ENVIRONMENTAL PROBLEMS

Vol. 5, No. 4, 2020

AERATED CONCRETE WITH THE USE OF FERRUGINOUS QUARTZITE PROCESSING WASTE

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https://doi.org/10.23939/ep2020.04.230

Received:10.10.2020

Abstract. Waste (tailings) of mining and processing plants of Kryvbas were studied by the stages of their magnetic enrichment. The granulometric compositions of the tailings, the amount of iron (total and magnetic) and the mass fraction of solid in them are determined. The expediency of disposing of ferruginous quartzite waste at the first stage of enrichment as a silica component in cellular concretes is proved. Optimal compositions of aerated concrete mixtures are determined based on the following criteria: the average density of cellular concrete in the dry state and its compressive strength.

Key words: ferruginous quartzite processing waste (tailings), recycling, aerated concrete.

1. Introduction

With the development of industry, the amount of technological waste is growing. This is especially true in the mining and processing industries. According to the currently existing technologies for mining and processing minerals, from 10 % to 99 % [1] of the initial mass of raw materials extracted from the subsurface is converted into waste, which is stored on the Earth's surface. This results in huge man-made waste accumulations.

Such accumulations of mining waste are associated with a set of processes of negative impact on the environment. This is, first of all, the contamination of the air basin (dust formation); high aggressiveness of man-made waters due to the presence of technological reagents; toxicity of minerals that make up the rock array and their elements; the presence of heavy metals, the probability of accidents at tailings facilities (dynamic stability of the array), etc. Due to the resulting man-made accumulation of industrial waste, natural systems of adjacent territories fall into the zone of long-term intensive pollution [1].

Man-made accumulation of mineral raw materials from waste can turn into one of the most important sources of mineral raw materials. Such neoplasms can be classified as man-made deposits – artificial accumulations of mineral matter in terms of quantity, quality and conditions of occurrence are suitable for industrial use currently or in the future.

Rational use of mineral resources of man-made deposits has the following aspects: environmental, resource, economic, technological, national security [2].

During the technological cycle, mining and processing enterprises in Ukraine generate about 600 000 m^3 annually (or over 1 billion tons) [1] of mineral waste, including 75–80 million m^3 of enrichment waste [1].

Mineral processing is a set of processes and methods for increasing the concentration of minerals during the primary processing of solid minerals [3]. As a result of enrichment, the minerals are divided into several products: concentrate (one or more) and waste. Besides, intermediates can be obtained during the enrichment process.

Concentrates are enrichment products that contain the main amount of a valuable component. Concentrates in comparison with the enriched material are characterized by a significantly higher content of useful components and a lower content of empty rock and harmful impurities.

Waste is the enrichment products that contain the main amount of waste rock, harmful impurities and a small (residual) amount of useful components.

Ferruginous quartzites extracted in quarries (Fig. 1) are sent to the ore processing plants of mining and processing plants, resulting in the iron ore concentrate and waste enrichment (tails) that are accumulated in tailings dumps (Fig. 2). The total mass of enrichment waste accumulated in the tailings dumps of iron ore plants in Ukraine is over 3 billion tons. [4].

Tailings dumps are places of accumulation of enrichment waste in the form of solid residues, which are transported by pulp pipelines in the form of an aqueous suspension (pulp) (Fig. 2) from the processing complexes and are washed on special alluvial maps (beaches) (Fig. 3). Structurally, tailings dumps can be planar or multi-tiered structures similar to dumps.

The core of the storage facility is formed uncontrollably due to underwater alluvium, that is, during the settling of powdery and clay particles in the water. Nowadays, it is impossible to say for certain, which processes are going on inside the nucleus and how the concentration and density of solid particles are distributed [5]. The core passes through the entire thickness of the vault; it has a pyramidal or cylindrical shape; its lower face rests on a water-resistant layer, and the upper one is the bottom of the pond (Fig. 3), which can be considered horizontal [6].

Fig. 1. Panorama of the Southern mining and processing plant quarry from the observation deck (Kryvyi Rih)

Fig. 2. Discharge of pulp into the tailings dump

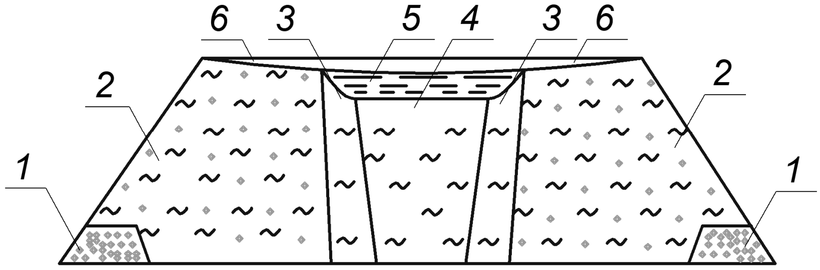

Fig. 3. Tailings dump diagram:
1 – initial collapse dam; 2 – thrust prisms; 3 – intermediate prisms; 4 – tailing core; 5 – pond; 6 – beach

According to Paragraph 3 of Article 3 of the Law of Ukraine "On Environmental Impact Assessment" of 23.05. 2017 No. 2059-VIII processing of minerals, including enrichment, are subject to environmental impact assessment and in accordance with Annex 2 "Methods for Identifying Potentially Dangerous Objects", approved by the Order of the Ministry of Emergency Situations and Protection of the Population from the Consequences of the Chernobyl Disaster on 23.02.2006 No. 98, technological equipment for mineral processing and tailings dumps are among the main sources of the danger which is inherent in potentially dangerous objects. Therefore, restoring ferruginous quartzite enrichment waste, the use of which is currently insufficient, is now particularly urgent.

The urgency of the problem lies in the development of environmentally and economically relevant production technologies with the recycling of generated waste, reducing stale industrial waste, reducing the degree of environmental pollution, reducing energy consumption and saving natural resources.

The development of technological solutions for the restoration of fine tailings is currently carried out (mainly) in two directions:

1) additional enrichment for additional extraction of iron-containing minerals and production of an additional amount of concentrate;

2) production of building materials and embedded mixes for the produced space.

