F200-F300, granite F300, limestone F50-F150. This makes crushed stone from gabbro and labradorite optimal for upper layers of road pavements in severe climatic conditions, airfield pavements, reinforced concrete structures of engineering facilities (bridges, tunnels), and concrete for hydraulic structures [10, 13].

An important characteristic of road crushed stone is adhesion (bonding) with bitumen. Gabbro and labradorite, as basic igneous rocks, have amphoteric surface properties, providing good adhesion with both anionic and cationic bitumen emulsions [4]. The adhesion index according to DSTU B V.2.7-75-98 is 4–5 points (excellent adhesion) [12].

Crushed stone from gabbro and labradorite meets the highest requirements of Ukrainian national standards. According to DSTU B V.2.7-75-98 (Dense natural crushed stone and gravel) [12]: strength grade is M1000-M1400 (requirement for the highest grade M1200), frost resistance grade F300-F400 (requirement F300), crushing grade Dr8-Dr12 (requirement Dr16 for grade I), content of dusty and clay particles 0.2–1.0 % (requirement ≤3 %), content of weak rock grains is absent (requirement ≤5 %).

According to DSTU 9177:2022 (Crushed stone materials for road construction) [13]: flakiness is 8–18 % depending on fraction (requirement ≤15 % for category I, ≤25 % for category II), wear in Los Angeles drum 10–14 % (requirement ≤18 % for category I), adhesion with bitumen 4–5 points (requirement ≥4 points).

According to DSTU 9179:2022 (Methods of physical and mechanical testing) [14], all indicators are determined in accordance with current testing methods, ensuring the reliability of characteristics and the possibility of product certification.

Thus, crushed stone from gabbro and labradorite can be certified for the most critical applications: upper layers of pavements of highways of categories I-II, airfield pavements, high-strength concrete of class C25/30 and higher (bridge structures), ballast for high-speed railway tracks [10, 13].

Technologies for processing waste dumps into crushed stone: comparative analysis. The choice of waste dump processing technology is a key factor in the project's economic efficiency. There are three main approaches: stationary crushing and screening plants (CSP), mobile crushing complexes, and semi-mobile systems [4, 15].

Stationary technology. A stationary crushing and screening plant (CSP) represents a complex of stationary equipment placed on capital foundations with a permanent supply of electricity, water, and other utilities. The technological process is organized as a sequential cascade of operations with the minimization of manual labor [4].

Table 2

Composition and characteristics of stationary CSP equipment

Stage of process	Type of equipment	Technical specifications	Functional purpose
Raw material receiving	Receiving hopper with vibrating screen	Volume: 50–150 m³ Pre-screening: 0–100 mm	Receiving waste rock from vehicles, screening of fine fraction
Primary crushing	Jaw crusher	Power: 200–350 kW Receiving opening size: 900×1200 mm Crushing ratio: 4–6 Capacity: 150–400 t/h	Crushing of sizes 200–800 mm to a fraction 0–150 mm
Transportation	Belt conveyors	Belt width: 800–1200 mm Speed: 1.5–2.5 m/s Length: 20–80 m	Transportation of material between stages
Secondary crushing	Medium crushing cone crusher	Power: 160–250 kW Cone diameter: 1200–1750 mm Crushing ratio: 3–5 Capacity: 120–320 t/h	Crushing of fraction 0–150 mm to 0–60 mm
Intermediate sorting	Vibrating screen (2–3 decks)	Screening area: 8–15 m² Vibration frequency: 850–950 rpm Opening sizes: 0–20, 20–40 mm	Separation of target fractions, return of oversize product
Tertiary crushing	Fine crushing cone crusher	Power: 110–200 kW Cone diameter: 900–1500 mm Crushing ratio: 2–4 Capacity: 80–250 t/h	Crushing of fraction 20–60 mm to 0–20 mm
Grain shape improvement (optional)	VSI crusher (vertical shaft)	Power: 250–400 kW Crushing type: impact + cascade Rotor speed: 60–75 m/s Capacity: 100–300 t/h	Conversion of flaky grains to cubical, reduction of flakiness to 5–10 % [4]
Final sorting	Vibrating screen (3–4 decks)	Screening area: 12–20 m² Vibration frequency: 850–950 rpm Opening sizes: 5, 10, 20, 40, 70 mm	Separation of commercial fractions: 0–5, 5–10, 10–20, 20–40, 40–70 mm
Storage	System of storage bunkers	Quantity: 6–8 units Volume of each: 30–80 m³ Construction: reinforced concrete/metal	Separate storage of commercial fractions
Dust suppression	Aspiration and irrigation system	Fan power: 15–30 kW Water consumption: 3–8 m³/h Filters: bag filters	Reduction of dust formation to regulatory standards
Automation	Process control system (SCADA system)	Number of monitored parameters: 50–100 Operating mode: automatic/semi-automatic	Process control, equipment protection, product accounting

