Показана ефективність використання процесу електросепарації для відділення мідного концентрату від подрібненої маси базальту, лавобрекчії і туфу після їх попередньої магнітної сепарації. Встановлені класи крупності у процесі рудопідготовки і класифікації складових базальтової гірської маси до електросепарації, а також залежності виходу мідного концентрату для базальту, туфу і лавобрекчії від напруженості електричного поля для різних класів крупності у вихідному продукті

Ключові слова: самородна мідь, титаномагнетит, електрична сепарація, лавобрекчія, базальт, туф, мідний концентрат

Показана эффективность использования процесса электросепарации для отделения медного концентрата от измельчённой массы базальта, лавобрекчии и туфа после их предварительной магнитной сепарации. Установлены классы крупности в процессе рудоподготовки и классификации составляющих базальтовой горной массы к электросепарации, а также зависимости выхода медного концентрата для базальта, туфа и лавобрекчии от напряжённости электрического поля для разных классов крупности в исходном продукте

Ключевые слова: самородная медь, титаномагнетит, электрическая сепарация, лавобрекчия, базальт, туф, медный концентрат

UDC 622.277
DOI: 10.15587/1729-4061.2016.79524

RESEARCH RESULTS PROVING THE DEPENDENCE OF THE COPPER CONCENTRATE AMOUNT RECOVERED FROM BASALT RAW MATERIAL ON THE ELECTRIC SEPARATOR FIELD INTENSITY

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1. Introduction

In Ukraine, basalt is used as gravel for construction purposes. In order to develop the Rafalovsky basalt deposits of the Rivne-Volyn region, it is necessary to conduct thorough research because extraction of metals from basalts in the world remains insufficiently studied. Basalt deposits worldwide do not contain metals in amounts of commercial interest [1–7], and it is only in the Rivne-Volyn region of Ukraine that basalts, which were formed by volcanic activities, contain native copper and related metals [8, 9]. Basalts of the Rivne-Volyn deposits of Ukraine are unique because they comprise native copper in a percentage (from 0.3 % to 5.0 %) that represents commercial interest. Therefore, it is essential to extract native copper out of the unique metal-containing basalt, using the method of a complex processing of basaltic raw materials. One of the promising methods of extracting it is electrical separation; therefore, the choice and the specification of the separators' parameters are of considerable importance.

2. Literature review and problem statement

In [1], a new technology is developed to improve the enrichment of copper and iron with copper slag by changing the slag melt, which promotes mineralization of precious minerals and a growth of mineral grains. Various parameters are investigated, including the binary properties and dosage of the compounds, temperature changes, the cooling rate, and the slow cooling end temperature. The results of this study show that the blister copper concentrate was increased from 6.43 % to 11.04 %; enrichment with magnetic separation boosted the iron content from 32.40 % to 63.26 %. Besides, the magnetite grains in the slag were grouped together, thereby increasing the average size of the material to more than 50 microns. The processes have resulted in an improved enrichment of copper and iron.

In the construction industry, only basalt is used in the production of crushed stone. Tuff and lava-breccia, which are related to and associated with basalt mining, are presented in the form of a blade of rock mass, which is currently stored in the form of man-made deposits with a high content of native copper, iron, titanium and other precious metals and not used [2].

The presence of impure solids such as lava-breccia and tuffs in the array of basalt does not diminish the value of the complex processing of basalt because these consistencies contain components as useful as basalt [3]. The main ingredients among them are native copper, iron, and titanium-magnetite. A spectral analysis has showed that the basalts contain copper oxides as well as rare and precious metals, and their extraction requires the use of advanced technology [4].

An analysis of studies on the use of separation in the processing of rare colour metals, ores and alluvial deposits has showed that separation of non-ferrous metals from ores is the main technology, whereas separation of the iron concentrate is secondary, indicating a lack of complex processing in the treatment of rare colour metals of ore and gravel deposits [5].

Copper is extracted by using a flotation of copper sulphides while there is a high intensity of the concentrate conditioning and recycling [6].

Slags in basic oxygen furnaces (BOF) of steel mills are a major problem of all steel and crude iron producers. For example, in Turkey, more than 6 million tonnes of slag get annually stored without being used. Slag heaps can be processed by means of a magnetic separator enrichment. As a result, the metal yield is increased from 18 % to 33 % [7]. In the world, man-made storages of slag that need processing are estimated in billions of tonnes.