Currently, there are only two projects in Ukraine where ferruginous quartzite processing waste is enriched: processing of lying sands of the sludge storage facility of the central mining and processing plant and the production of concentrate from tailings at the facilities of the pilot industrial complex "Zhovti Vody" (Dnipropetrovsk region) [7].

Effective technologies for the disposal of wet magnetic separation waste are implemented by introducing embedded, concrete and asphalt-concrete mixtures and fusion mixture for the production of ceramic bricks in the form of a hydraulic mixture and mineral powder. Iron oxides affect the increase in the strength of autoclaved concrete 2–2.5 times (compared to natural hardening concretes). Enriched waste with a fineness modulus of less than 1.8 is used in asphalt-concrete mixtures as a fine aggregate; as a mixing additive for manufacturing clay bricks. Fine waste of less than 0.14 mm can be used as a mineral powder in asphalt mixes [8].

The conducted studies [9] showed that the tailings of iron ore enrichment, when activated with lime and cement, can produce a material with a strength of up to 10 MPa; when activated with sodium silicates – up to 40 MPa; and when activated with sodium silicates and man-made glass – up to 60 MPa. The role of binder in such materials is performed by hardening activators, dispersed components of tailings and products of sulfide oxidation. Studies also prove the possibility of obtaining material for road surfaces based on tailings. With the incomplete replacement of river sand with ordinary (all fractions) tailings of ferruginous quartzite enrichment (but only partially with the addition of polyspyrte), a significant increase in the strength of mortars can be achieved [9].

When using ilmenite ore processing waste from the Volnogorsk mining and Metallurgical Plant (Dnipropetrovsk region) as an aluminosilicate component of the raw material mixture for clinker firing, the consumption of blast furnace granulated slag is reduced while increasing the consumption of limestone. In terms of basic construction and technical properties, cement made with the use of such waste is practically not inferior to traditional Portland cement. Using man-made waste in the production of cement clinker contributes to the preservation of the natural environment in the Dnieper Region [10].

Partial replacement of the clay component in the raw material mixture with enrichment waste from the Volnogorsk Mining and Metallurgical Plant improves sintering and decarbonization during firing, increases heat resistance, and reduces the firing temperature of Portland cement clinker by 40 ^{o}C [11].

The aim of the work is to substantiate the raw material value of waste from the processing of ferruginous quartzites (tailings) of mining and processing plants of Kryvbas for the production of cellular concrete.

2. Methodology and materials

The paper examines the processing waste of ferruginous quartzites (tailings) of "Southern mining and processing plant" and "Inguletsky mining and processing plant", which are located in the Kryvyi Rih iron ore basin. At the processing factories of these plants, multi-stage magnetic ore enrichment is used with the gradual release of production waste-tailings. The technological scheme of the ore processing plant No. 1 of the Ingulets mining and processing plant is shown in Fig. 4 [12].

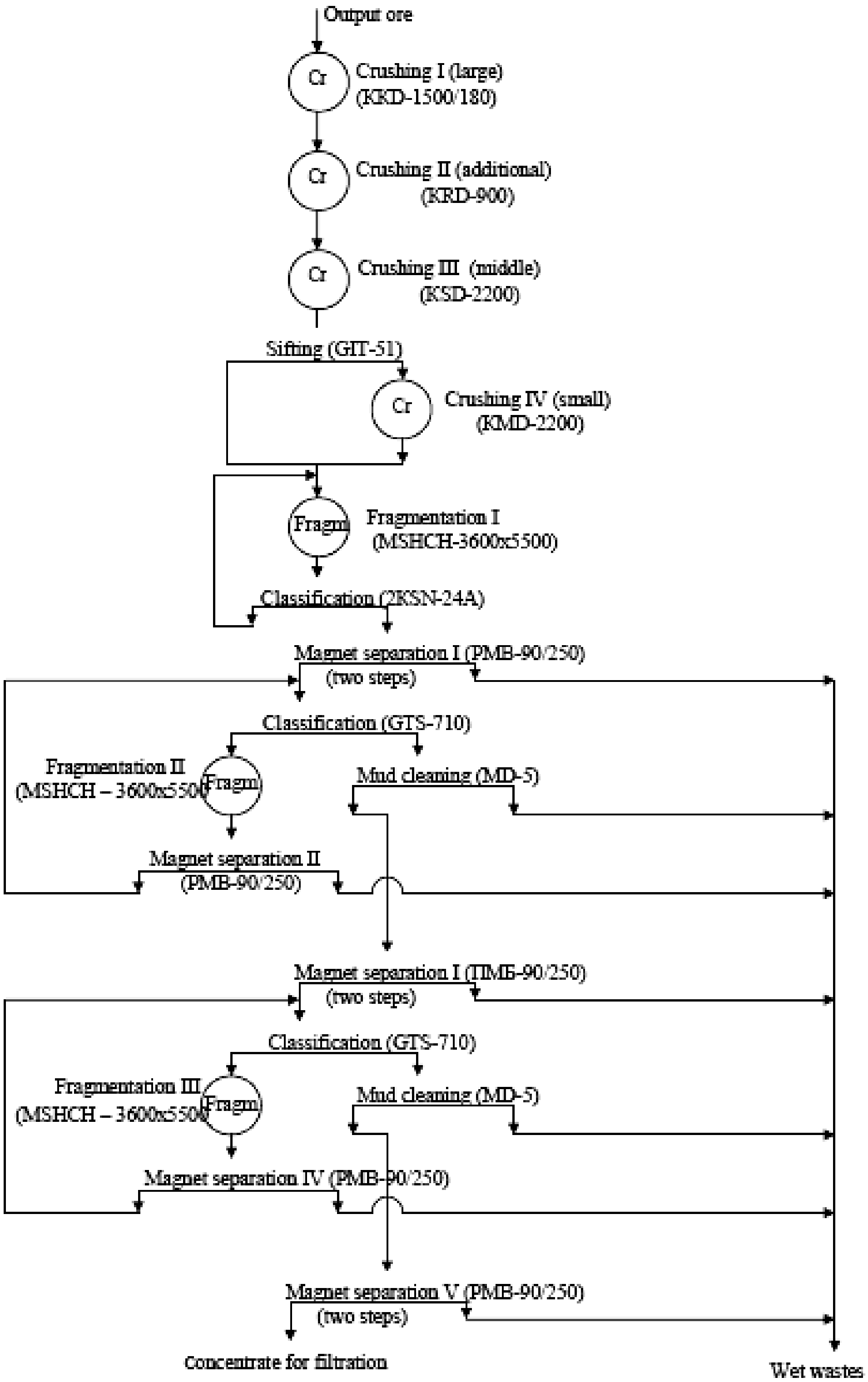

Fig. 4. Technological scheme of ore processing plant No. 1 of the Inguletsky mining and processing plant

After crushing iron ore in three stages, the next technological processing is sifting (Fig. 4) a very important process of enrichment and processing minerals [3]. A sift is a machine or device for separating (sorting) bulk material by the size of lumps of material on sieving surfaces with calibrated holes in order to obtain products of different granulometric composition.