Advantages of stationary technology:

– high productivity (150–400 t/h) is ensured by powerful equipment and an optimized transportation scheme [4];
– low operational costs (15–25 uah/ton) due to the use of electricity instead of diesel fuel, automation, and maintenance savings;
– ability to obtain up to 6–8 commercial fractions thanks to multi-deck screens;
– stable product quality due to constant control of process parameters;
– high level of automation reduces personnel costs;
– low flakiness index (8–12 % for cone crushers, 5–10 % when using VSI) [4];
– long inter-repair period of equipment (6–12 months);
– minimal losses during material transportation;
– possibility of integrating environmental control systems.

Disadvantages of stationary technology:

– high capital costs (30–80 million UAH) depending on capacity and configuration;
– necessity of constructing capital foundations (foundation depth 2–4 m, concrete M300-M400);
– connection of external utilities: electrical network 6–10 kV, water supply, sewerage;

– minimum processing volume for profitability: 100–150 thousand tons/year [18];
– complete lack of mobility – impossibility of moving to other sites;
– long design and construction period (6–12 months);
– necessity of obtaining permits for the construction of capital structures;
– high costs for dismantling in case of raw material reserves depletion.

Economic model of stationary technology:
– payback period: 4–7 years with loading of 120–150 thousand tons/year;
– processing cost: 150–180 UAH/ton (includes depreciation, electricity, wages, repairs);
– personnel number: 12–18 people (2–3 shifts);
– electricity consumption: 6–10 kWh/ton.

Recommended application: large deposits with waste dump volume exceeding 1 million m³ and guaranteed operation period from 10 years, ensuring return on capital investments.

Mobile technology. A mobile crushing and sorting complex consists of self-propelled autonomous modules on tracked or wheeled chassis, which can operate independently of each other or as part of a technological line. Each module is equipped with its own power unit (diesel engine 200–500 kW), control system, and telescopic conveyors for material transfer [18].

Table 3

Composition and characteristics of the mobile crushing complex

Module	Equipment and characteristics	Movement parameters	Functional purpose
Primary crushing module	Jaw crusher on a tracked platform Engine power: 250–350 kW (diesel) Receiving opening size: 700×900 mm Built-in scalping screen: 1–2 decks Capacity: 80–250 t/h Weight: 35–45 tons	Dimensions: 14×3×3.5 m Movement speed: 1–2 km/h Deployment time: 2–4 hours Transportation: trailer truck	Primary crushing of sizes up to 600 mm, preliminary screening of fine fractions 0–40 mm
Secondary crushing module	Cone crusher on tracked platform Engine power: 200–280 kW (diesel) Cone diameter: 1000–1300 mm Magnetic separator (optional) Capacity: 70–200 t/h Weight: 30–38 tons	Dimensions: 13×2.8×3.2 m Movement speed: 1–2 km/h Deployment time: 1–3 hours Transportation: trailer truck	Secondary crushing of fraction 40–150 mm to 0–40 mm, removal of metallic inclusions
Sorting module	Vibrating screen 2–3 decks on a tracked platform Engine power: 120–180 kW (diesel) Screening area: 6–10 m² 3–4 product outputs Capacity: 80–220 t/h Weight: 25–2 tons	Dimensions: 12×2.8×3.5 m Movement speed: 1–2 km/h Deployment time: 1–2 hours Transportation: trailer truck	Separation of commercial fractions 0–5, 5–20, 20–40 mm, formation of product stockpiles
Radial stacker conveyors	Telescopic conveyor Power: 15–0 kW Length: 15–5 m (adjustable) Belt width: 650–800 mm Lifting angle: 0–20 ° Weight: 3–6 tons	Dimensions (folded): 8×2×2 m Deployment time: 15–30 min Transportation: trailer	Formation of separate stockpiles for each commercial fraction at a distance of up to 20 m