Studies of regularities of a group motion of charged particles in a changing electric field have produced findings for drum separators to increase the capacity up to 3.0 tonnes/hour per one meter of the electrode length. Detailed research has been undertaken on performance characteristics, including the effect of humidity on the process of electric separation; technological solutions have been devised for its use in various circuit points of circuit devices. The attention given to the problem and the practice of using electric separation for non-magnetic materials suggest its application advisable for separation of native copper deposits from basalt deposit products. Therewith, the magnetic portion of the concentrate (Fe, Ti) is extracted efficiently by a magnetic separator, whereas native copper can be recovered by an electric separator. Given that in all three solids of basalt fields, except for large inclusions, native copper is contained in an amount of 0.3 % to 5.0 % as dotted inclusions, it can be recovered successfully by the electric separator.

To do this, it is necessary to determine the rational fineness of processing and the impact of aggregates on the extraction percentage, and then to set the minimum allowable fineness in the process of pre-treating the ore [8].

Our analysis of the available literature has revealed that the extraction of native copper and other associated metals from basalt deposits requires new technologies. Metal production from basalt can be increased by separation, which still requires thorough research due to lack of knowledge about extraction of metals from basalts.

3. The aim and objectives of the study

The aim is to determine the dependence of the parameters and operating modes of electric separators on the magnetic field intensity as well as the physical and mechanical properties of the metal-containing basalt raw material, depending on the size of the crushed rock mass to determine the maximum percentage yield of native copper from the basalt concentrate.

To achieve the aim, it is necessary to solve the following tasks:

– to analyse the output of native copper content, depending on the parameters of the electric field of the separator,

– to determine the distribution of native copper, depending on the particle size distribution of the basalt raw material, and

– to estimate the native copper output in the accompanying solids of tuff and lava-breccia.

4. The results of studies on the effectiveness of using electric separators for complex processing of basalts from Volyn

Before using electrostatic separators in an experimental technological scheme of a complex processing of the basalt raw material, it is primarily necessary to determine the dependence of the amount of the concentrate extracted from basalt, lava-breccia, and tuff on the electric field voltage to ensure a maximum output of the concentrate and copper recovery. It does not include a task of choosing the most effective separator; our objectives are to be achieved as a result of conducting laboratory tests concerning electric separation of these materials by the electric separator PS-1 of a laboratory type.

All samples of crushed rock mass of each type, weighing 2.5÷3.0 kg with a particle size of less than 1.0 mm, were passed through the electric separator. The experiments were performed using supplies of all the three components of the basalt raw material after a magnetic separator had previously removed the magnetically receptive part. The electric separator was loaded with tailings of the magnetic separation – that is, with the non-magnetic fraction. This fraction was divided by the electric separator into three products: the concentrate as a conductive part, middlings as a semi-conductive part, and tailings as a non-conductive portion.

The average results of the experiments – the percentage outputs of the final product in the samples of basalt, lava-breccia, and tuff – are shown in Table 1. Tables 2 and 3 contain interpretation of Table 1 data, depending on the form suitable for analysis. The reliability of the average outcomes of the experiments was evaluated by the Fisher test.

The mineralogical analysis of the research results has shown that the non-conductive part of the separation product contains mainly quartz and other silicates. The semiconductor product comprises splices of silicates, iron, and copper, whereas the conductor fraction contains crushed particles of native copper and iron aggregates [9].

Table 1

The results of the electric separation of the basalt raw material (unit PS-1)

Type of the solid	Classes of fineness, mm	Magnetic separation of the sample: Magnetic fraction		Non-magnetic fraction		Electric separation of the non-magnetic fraction: The concentrate as a conductive part		Middlings as a semiconductive part		Tailings as a non-conductive part		Total sample weight
		g	%	g	%	g	%	g	%	g	%	g
Basalt	–1+0.63	370	63.8	210	36.2	190.2	32.8	19.7	3.4	0.0	0	580
Basalt	–0.63 +0.25	740	67.3	360	32.7	49.5	4.5	29.7	2.7	280.5	25.5	1.100
Lava-breccia	–0.63 +0.25	220	51.2	210	48.8	60.2	14	49.9	11.6	100.2	23.3	430
Tuff	–0.63 +0.25	29	48.3	31	51.7	4.02	6.7	6.0	10	21.0	35	60

Table 2

The indicators of the output products of the magnetic separation and the indicators of the electric separation of magnetic separation tailings