After sifting (and after the IV stage of crushing), the material is fed for fractioning. There is no fundamental difference between crushing and fractioning. Conventionally, it is believed that when crushing, grains with a size of more than 0,005 m. are obtained, and when fractioning – less than 0.005 m. Depending on the size of the initial and fractioned products, three stages of grinding are distinguished [13].

Classification is the process of separation of crushed material in a liquid or air environment, based on differences in the settling rates of particles of different sizes, shapes and densities. The purpose of classification is to obtain products of different granulometric composition and density [3].

Magnetic enrichment processes are based on the use of differences in the magnetic properties of minerals and rocks (values of magnetic susceptibility, residual induction, etc.) and are carried out in magnetic separators in an inhomogeneous constant or alternating magnetic field in air and water media [13].

Magnetic deshlamators are used for neutralization and thickening of finely ground strong magnetic material before magnetic enrichment or before filtering magnetic concentrates at Yugok and Ingok [13].

Samples of current tailings in the form of pulp for research were taken after stages (from I to V) of enrichment and draining of the deshlamator, as well as from the opening of the tailings dump, which were dried in drying cabinets after settling and draining the liquid. The average and mothballed samples were an average sample for each of the plants weighing 1.5–2.5 kg. The samples were taken from the production line since their composition is more uniform than that of the tailings dump.

The granulometric composition of ferruginous quartzite processing waste was determined by dry sieving on laboratory sieves with hole diameters from 3.0 mm to 0.05 mm. Tail residues on each sieve were weighed and partial residues a_i, %, on each sieve were calculated using the formula:

$$a_i = \frac{m_i}{m} 100\ \%, \tag{2.1}$$

where m_i is the mass of the material on the i-th sieve, kg(g); m is the mass of the sieving material, kg(g).

The yield of tails was expressed as a percentage by the formula [13]:

$$\gamma = \frac{Q_{npr}}{Q_{out}} 100\ \%, \tag{2.2}$$

where Q_{npr} and Q_{out} are the masses of the product and the starting material.

The total iron content was determined according to [14], and the magnetic content – according to [15].To calculate the mass fraction of solid in the enrichment waste, the pulp was taken, weighed, water was drained, and the remainder was dried to a constant mass. The ratio of the mass of the dry residue to the mass of the pulp is the mass fraction of solid in this pulp.

The specific surface area of dispersed materials was determined using the PSH-2 device (Khodakov System device) for gas permeability [16]. The gas permeability index of the ground material was determined by the duration of filtration of the air passing through it. The initial and final vacuum of the air (pressure) in the working volume of the device is taken as a constant. To calculate the specific surface area of ferruginous quartzite enrichment waste, the density, mass and height of the tail layer in the cuvette (sleeve) of the device were taken into account.

The resource value of ferruginous quartzite processing waste (tailings) was determined by the physical and mechanical properties of autoclaved aerated concrete (the average density of aerated concrete in the dry state and its compressive strength). The following materials were used to prepare the aerated concrete mixture:

1. A siliceous component – waste from the enrichment of ferruginous quartzites (tailings). In the state waste classifier DC-005-96 (qualification group “sludge” and “tails” of iron ore processing) they belong to the waste of metal ore extraction (A. 7, group 13, code 1310.2.3.01).

2. Portland cement of PJSC “Ivano-Frankivskcement” PC II/A-Sh-500 (II-type of Cement-Portland Cement with mineral additives from 6 % to 35 %; A – a subtype of cement (differs in the content of components), A-sh – Portland cement clinker 80-94 % with the addition of blast furnace granulated slag from 6 to 20 %, 500 – a brand of cement by compressive strength in kgf/cm2), which meets the requirements of UNSS B V.2.7-46:2010 [17].

3. Quicklime calcium lump Collective enterprise “Company Azovstroymaterialy” (Mariupol, Donetsk region) – meets the requirements of UNSS B V.2.7-90:2011 [18].

4. Gas-forming agent – aluminum powder PAP-1 (pigment), which corresponds to GOST 5494-95 Aluminum Powder. Manufacturer – LLC NPP “Ukrvtorresurs” (Rivne).

5. Surfactant-sulfanol.

6. The water met the requirements of UNSS B V.2.7-273:2011 [19].

The lime-silica binder was prepared in a laboratory mill by joint grinding of lime and enrichment waste in a ratio of 1:1, the activity (total content of active calcium and magnesium) of which was determined by [18]).

Selection and calculation of aerated concrete was carried out for the D600 brand according to the average density (according to [20]) and adjusted based on the characteristics of concrete produced during test mixes. Cellular concrete (aerated concrete) of a given brand has the optimal composition in terms of average density, which provides the required concrete class in terms of strength and frost resistance grade with minimal binder consumption. The mass ratio of the silica component to the binder (cement, lime) was taken in accordance with Table. 2 [20

Aluminum suspension was prepared in a mixer by continuous mixing of aluminum powder, surfactant and water [20]. The consumption of aluminum powder (0.08–0.1 % of the consumption of dry components), sulfanol (4 % by weight of aluminum powder) and the ratio of aluminum powder content: water (1:6) met the requirements [20]. The aerated concrete mixture was prepared in a laboratory mixer, mixing the components for 2–3 minutes at the water: solid ratio W/S = 0.50–0.52.].