Advantages of mobile technology:
– low capital costs (15–35 million UAH) compared to stationary CSP;
– fast commissioning (2–4 weeks from delivery to start of operation);
– high mobility – possibility of moving between quarries within 1–2 days;
– does not require capital foundations – a compacted platform is sufficient;
– effective for volumes of 20–100 thousand tons/year due to flexibility;
– possibility of equipment rental for short-term projects;
– minimal costs for dismantling and conservation;
– autonomy of operation – does not require connection to electrical networks;
– possibility of working at remote sites;

– quick adaptation to changes in the raw material base.

Disadvantages of mobile technology:

– lower productivity (50–150 t/h) compared to stationary CSP;
– high operational costs (30–45 UAH/ton) due to diesel fuel consumption (15–25 l/h per module) [18];
– limited number of commercial fractions (3–4 instead of 6–8);
– higher flakiness (15–20 %) due to absence of VSI crushers in standard configuration;
– increased wear of tracked chassis (replacement every 3–5 years);
– need for regular maintenance of mobile components;
– dependence on weather conditions (work limitations at temperatures below -20 °C);
– increased noise level (85–95 dB) due to diesel engines;
– need for qualified personnel to move equipment;
– limited process automation.

Economic model of mobile technology:

– payback period: 3–5 years with multi-site operation;
– processing cost: 220–280 UAH/ton (includes fuel, depreciation, wages, repairs);
– personnel number: 8–12 people (2 shifts);
– diesel fuel consumption: 0.8–1.2 l/ton of product.

Recommended application: small and medium deposits with waste dump volume of 200–800 thousand m³, contract work on processing waste dumps of several quarries in the region, projects with uncertain operation period.

Semi-mobile technology. A semi-mobile system represents a compromise between stationary and mobile technologies, combining the advantages of both approaches. The main equipment is installed on modular metal frames and can be dismantled and moved by specialized transport within 1–2 months [4, 15].

Table 4

Composition and characteristics of semi-mobile system

Component	Technical specifications	Assembly/disassembly features	Functional purpose
Modular receiving hopper	Volume: 40–100 m³ Material: steel 8–12 mm Built-in screen 2 decks Section weight: 8–15 tons	Consists of 4–6 sections Assembly time: 3–5 days Fastening: anchor bolts M24-M36 Foundation: shallow (0.5–1 m)	Receiving raw materials from vehicles with preliminary screening of fine fractions
Jaw crusher on frame	Power: 180–300 kW Opening size: 800×1100 mm Frame: welded structure Capacity: 100–300 t/h Complete set weight: 25–35 tons	Frame mounting: bolted connections Dismantling time: 2–3 days Movement: truck crane 50–70 t Foundation: reinforced concrete slab 0.8–1.2 m	Primary crushing of sizes 200–700 mm to fraction 0–120 mm
Cone crushers (2 units)	Power: 132–220 kW (each) Cone diameter: 1100–1500 mm Frame: modular metal structure Capacity: 80–220 t/h (each) Weight: 18–28 tons (each)	Quick mounting to frame Dismantling time for one: 1–2 days Movement: truck crane 40–50 t Foundation: temporary supports	Secondary (medium) and tertiary (fine) crushing to commercial fractions
Screens (2–3 units)	Screening area: 8–14 m² (each) Decks: 2–3 replaceable Drive: electric 30–55 kW Frame: quick-release Weight: 12–20 tons (each)	Sectional design Dismantling time: 1 day Movement: truck crane 25–35 t Installation: on metal supports	Sorting into 5–6 commercial fractions, circulation of oversize products
Conveyor lines	Section length: 5–10 m Belt width: 800–000 mm Drive: 15–30 kW Number of sections: 6–12 Total weight: 15–25 tons	Quick-assembly connections Assembly/disassembly time: 3–5 days Movement: manipulator Foundation: metal supports	Transportation of material between processing stages
Control system	Control cabinet in container Power: 600–1000 kW Automation: partial Protection: IP54-IP65 Weight: 3–5 tons	Container design Quick connection Dismantling time: 0.5 day Movement: crane-manipulator	Process control, parameter monitoring, equipment protection