Type of the solid	Classes of fineness, mm	The outputs from the initial product, %: Magnetic separation of the sample: Magnetic fraction	Non-magnetic fraction	Electric separation of the non-magnetic fraction: The concentrate	The middlings	The tailings
Basalt	–1 +0.63	63.8	36.2	32.8	3.4	0
Basalt	–0.63 +0.25	67.3	32.7	4.5	2.7	25.5
Basalt	–1 +0.25	66.1	33.9	14.3	2.1	25.5
Lava-breccia	–0.63 +0.25	51.2	48.8	14.0	11.6	23.3
Tuff	–0.63 +0.25	48.3	51.7	6.7	10	35

Table 3

The indicators of the outputs products of electric separation

Type of the solid	Classes of fineness, mm	The outputs of electric separation, %: The concentrate	The middlings	The tailings
Basalt	–1 +0.25	42.1	8.6	49.3
Lava-breccia	–0.63 +0.25	28.7	23.8	47.7
Tuff	–0.63 +0.25	13.0	19.4	67.7

Let us specify the peculiarities of the electric separation of basalt (Table 2).

At a relatively high feed size of –1 +0.63 mm (the first row of Table 2), basalt yields no waste (tailings). This size class is almost completely (91 %) recovered in the concentrate. A smaller class of basalt, –0.63 +0.25 mm (the second row of Table 2), produces very little concentrate: only 4.5 % of the original, which means that 78 % of the mass of this class becomes the tailings. These results hardly agree with the textural and structural distribution of copper in basalt and the physical division by the electric separator; therefore, we continue by analysing basalt of a broader feed size range, combining both narrow classes and constituting –1 +0.25 mm (Table 2, line 3 from the top down).

In the mentioned classes, the copper concentrate outputs from the source feed for basalt and lava-breccia are the same – about 14 %, whereas for tuff it is two times smaller (6.7 %). The highest yield of tailings is obtained from tuff (35 %), whereas slightly lower values are produced from basalt (25.5 %) and lava-breccia (23.3 %). It follows that the lowest content of copper was in the tuff sample. The amount of the concentrate for lava-breccia could have been the biggest, if there had not been such a high yield of the intermediate product (middlings), which, by the way, is of the biggest amount in the three samples. Thus, lava-breccia does not produce a sufficient output, and the feed size clearly needs to be smaller. The same applies to tuff, where the middlings even exceeded the concentrate. Only for basalt, the amount of middlings was technically acceptable.

The data of Table 2 were used to calculate the operational yield (Table 3): that is, not from the whole initial sample, as in Table 2, but from 100 % of the electric separator feed.

Table 3 is used to carry out a serial analysis of the products obtainable in working conditions (i.e., from a 100 % feed):

– the concentrate output amounts to 42.1 % for basalt, 28.7 % for breccia, and 13.0 % for tuff;

– the outputs of tailings are the following: for tuff it is ~68 % of the feed, whereas for breccia and basalt it is about 20 % lower – amounting to 48 % and ~49 %, respectively;

– the output of middlings is of the lowest value for basalt – 8.6 %, compared to ~19 % for tuff and 24 % for breccia.

For lava-breccia, the concentrate output is slightly higher than the yield of middlings (28.7 % vs. 23.8 %). The amount of the concentrate can obviously be increased by reducing the output of middlings.

For tuff, conversely, the output of middlings is bigger than the output of the concentrate (19.4 % vs. 13 %), and the amount of tailings is of the highest rate compared to the other solids. It means the lowest (among the three solids) copper content in tuff, as well as its finer dissemination there, which produces a high yield of middlings.

These results show that electric separation is of the highest efficiency for basalt, even if the feed is of a somewhat larger size. The difference in the performance results in this case is not so much caused by different grain size in the feed for basalt and the other solids (moreover, it is not so substantial) but by different content of copper in the original feed. This is confirmed by the rough calculation of copper concentrate quality, which is suggested below.

To calculate the quality, we use the data from Table 2 of the output of the copper concentrate (from the original) with the aim to extract the copper concentrate: 80 % of the original. This is a big figure, but in this case it does not matter much. It is possible to take 75 % or 70 % – the quality will slightly decline, but the overall picture will remain. From study [9], we will use a formula obtained to determine the resulting extract: $\beta=\varepsilon\cdot\alpha/\gamma$.

The quality of the copper concentrate as a result of electric separation will be:

– for lava-breccia: $\beta=80\cdot1.36/14=7.8$ %;

– for basalt: β=80·2.62/14.3=14.7 %;
– for tuff: β=80·0.53/6.7=6.3 %.