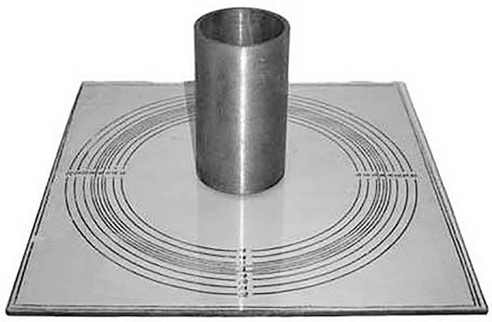

Fig. 5. Suttard viscometer

The fluidity value of the aerated concrete mixture was determined by the diameter of the cone spread on a Suttard viscometer (Fig. 5), which consists of a copper or brass hollow cylinder with a diameter of 0.05 m and 0.01 m high, square-shaped glass with a side of 0.45 m and a sheet of paper with concentric circles applied on it every 0.005 cm or 0.01 cm, which are placed under the glass during the experiment [21], [22].

The glass is placed in a strictly horizontal position and the cylinder is placed on it so that the outer contour of the cylinder coincides with a circle with a diameter of 6 cm. The test solution is poured into a cylinder up to the top and the surface is leveled with a knife or spatula. Then, with a quick and precise movement, the cylinder is lifted from the bottom up; the solution spreads in the form of a “splash”, the diameter of which determines the consistency of the mixture.

The temperature of the aerated concrete mixture on the cement-lime binder at the time of unloading into the mold (with the impact method of forming) met the requirements [20] and was 40 °C. The formed samples-cubes with an edge of 0.07 m which, when reaching the required plastic strength of the raw material were subjected to autoclaved processing according to the mode: warming up and raising the steam pressure to 1 MPA – 3 hours; holding at a steam pressure of 1 MPA – 6 hours; reducing the steam pressure – 2 hours (the total duration of autoclave processing – 11 hours). Before testing the samples-cubes of 0.07×0.07×0.07 m for average density in the dry state and compressive strength, they were dried in an electric cabinet at a temperature of $(105\pm10)^{o}$C to a constant mass (clause 3.1.13 [23]). The average density of concrete was determined by the formula [23]:

$$\rho_m = \frac{m}{v}, \tag{2.3}$$

where m is the mass of the sample, kg; V is the volume of the sample, m^3.

The humidity of aerated concrete by weight Wm as a percentage was determined by the formula [23]:

$$W_m = \frac{m_w - m_d}{m_d}, \tag{2.4}$$

where m_w is the mass of the concrete sample before drying, g; m_d is the mass of the concrete sample after drying, g.

The compressive strength of cellular concrete (MPa, kgf/cm^2) was calculated with an accuracy of 0.1 MPa (1 kgf/cm^2) by the formula [24]):

$$\sigma_{\text{ст}.cube} = \frac{\alpha\text{-}F\text{-}K_w}{A}, \tag{2.5}$$

where F is the breaking load, H, (kgc); A is the working cross-sectional area of the sample, mm^2 (cm^2); α is the scale coefficient for reducing the strength of concrete to the strength of concrete in the samples of basic size and shape (α = 0.9, Note 2 Table 5 [24]); K_w correction factor for cellular concrete, which takes into account humidity at the time of testing (for humidity of 0 %, samples dried to a constant mass K_w = 0.8, Table. 6 [24]).

3. Results and Discussion

3.1. Research of waste from mining and processing plants of Kryvbas by stages of their enrichment

A study of ferruginous quartzite enrichment waste from Southern MPP and Inguletsky MPP was carried out at the stages of their magnetic enrichment, depending on which the size of the extracted tailings, their output and iron content change. Granulometric compositions of current waste by enrichment stages are given in Table 1–5.

Table 1

Granulometric composition of ferruginous quartzite processing waste (partial residues on sieves, %) of sections 1–10 of the OPP*-1 of the Southern MPP

Product name	Size classes**, mm						
	-3.0 +1.0	-1.0 +0.5	-0.5 +0.25	-0.25 +0.16	-0.16 +0.071	-0.071 +0.05	-0.05
Tailings I stage, I step	0.3	3.0	8.6	11.2	5.7	7.2	84.0
Tailings I stage, II step	0.1	4.1	11.2	7.6	7.8	5.6	63.6
Tailings II stage	–	1.2	8.6	15.8	6.8	5.1	62.5
Tailings III stage, I step	–	0.2	1.4	15.2	13.4	11.4	58.4
Tailings IIIstage, II step	–	0.3	1.6	14.8	13.5	12.0	57.8
Tailings IVstage			0.2	0.8	7.6	8.2	83.2
Deshlamator drain, I step			0.2	0.3	0.4	2.4	95.7
Deshlamator drain, II step			–	0.2	0.4	0.6	98.8
Tailings general	0.1	1.3	6.3	8.1	6.0	8.1	70.1

Notes:

** OPP – ore processing plant;*

*** size classes are products with precisely defined grain sizes, which are indicated with a plus "+" or minus "-" sign, as well as two numerical indicators indicating the minimum and maximum grain sizes in this class [13]. The material that has passed through the screen openings is marked with a "-" sign; the material remaining on the screen is marked with a "+"sign.*

Table 2

Granulometric composition of ferruginous quartzite processing waste (partial residues on sieves, %) of sections 1-4 of the OPP*-2 of the Southern MPP

Product name	Size classes**, mm						
	-3.0 +1.0	-1.0 +0.5	-0.5 +0.25	-0.25 +0.16	-0.16 +0.071	-0.071 +0.05	-0.05
Tailings I stage, I step	0.1	2.4	12.7	9.4	5.3	6.3	63.9
Tailings I stage, II step	0.1	3.1	12.1	7.4	4.5	5.1	67.8
Tailings II stage	–	0.8	8.6	11.3	7.0	7.4	64.9
Tailings III stage, I step	–	0.1	3.0	14.9	11.6	11.6	58.9
Tailings III stage, II step	–	0.2	4.3	18.3	12.4	11.2	53.6
Tailings IV stage	–	0.1	1.0	8.4	8.8	9.7	72.0
Tailings V stage	–	–	0.2	2.9	9.0	13.1	74.8
Deshlamator drain, I step	–	0.1	0.3	0.4	0.9	5.6	92.7
Deshlamator drain, II step	–	–	0.2	0.8	1.2	5.0	92.8
Tailings general	0.1	1.5	7.5	8.2	6.2	7.7	68.8

It was found that current processing waste at Southern MPP is represented (as a percentage by weight) by 0.2–15.4 % of the fraction >0.25 mm; by 0.2–18.3 % – by the fraction of 0.25–0.16 mm; by 0.4–19.0 % – 0.16–0.071 mm; by 51.33 % – by the size <0.071 mm; by 45.0–98.8 % – by the size <0,05 mm (Table 1 – Table 3).