Advantages of semi-mobile technology:

– medium capital costs (20–45 million UAH) – balance between stationary and mobile;
– optimal productivity of 100–250 t/h for medium-sized deposits;
– possibility of relocation within 1–2 months without complete loss of investments;
– medium operational costs of 20–35 UAH/ton (electricity, but simplified infrastructure);
– formation of up to 5–6 commercial fractions;
– flakiness of 10–15 % – better than mobile complexes;
– flexibility in choosing equipment configuration for specific needs;
– possibility of phased investment (complex expansion);
– lower personnel qualification requirements compared to stationary CSP.

Disadvantages of semi-mobile technology:

– need for temporary foundations (shallow, 0.5–1 m);
– commissioning period of 2–3 months (design, installation, adjustment);
– costs for dismantling/installation during relocation (3–7 million UAH);
– necessity of connecting electrical network (although temporary);
– limited possibility of full automation;
– increased wear of connections due to installation/dismantling cycles;
– need for preliminary design of equipment layout.

Economic model of semi-mobile technology:

– payback period: 4–6 years with loading of 80–120 thousand tons/year;
– processing cost: 180–220 UAH/ton;
– personnel number: 10–15 people (2 shifts);
– electricity consumption: 7–9 kWh/ton.

Recommended application: medium deposits with waste dump volume of 500 thousand – 2 million m³, having development prospects of 5–10 years with possible relocation to adjacent areas or deposits within the region. The optimal technological scheme for processing waste dumps of gabbro and labradorite includes the following stages [4, 14]. At the raw material preparation stage, vegetation cover is removed from the waste dump surface, selective material extraction occurs (separation of heavily weathered areas), and preliminary crushing of large blocks (> 800 mm) by mobile jaw crusher to fraction 150–300 mm. The crushing stage includes primary crushing by jaw crusher (output fraction 0–100 mm), secondary crushing by medium crushing cone crusher (output fraction 0–40 mm), and tertiary crushing by fine crushing cone crusher or VSI crusher (output fraction 0–20 mm) [4]. At the sorting stage, multi-deck screening occurs with separation of commercial fractions: screenings 0–5 mm (by-product, possible use as sand for concrete), crushed stone 5–10 mm, crushed stone 10–20 mm, crushed stone 20–40 mm, and crushed stone 40–70 mm [16, 14]. The final stage includes storage of commercial fractions in separate bunkers or on sites with hard pavement, quality control of each batch (crushing strength grade, frost resistance, flakiness, radioactivity) in accordance with DSTU 9179:2022 [14], and shipment by road or rail transport.

The productivity of a typical crushing and screening plant is 100–250 tons per hour. When operating in two shifts, the annual production volume can reach 200–400 thousand tons of crushed stone.

The efficiency of processing gabbro and labradorite waste dumps largely depends on the proper organization of cargo-transport operations. Front-end loaders and dump trucks perform key functions at all stages of the technological process, ensuring continuous operation of crushing and screening equipment.

Stationary crushing and screening plants require the most powerful cargo-transport fleet due to high productivity of 150–400 t/h. The use of front-end loaders with a lifting capacity of 5–8 tons (for example, CAT 966, XCMG LW500, Liugong CLG856) is recommended for loading the receiving hopper with a cycle of 40–60 seconds. Dump trucks with a carrying capacity of 20–30 tons such as Shacman X3000, HOWO T7H, MAN TGS ensure transportation of finished products to storage areas. With an annual processing volume of 150–200 thousand tons, the optimal fleet consists of 2–3 loaders and 4–6 dump trucks operating in two shifts.