The estimates show that the richest concentrate is obtained by electric separation of basalt, which is followed, in a descending order, by lava-breccia and tuff. These latter solids produced poorer concentrates not only due to lower copper contents in the initial material but also because of the high yields of middlings, which took away (wasted) much copper. For example, middlings for tuff exceed the yield of the concentrate. Middlings are always inferior to the concentrate, but because they are plentiful, they take away a lot of copper. The resulting concentrate is, therefore, poor. It means a necessity to reduce the output of middlings from lava-breccia and tuff, which can be achieved by reducing the size of the feed and by using more powerful electric separators.

The basic enterprise used in the research is one of the largest Ukrainian basalt quarries – Rafalovsky, with samples of solids to develop and test a complex technology of waste-free processing of raw materials; it is necessary to create a research and production site with a capacity of 6–10 tonnes per hour for each of the three types of raw material. For these conditions, it is expedient to take the following corona-electrostatic separators: SE-25/150 with a capacity of 0.5 tonnes/hour per 1 m of the length of the precipitation electrode, SE-70/100 with a capacity of 2.5...6 tonnes/hour, or similar separators produced by foreign firms such as Carpco, Inc. (USA), Rapid (UK), or Lurgi (Germany) (for the feed size of 80 % of the passing class of minus 0.074 mm) as well as separators EKS-1250 (the capacity of 2 tonnes/hour) and SES-2000 (the capacity of 8.5 tonnes/hour), running on the feed size of 0.3...0.074 mm.

In general, we can conclude that it is feasible to use electric separation in the technological scheme of processing basaltic raw materials. For all the three copper-bearing solids (basalt, lava-breccia, and tuff) of the Rafalovsky basalt quarry, it is possible to improve the quality of the concentrate as a result of electric separation by reducing the size of the feed as well as by using all of the above-described procedures.

With a complex processing of basalt raw material, it is necessary to determine the extraction amount of native copper from basalt, lava-breccia, and tuff, depending on the voltage of the electric field and the size of the feed material.

In the experiment, we used a basaltic raw material containing all three components of basalt, with the magnetically receptive part having been removed by a magnetic separator. Thus, an electric separator during the experiments was fed with a granular mass containing the conductor (native copper), semiconductor (aggregates), and the nonconductive portion in the form of silicates. The tests were carried out at a changing intensity of the electric field of the separator in the range of 10÷30 kW, with the size of the solids classed as –1.0 +0.63 mm, –0.63 +0.25 mm, and –0.25 +0.05 mm. In each experiment, the samples weighed 27 g and represented each particle-size class; the concentrate extract in grams was recorded at the electric field intensity of 10 kW, 15 kW, 20 kW, 25 kW, and 30 kW. The experimental results were represented by a cumulative output at an increasing voltage. The obtained data were used to calculate the concentrate output Q, %. Table 4 shows the results of the experiments for each solid.

Table 4

The results of extracting the concentrate at changing the voltage of the electric field

Fineness, mm	The concentrate output	The field voltage, kW				
		10	15	20	25	30
Basalt, a sample of 2,700 g						
–1.0 +0.63	gram	75	120	170	205	280
	%	2.778	4.444	6.296	7.93	10.370
–0.63 +0.25	gram	50	75	95	100	150
	%	1.852	2.778	3.519	3.704	5.556
–0.25 +0.05	gram	20	35	50	55	70
	%	0.741	1.296	1.852	2.037	2.593
Lava-breccia, a sample of 2,700 g						
–1.0 +0.63	gram	40	75	110	120	155
	%	1.481	2.778	4.074	4.444	5.741
–0.63 +0.25	gram	30	55	70	75	90
	%	1.111	2.037	2.593	2.778	3.333
–0.25 +0.05	gram	25	40	50	55	62
	%	0.926	1.481	1.852	2.037	2.296
Tuff, a sample of 2,700 g						
–1.0 +0.63	gram	20	50	80	100	110
	%	0.741	1.852	2.963	3.704	4.074
–0.63 +0.25	gram	20	30	50	70	105
	%	0.741	1.111	1.852	2.593	3.889
–0.25 +0.05	gram	20	28	40	50	60
	%	0.741	1.037	1.481	1.852	2.222

To study the three solids of each size class, coupled linear regression equations were obtained, with the concentrate output Q depending on the electric field voltage of the separator E. The basalt calculation results are presented in Table 5.

Table 5

A correlation analysis of the concentrate output dependence on the field intensity for basalt

Fineness, mm	The regression equation	R^2	F
–1.0 +0.63	Q=–1.037+0.367E	0.986	1.014
–0.63 +0.25	Q=0.148+0.167E	0.925	1.080
–0.25 +0.05	Q=–0.074+0.089E	0.979	1.020

Table 5 shows that the coefficients of determination R^2 of the obtained models are close to the limit value of 1.0, indicating a strong influence of the field voltage on the concentrate output. The value of the Fisher statistics F is less than critical (Fcr=6.388) for the regression dependence, indicating the adequacy of the coupled linear model.