Tailings at the Inguletsky MPP have the following granulometric composition (as a percentage by weight): particles of size >0.25 mm – 0.1–5.2 %; particles of fraction 0.25–0.16 mm – 0.1–11.0 %; particles of fraction 0.16–0.071 mm – 0.4–20.2 %; particles of size.<0.071 mm – 61.7–98.6 %; particles of size <0.05 mm – 53.6–95.6 % (Table 4, Table 5). Thus, the waste of ferruginous quartzite enrichment at the Southern MPP is larger than that at the Inguletsky MPP. Starting from the fraction of 0.16–0.071 mm, the number of particles of which is the same at both plants (0.4–19.0 % and 0.4–20.2 %, respectively), the proportion of grains of size of <0.071 mm and <0.05 mm at the Inguletsky MPP is 10 % higher.

The nature of the distribution of the material by fractions is determined by the mineral composition, grain size and the nature of aggregates of magnetite with other nonmetallic minerals in the initial ferruginous quartzites, as well as the degree of grinding of mineral raw materials in processing plants [25].

There is a clear pattern: the later the enrichment stage, the significantly higher the percentage of tail particles of the smallest size (<0.05 mm) in the samples of both mining and processing plants (Table 1–5). The maximum number of grains of the smallest size (<0.05 mm) is contained in the tails of the last stage of enrichment and ranges from 95.6 % (Table 5) in the samples of Inguletsky MPP up to 74.8 % (Table 3) in the samples of Southern MPP.

The output of tails by enrichment stages, the iron content and mass fraction of solid in them are shown in Table 6 – Table 10.

It was found that the maximum output of tails is formed at the first stage (I step). Its amount ranges from 32.29 % (Table 8) for the Southern MPP up to 41.81 % (Table 9) for the Inguletsky MPP.

Table 3

Granulometric composition of ferruginous quartzite processing waste (partial residues on sieves, %) of sections 1-5 of the OPP*-2 of the Southern MPP

Product name	Size classes**, mm						
	-3.0 +1.0	-1.0 +0.5	-0.5 +0.25	-0.25 +0.16	-0.16 +0.071	-0.071 +0.05	-0.05
Tailings I stage, I step	0.1	2.4	12.7	9.4	5.3	6.3	63.9
Tailings I stage, II step	0.1	3.1	12.1	7.4	4.5	5.1	67.8
Tailings II stage	–	0.8	8.6	11.3	7.0	7.4	64.9
Tailings III stage, I step	–	0.1	3.0	14.9	11.6	11.6	58.9
Tailings III stage, II step	–	0.2	4.3	18.3	12.4	11.2	53.6
Tailings IV stage	–	0.1	1.0	8.4	8.8	9.7	72.0
Tailings V stage	–	–	0.2	2.9	9.0	13.1	74.8
Deshlamator drain, I step	–	0.1	0.3	0.4	0.9	5.6	92.7
Deshlamator drain, II step	–	–	0.2	0.8	1.2	5.0	92.8
Tailings general	0.1	1.5	7.5	8.2	6.2	7.7	68.8

Table 4

Granulometric composition of ferruginous quartzite processing waste (partial residues on sieves, %) of the OPP*-1 of the Inguletsky MPP

Product name	Size classes**, mm						
	+1.0	-1.0 +0.56	-0.56 +0.25	-0.25 +0.16	-0.16 +0.071	-0.071 +0.05	-0.05
Tailings I stage, I step	0. 8	2.6	13.0	8.0	10.0	6.1	59.5
Tailings I stage, II step	0.6	3.0	11.2	2.6	9.9	5.4	62.3
Tailings II stage	–	1.2	8.5	11.0	17.6	8.1	53.6
Tailings III stage, I step	–	0.5	1.0	8.0	19.6	13.0	57.9
Tailings III stage, II step	–	0.1	0.6	7.1	20.2	12.6	59.4
Tailings IV stage	–	0.1	0.2	1.3	8.5	10.0	79.9
Tailings V stage, I step	–	–	–	0.4	2.7	5.3	91.6
Tailings V stage, II step	–	–	–	0.1	1.9	5.0	93.0
Deshlamator drain, I step	–	0.1	0.1	0.1	1.8	9.0	88.9
Deshlamator drain, II step	–	–	0.1	0.1	1.6	4.2	94.0
Tailings general	2.8	0.6	1.8	2.8	6.7	8.9	77.1

Table 5

Granulometric composition of ferruginous quartzite processing waste (partial residues on sieves. %) of the OPP*-2 of the Inguletsky MPP

Product name	Size classes**, mm					
	+0.56	-0.56 +0.25	-0.25 +0.16	-0.16 +0.071	-0.071 +0.05	-0.05
Tailings I stage, I step	0.6	4.7	4.2	8.1	8.0	74.4
Tailings I stage, II step	0.6	4.6	5.0	8.2	7.0	74.6
Tailings II stage	0.1	0.5	1.4	3.0	5.4	89.6
Tailings III stage, I step	–	0.1	0.5	3.8	8.0	87.6
Tailings III stage, II step	–	0.2	0.2	2.2	8.0	91.4
Tailings III stage, III step	–	0.1	0.2	1.1	3.0	95.6
Deshlamator drain	–	0.1	0.1	0.4	1.8	92.6
Tailings general	0.4	1.7	2.7	7.3	7.2	80.7

Table 6

Characteristics of ferruginous quartzite enrichment waste of sections 1–10 of the OPP-1 of the Southern MPP