Mobile complexes are characterized by lower productivity of 50–150 t/h, which allows the use of more compact machines. Front-end loaders with a lifting capacity of 3–5 tons (CAT 950, SDLG LG953, Lonking CDM855) provide sufficient productivity with maneuverability in confined areas. The advantage is the possibility of rapid movement of equipment together with the complex between quarries. Typical fleet composition: 1–2 loaders and 2–3 dump trucks with a carrying capacity of 15–20 tons (FAW J6P, Dongfeng KC).

Semi-mobile systems occupy an intermediate position with productivity of 100–250 t/h. The optimal solution is the use of universal loaders of 4–6 tons (XCMG LW400, Shantui SL50W), which combine productivity and mobility. A fleet of 2 loaders and 3–4 dump trucks ensures rhythmic operation with the possibility of equipment relocation after 5–7 years of operation.

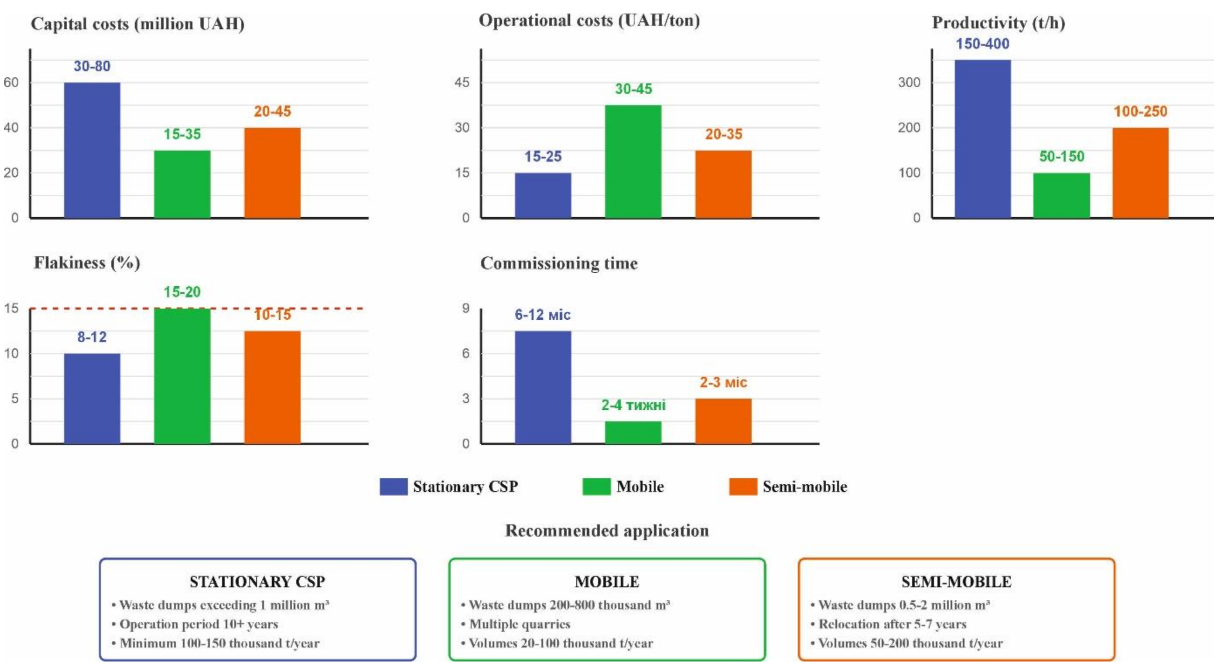

Fig. 3. Comparative diagrams of gabbro and labradorite waste dump processing technologies by main technical and economic indicators

Critical parameters for equipment selection are: loader bucket capacity (3–5 m³ to ensure a loading cycle of 45–90 seconds), dump truck engine power (240–400 hp for operation on haul roads with grades up to 12 %), and operational reliability in dusty conditions. Proper selection of the cargo-transport fleet reduces crushing equipment downtime by 15–25 % and decreases processing costs by 8–12 %.