Product name	Tail output, %	Iron content, %	Mass fraction of solid, %
Tailings I stage, I step	31.1	10.6	21.0
Tailings I stage, II step	5.16	12.0	8.0
Tailings II stage	5.31	9.4	6.0
Tailings III stage, I step	2.09	12.04	5.2
Tailings III stage, II reception	2.09	12.04	1.8
Tailings IV stage	1.82	14.8	1.5
Deshlamator drain, I step	3.85	10.0	2.4
Deshlamator drain, II step	1.57	10.8	0.53
Tailings general	54.7	10.8	0.19

Table 7

Characteristics of ferruginous quartzite enrichment waste of sections 1–4 of the OPP-2 of the Southern MPP

Product name	Tail output, %	Iron content, %	Mass fraction of solid, %
Tailings I stage, I step	30.6	11.2	30.8
Tailings I stage, II step	4.75	11.5	7.8
Tailings II stage	5.83	2.6	9.6
Tailings III stage, I step	4.23	11.8	3.9
Tailings III stage, II step	0.98	12.9	1.7
Tailings IV stage	1.47	15.0	1.7
Deshlamator drain, I step	4.07	10.0	1.9
Deshlamator drain, II step	3.21	12.8	1.1
Tailings general	54.6	11.2	5.45

Table 8

Characteristics of ferruginous quartzite enrichment waste of sections 5–10 of the OPP-2 of the Southern MPP

Product name	Tail output, %	Iron content, %	Mass fraction of solid, %
Tailings I stage, I step	32.29	11.0	25.3
Tailings I stage, II step	4.06	11.3	8.0
Tailings II stage	4.54	8.8	5.0
Tailings III stage, I step	4.32	11.8	4.7
Tailings III stage, II step	1.01	13.0	1.8
Tailings IV stage	1.27	9.8	1.0
Tailings V stage	1.0	16.4	0.8
Deshlamator drain, I step	4.88	9.9	2.8
Deshlamator drain, II step	1.19	12.3	0.54
Tailings general	54.5	10.9	0.24

Table 9

Characteristics of ferruginous quartzite enrichment waste of the OPP-1 of the Inguletsky MPP

Product name	Tail output, %	Iron content, %	Mass fraction of solid, %
Tailings I stage, I step	41.81	14.26	19.9
Tailings I stage, II step	2.79	13.7	7.2
Tailings II stage	3.28	11.7	3.6
Tailings III stage, I step	2.63	14.6	2.1
Tailings III stage, II reception	0.92	15.0	0.9
Tailings IV stage	2.11	10.9	0.8
TailingsV стадія, I step	0.42	16.1	0.6
TailingsV стадія, II step	0.27	20.1	0.3
Deshlamator drain, I step	6.16	12.6	3.0
Deshlamator drain, II step	1.46	11.7	0.7
Tailings general	61.85	13.80	5.49

Table 10

Characteristics of ferruginous quartzite enrichment waste of the OPP-2 of the Inguletsky MPP

Product name	Tail output, %	Iron content, %	Mass fraction of solid, %
Tailings I stage, I step	27.53	12.3	25.4
Tailings I stage, II step	10.2	12.5	12.3
Tailings II stage	5.09	10.31	6.2
Tailings III stage, I step	2.39	21.2	1.2
Tailings III stage, II step	0.29	20.07	0.3
Tailings III стадія, III step	0.39	22.5	0.2
Deshlamator drain	11.6	12.4	0.9
Tailings general	57.46	12.65	2.0

A higher amount of iron was found in the processing waste of the Inguletsky MPP compared to those of the Southern MPP: 24.8–27.96 % by weight (Table 9, Table. 10) compared to 22.3–22.7 % by weight (Table 6– 8) respectively for the and stage of enrichment of both steps. The maximum amount of iron is in the samples of the last stage of magnetic (wet) enrichment and ranges from 16.4 % (Table 8) for the Southern MPP up to 22.5 % (Table 10) for the Inguletsky MPP.

The mass fraction of solid in the tail pulp of stage I is from 19.9 % (Table 9) up to 30.8 % (Table 7) for tailings and reception and from 7.2 % (Table 9) up to 12.3 % (Table 10) for tailings of step II, which will reduce energy costs for thickening and dewatering the material (compared to preparing tailings of other stages of enrichment). Therefore, for the production of building materials, it is advisable to select tailings at the first stage of enrichment.

We also observe the dependence of the output of tailings and the mass fraction of solid in them: after each stage of enrichment, these indicators decrease (Table 6– 10).

3.2. Research on pre-ironing of tailings of mining and processing plants in Kryvbas

An obstacle to the widespread use of enrichment tailings as construction raw materials, first of, are substances that are not extracted during metal processing. Recycling tailings without pulling is dangerous. The presence of undigested metals in commercial products is dangerous for chemical and radiological contamination since metals in waste migrate to environmental ecosystems under the influence of natural leaching processes.

Reduction of the mass fraction of iron in the waste of ferruginous quartzite enrichment of the Southern MPP and the Inguletsky MPP (total (magnetic) iron content of 15.2 (8.4) % by weight and 12.9 (2.0) % by weight was carried out on a laboratory magnetic separator CRS 400x300. The magnetic field induction was 0.2; 0.5; 1.2; 1.5 Tℓ. The dependences of the mass particles of iron (total and magnetic) in the samples of the tails of the Inguletsky MPP, as well as solid in them, are shown in Figure 6.