Environmental benefits include reclamation of disturbed lands (processing of 1 million m³ of waste dumps releases 10–15 hectares of land) [3], reduction of dust pollution (elimination of waste dumps reduces dust emissions by 80–90 %), restoration of hydrological regime (waste dumps disrupt natural surface water runoff), reduction of CO_2 emissions (processing 1 ton of waste dumps instead of extracting primary raw materials reduces greenhouse gas emissions by 10–15 kg CO_2-eq) [6], and conservation of natural resources (each ton of crushed stone from waste dumps preserves geological resources for future generations).

Economic benefits are manifested in reduction of crushed stone production costs (waste material does not require mining operations, which reduces production costs by 30–40 % compared to primary raw material extraction; waste dump processing costs 150–200 UAH/ton versus 250–350 UAH/ton for extraction), creation of additional sources of income for quarries (at a crushed stone selling price of 300–450 UAH/ton, waste dump processing provides profitability of 50–100 %; annual income from processing 100 thousand tons can be 15–30 million UAH), savings on fines and environmental payments, increase in land value (reclaimed territories can be sold or leased), and possibility of state support (waste processing projects can qualify for preferential lending, environmental fund grants, profit tax reduction within the framework of «green» investments) [6, 15].

Analysis of the Ukrainian construction materials market shows stable demand for high-quality crushed stone [10]. Road construction accounts for 55–60 % of the potential market (construction and repair of highways, city roads and streets, airfield pavements).

Reinforced concrete industry consumes 25–30 % (production of ready-mix concrete, precast reinforced concrete structures, monolithic construction). Railway construction uses 10–15 % (ballast for track superstructure, track foundation). Other applications account for 5–10 % (hydraulic engineering construction, landscaping, decorative applications).

Zhytomyr Region has a favorable geographical location with access to major transport routes, providing opportunities for deliveries to Kyiv, Vinnytsia, Khmelnytskyi regions and for export (Poland, Romania).

Conclusions and prospects for further research. Gabbro and labradorite from Zhytomyr Region are characterized by exceptionally high physical and mechanical properties (compressive strength 150–280 MPa, frost resistance F300–F400, water absorption 0.1–0.4 %), which significantly exceed the requirements of national standards for high-quality construction crushed stone [4, 5, 15].

Waste dumps of substandard raw materials from dimension stone quarries, which account for 70–80 % of the extracted rock mass (approximately 3–5 million m³ in Zhytomyr Region), represent a promising resource for the production of crushed stone grades M1000-M1400 of fractions 5–20, 20–40, and 40–70 mm [1, 2].

The global experience of Italy, Norway, Portugal, and the UAE demonstrates the technical and economic feasibility of processing block stone waste dumps with achievement of profitability of 50–100 % at production scales exceeding 100 thousand tons/year [1, 7, 8, 12, 17].

Comparative analysis of technologies showed that the choice between stationary (capital costs 30–80 million UAH, productivity 150–400 t/h, flakiness 8–12 %), mobile (capital costs 15–35 million UAH, productivity 50–150 t/h, flakiness 15–20 %), and semi-mobile systems (capital costs 20–45 million UAH, productivity 100–250 t/h, flakiness 10–15 %) depends on the volume of waste dumps, operation period, and financial capabilities of the enterprise [4, 15].

Crushed stone from gabbro and labradorite fully complies with the requirements of DSTU B V.2.7-75-98 and DSTU 9177:2022, can be certified for the most critical applications (upper layers of road pavements, airfields, high-strength concrete), and has competitive advantages over traditional granite crushed stone in terms of frost resistance and strength [12–14].

Implementation of waste dump processing projects provides comprehensive environmental (reclamation of 10–15 hectares of land per 1 million m³ of waste dumps, reduction of dust pollution by 80–90 %, reduction of CO_2 emissions by 10–15 kg/ton) and economic (reduction of production costs by 30–40 %, additional income of 15–30 million UAH/year when processing 100 thousand tons) benefits [3, 6].