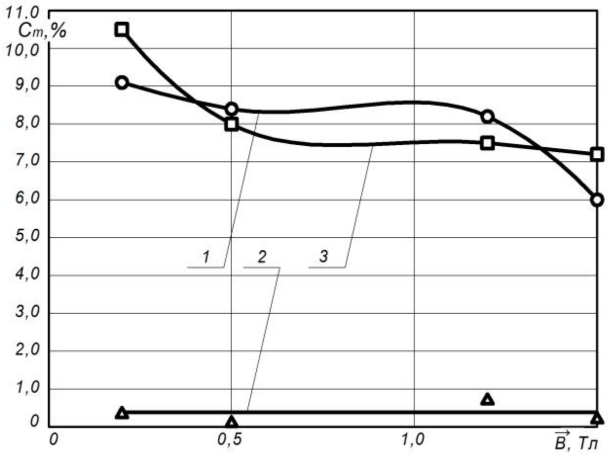

Fig. 6. Dependence of the mass fraction in the tails C_m on the induction of the magnetic field *B*:
1 – general iron; 2 –magnetic iron; 3 – solid

As shown in Fig. 6, as the magnetic field strength increases, the mass fractions of the iron total (curve 1) and solid (curve 3) in the enrichment tailings decrease. The smallest amount of total iron (6 % by weight) was observed when the magnetic field was induced by 1.5 Tℓ.). The mass fraction of iron magnetic at this magnetic field induction is 0.2 %. But the mass fraction of magnetic iron (straight line 2) does not depend on the magnetic field strength. I can explain this phenomenon as follows. The highest values of magnetic susceptibility are characterized by ferruginous quartzites [13]. Minerals of ferruginous quartzites according to their specific magnetic susceptibility (a physical quantity that characterizes the ability of a body to magnetize under the action of a magnetic field) belong to the group of strong magnetic (ferromagnetic) minerals (specific magnetic susceptibility $\chi > 3 \cdot 10^{-6}$ m^3/kg). These minerals can be extracted into a magnetic fraction on separators with a weak magnetic field with a strength of H = 70–120 kA/m. Therefore, the magnitude of the magnetic induction of 0.2 Tℓ is sufficient to “pull” magnetic particles into the magnetic product.

3.3. Development of aerated concrete composition based on tailings enrichment of the Southern and Inguletsky MPP

The specific surface area of the lime-silica binder (determined on the device of the Khodakov PSH-2 system according to the method [16]) was 510 m^2/kg. Its activity (according to [18]) was 38 %.

Portland cement is accepted of grade M500 with a specific surface area of 320 m^2/kg [18]; setting time (according to UNSS EN 196-3:2007 cement testing methods): the beginning of setting is 3 hours and 20 minutes, the end of setting is 5 hours and 5min.

The activity of calcium quicklime was 76 % (lime of grade III [18]; the quenching time was 15 minutes. (type of lime by quenching duration – average quenching. quenching time index – B).

The fluidity of the aerated concrete mixture which is determined on the Suttard viscometer [22] under the impact moulding method was 170 mm for the cellular concrete grade with an average density of D600 in accordance with [20]. The essence of the impact moulding method is to intensify the swelling process when using vibration due to thixotropy (dilution) of the mixture and accelerate the course of the gas release reaction [22]. In comparison with injection moulding technology, the impact moulding technology has a number of advantages [22]:

– a sharp increase in structural strength immediately after the vibration stops;

– reduction of the maturation period to 40 minutes;

– reduction of the duration of autoclave treatment due to sufficient initial strength and preservation of the temperature of 60–70 °C inside the array before autoclave treatment, which occurs as a result of the gas release reaction;

– the strength and frost resistance of expanded concretes is higher than usual, etc.

The compositions of raw mixes (calculated according to the method [20] and corrected by test mixes) and the humidity of aerated concrete using ferruginous quartzite processing waste are shown in Table 11 and Table12.

Table 11

Compositions of raw mixes and humidity of aerated concrete based on the tailings of the Southern MPP

No.	Component consumption. kg per 1 m^3 of aerated concrete mix			Watersolid ratio. W/S	Humidity of aerated concrete. % by weight
	lime calx	portland cement	enrichment waste		
1	131	110	369	0.5	29
2	136	113	382	0.5	29
3	127	106	357	0.5	28
4	125	105	352	0.52	30
5	129	108	364	0.52	31

Table 12

Compositions of raw mixes and humidity of aerated concrete based on the tailings of Inguletsky MPP

No.	Component consumption. kg per 1 m^3 of aerated concrete mix			Watersolid ratio. W/S	Humidity of aerated concrete. % by weight
	lime calx				
1	128	107	375	0.5	24
2	132	110	388	0.5	21
3	122	102	357	051	24
4	124	105	355	0.5	25
5	133	84	393	0.5	31

In Table 11 and Table 12 it is shown that the humidity of aerated concrete (on average) on the tailings of the Southern MPP is 4.4 % higher than that of concrete on the tails of the Inguletsky MPP. Cement consumption (on average) per 1 m3 of the aerated concrete mix using the Southern MPP processing waste is 6.8 kg higher than that of a mixture based on the Inguletsky MPP waste. During the mixing of the components in the mixture on the tailings of the Southern MPP, when cement is hydrated, a larger amount of water will pass into a chemically bound state with the formation of hydrosilicates (2CaO•SiO2•nH2O), hydroaluminates (3CaO•AI2O3•6H2O). hydropherites (4CaO•Al2O3•Fe2O3•4•nH2O) of calcium. When the aerated concrete samples are dried to a constant mass (at a temperature of 105±2 °C), chemically bound water does not evaporate. Therefore, the humidity of concrete on the tailings of the Southern MPP is higher than that of concrete on the tailings of the Inguletsky MPP.

The average density of the studied aerated concrete in the dry state using the tailings of the Kryvbas MPP ranged from 580 kg/m^3 to 630 kg/m^3 (Fig. 7).

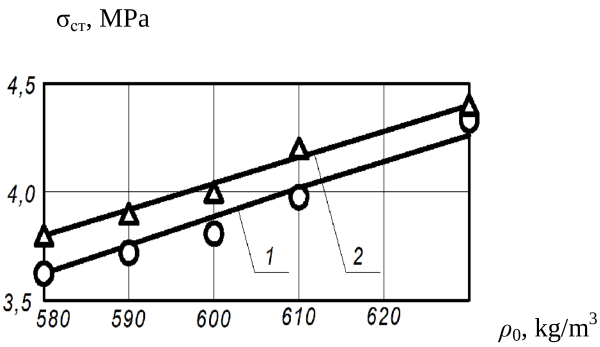

Fig. 7. Dependence of the compressive strength of aerated concrete $\sigma_{ст}$ from the average density of aerated concrete ρ_0: 1 – Southern MPP; 2 – Inguletsky MPP

According to [26, Table 1] such concrete belongs to brand D600 in terms of average density. The compressive strength of this concrete ranged from 3.65 MPa to 4.40 MPa. According to [26, Table 2] such concrete belongs to Class B 2.5 in terms of compressive strength and belongs to the thermal insulation and structural type [26, Table 3].

Ferruginous quartzite processing waste at the Inguletsky MPP is smaller than that at the Southern NPP: the number of particles <0.071 mm is 61.7–98.6 % against 51.3–99.4 %, respectively (Table 1–5). The packing density of small grains is higher than that of large ones, and the average density of the mixture using small particles will be higher. The strength of a material is directly proportional to its density. Therefore, the strength of aerated concrete using the tailings of the Inguletsky MPP is higher than that on the tailings of the Southern MPP.

Products made on the basis of ferruginous quartzite processing waste meet the requirements of UNSS B V. 2.7-45:2010 "Cellular concretes. General technical conditions" and UNSS B V.2.7-137:2008 "Small cellular concrete wall blocks. Technical specifications".

Blocks are non-flammable explosion-proof products that do not emit toxic substances [27]. In their manufacture, cement, silica component, lime, and aluminium powder are used. The maximum permissible concentration of dust components in the air of the working area is as follows: cement–6 mg/m^3, silica component–1 mg/m^3, lime–3 mg/m^3, aluminum–2 mg/m^3. Thus, according to GOST 12.1.007-76, aerated concrete belongs to the substances of the 3rd hazard class – moderately hazardous substances.

Conclusions

The ecological efficiency of the production of ferruginous quartzite processing waste from mining and processing plants contributes to the elimination of tailings dumps and frees up areas of useful land reducing the load on the natural environment in iron ore regions.

Rational use of enrichment tailings, on the one hand, will improve (preserve) the ecological situation on the territory of the mining and processing enterprise, and, on the other hand, expand the raw material base for the production of building materials and reduce their shortage.

The advantages of using waste from mining and processing plants in environmental protection are as follows: the possibility of waste disposal in the production of aerated concrete; low cost of materials based on this waste.

According to the negative impact on environmental objects, aerated concrete belongs to the 3rd hazard class (moderate-hazard substances).

References

[1] Kopach P., Yakubenko L., Romanenko V. et al.: Ecolog. I Pryrod., 2013, 16, 210. (in Russian)

[2] Shapar A. and Vilkul U., Yakubenko L.: Formir. I Razrab. Rechnogen. Mestorozd. Zhelezn. Ta Margan. Rud., Monolit, Dnepr., 2012. (in Russian)

[3] Maliovanuy M., Bogolubov V., Shanina T. et al.: Technoecol., Nation. Univer. "Lvivsk. Politechn", Lviv., 2013. (in Ukrainian)

[4] Gubina V.: Geolog.-Mineral. Visn., 2010, 1-2 (23-24), 97. (in Russian)

[5] Medvedeva O.: Geotexn. Mehan. IGTM NANU, Dnepr., 2012, 103, 297. (in Russian)

[6] Bluss B, and Golovach N.: Sovершh. Tehnolog. Predobog. Ilmen. Rud. Poligr. Dnepr., 1999. (in Russian)

[7] Sokolova V. and Uchitel A.: Pererab. Shlam. Othod. Zhelez-Rud., Zbagach. Korysn. Kopal., 2017, 66 (107), 3, (in Russian)

[8] Shevchenko B.: Konstr. Iz Beton. Na Othod. Obogashch, Zhelezn. Rud, Vishch. Shkol., Kyiv 1989. (in Russian)

[9] Shishkin A. and Shishkin B., Shcherba V.: Visn. Donb. Natsion. Acad. Budiv., 2013, 1(99), 9. (in Russian)

[10] Bolshkov B., Prihodko A., Savin L. et al.: Visn. Pridn. Acad. Budiv. Ta Arhit., 2008, 3, 4. (in Russian)

[11] Prihodko A., Savin L., Storchay N. et al.: Ispolz. Othod. Pri Proizv. Portlan. Klink., Stroit., Mater., Mashin., 2009, 50, 428. (in Russian)
[12] https://uk.wikipedia.org/wiki/
[13] Kravets V. and Biletskiy S., Smirnov V.: Techn. I Technol. Zbagach. Korys. Kopal., KPI im. Igor. Sikorsk., Kyiv 2019. (in Ukrainian)
[14] DSTU ISO 2597-1:2012.: Minregionbud Ukraïni, Kyiv 2013. (in Ukrainian)
[15] DSTU 2593-98.: Minregionbud Ukraïni. Kyiv 1999. (in Ukrainian)
[16] Dvorkin L. and Skrypnik I.: Phiz.-him. I Phiz. Metod. Doslid. Bud. Mater., NYBGP, Rivne 2006. (in Ukrainian)
[17] DSTU B V.2.7-46:2010.: Minregionbud Ukraïni. Kyiv 2011. (in Ukrainian)
[18] DSTU B V.2.7-90:2011.: Minregionbud Ukraïni. Kyiv 2012. (in Ukrainian)
[19] DSTU B V.2.7-273:2011.: Minregionbud Ukraïni. Kyiv 2012. (in Ukrainian)
[20] DSTU H B V.2.7-308:2015.: Minregionbud Ukraïni. Kyiv 2016. (in Ukrainian)
[21] DSTU B V.2.7-82:2010.: Minregionbud Ukraïni. Kyiv 2012. (in Ukrainian)
[22] Dvorkin L. and Zhitkovskiy V.: Tehn. Oporyad. Teploiz. I Gidroiz. Mater., NYBGP, Rivne, 2010. (in Ukrainian)
[23] DSTU B V.2.7-170:2008.: Minregionbud Ukraïni. Kyiv 2009. (in Ukrainian)
[24] DSTU B V.2.7-214:2009.: Minregionbud Ukraïni. Kyiv 2010. (in Ukrainian)
[25] Gubina V. and Zaborovskyi V.: Osobl. Rechov. Sklad. Vidh. Zbagach. Zaliz. Kvarts. Krivb. Geoh. Ta Rydoutv., 2015, 56. (in Ukrainian)
[26] DSTU B V.2.7-45:2010.: Minregionbud Ukraïni. Kyiv 2011. (in Ukrainian)
[27] DSTU B V.2.7-137:2008.: Minregionbud Ukraïni. Kyiv 2009. (in Ukrainian)