For successful implementation of waste dump processing projects, it is recommended to create consortiums of quarries to achieve optimal production scales, attract state programs supporting «green» investments, conduct detailed characterization of waste dumps at each deposit, implement multi-stage crushing schemes using VSI crushers to ensure flakiness ≤15 %, and develop regional quality standards for crushed stone from gabbro and labradorite waste dumps.

Further research should be directed toward detailed petrographic and geomechanical characterization of waste dumps at specific deposits in Zhytomyr Region with mapping of zones of different quality, industrial testing of various crushing and screening schemes with optimization of commercial fraction yield and flakiness index [4, 17], research on the durability of concrete and asphalt concrete on aggregates from gabbro and labradorite under real operating conditions (test road sections) [10, 11], technical and economic modeling of waste dump processing projects considering logistics, capital and operational costs, sales markets, assessment of the possibility of using fine fraction (screenings 0–5 mm) as sand for concrete and asphalt concrete with appropriate testing, and development of recommendations for reclamation of territories after waste dump elimination considering environmental and socio-economic factors [3, 15].

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Shlapak Volodymyr – PhD, Associate Professor, Mine Surveing Department of Zhytomyr Polytechnic State University.
https://orcid.org/0000-0002-4183-1922.
Scientific interests:
– open-pit mining;
– mining transport;
– mining engineering;
– processing and enrichment of minerals.
E-mail: v.shlapak@ztu.edu.ua.

Davydova Iryna – PhD, Associate Professor, Department of Ecology and Environmental Technologies of Zhytomyr Polytechnic State University.
https://orcid.org/0000-0001-6535-3948.
Scientific interests:
– industrial ecology;
– mining ecology;
– cartographic methods in ecology;
– radioecology;
– resource and energy conservation.
E-mail: div@ztu.edu.ua.

Kryvoruchko Andriy – PhD, Associate Professor, Mine Surveing Department of Zhytomyr Polytechnic State University.
https://orcid.org/0000-0003-3332-2631.
Scientific interests:
- mining machines and complexes;
- subsoil geometry;
- block stone mining.

Email: km_kao@ztu.edu.ua.

Kalchuk Sergii – PhD, Associate Professor, Mine Surveing Department of Zhytomyr Polytechnic State University.
https://orcid.org/0000-0003-3179-2787.
Research interests:
- mathematical modeling;
- open-pit mining;
- resource assessment.

E-mail: kgt_ksv@ztu.edu.ua.

Шлапак В.О., Давидова І.В., Криворучко А.О., Кальчук С.В.

Перспективи переробки відвалів некондиційної сировини з кар'єрів габро та лабрадориту на щебінь: світовий досвід та українські реалії

У статті розглядаються перспективи утилізації відвалів некондиційної сировини з кар'єрів габро та лабрадориту в Житомирській області шляхом переробки на будівельний щебінь. Проаналізовано світовий досвід управління відходами кар'єрів з видобутку блочного каменю, фізико-механічні властивості габро та лабрадориту як сировини для виробництва щебеню, а також відповідність продукції українським стандартам ДСТУ Б В.2.7-75-98 та ДСТУ 9177:2022. На родовищах Житомирської області вихід промислових блоків становить 20–0 %, що призводить до накопичення 70–80 % гірської маси у відвалах, які займають сотні квадратних метрів та досягають висоти десятків метрів. Проведено порівняльний аналіз стаціонарних та мобільних технологій переробки відвалів. Встановлено, що габро та лабрадорит мають високі показники міцності (міцність на розчавлення 800–1200), низьке водопоглинання (0,1–0,4 %) та морозостійкість F300-F400, що робить їх перспективною сировиною для виробництва високоякісного щебеню фракцій 5–20, 20–40 та 40–70 мм. Показано, що реалізація проєктів з переробки породних відвалів зменшить вплив на навколишнє середовище, забезпечить додаткові джерела доходу для гірничодобувних підприємств та задовольнить зростаючий попит на високоміцний щебінь у дорожньому та промисловому будівництві.

Ключові слова: кар'єри з видобутку деревного каменю; збагачення корисних копалин; гірничі машини та комплекси; гірничий транспорт; породні відвали; щебінь; економіка; екологія.

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