The Student index t_v of the coefficient with regard to the factor value also significantly exceeds the critical value (t_{cr}=3.18), which confirms the importance of this factor in the regression model at a significance level of 0.05.

A graphical representation of the experimental and calculated values for basalt of various particle-size classes is shown in Fig. 1.

The separator practically processes a rock mass in which all particle-size classes are contained together in a certain ratio. It is interesting to study the effect of the ratios between the different classes on the concentrate output. Let us designate as d_i the share in a mixture of an i-th particle-size class, where i=1, 2, and 3. It is assumed to correspond to the class of –1.0 +0.63 mm; d_2 and d_3 correspond to the classes of the following order. Thereby, $\sum d_i=1$. For definiteness, we assume the ratio as $d_2/d_3=1.5$. Since the set values for the first class are d_1=0.4; 0.5; 0.6; 0.7; 0.8, we obtain, for the other classes, the following values: $d_3(1-d_1)/2.5;\ d_2=d_3=1.5$.

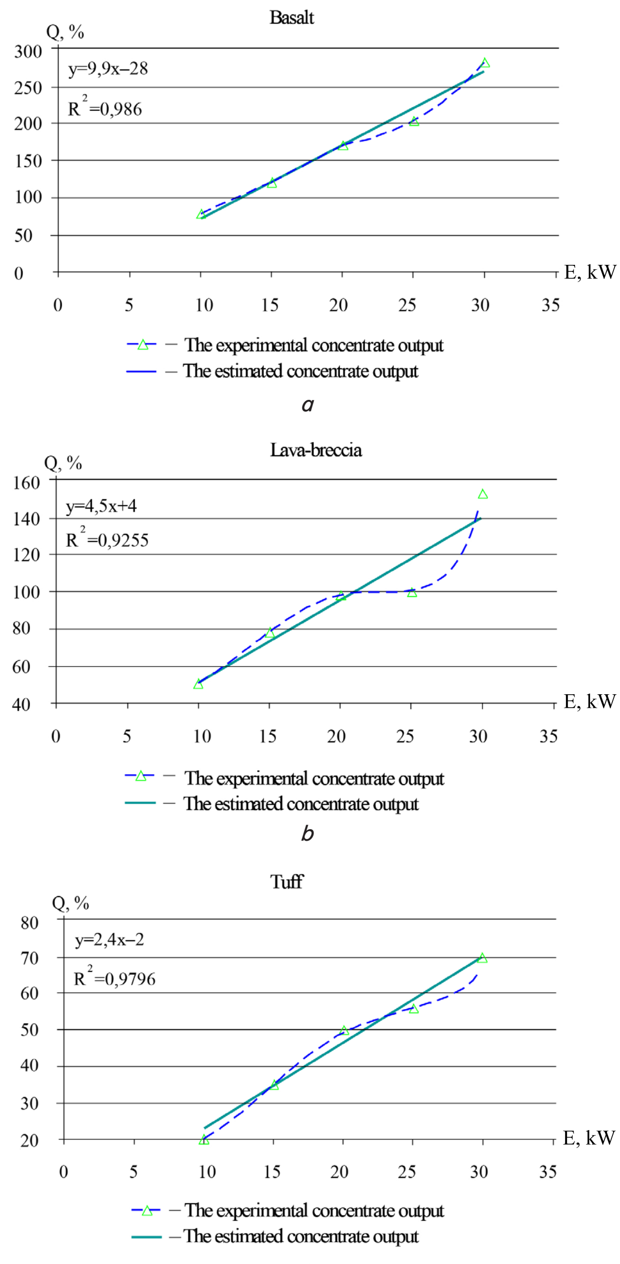

Fig. 1. The dependence of the experimental and estimated outputs of the concentrate on the field voltage for basaltic raw materials: *a* — basalt; *b* — lava-breccia; *c* — tuff

Given the ratios of the particle-size classes in the sample to determine the yield of the concentrate, we obtain the following model:

$$Q=-1.037d_1+0.148d_2-0.074d_3+ \\ +(0.367d_1+0.167d_2+0.089d_3)\cdot E. \quad (1)$$

The results of calculating the concentrate outputs for different values of the shares of the particle-size classes are presented in Table 6, depending on the voltage of the electric field; the variations in the first class (d_1) are graphically represented in Fig. 2.

Table 6

The concentrate output results for different values of the shares of the particle-size classes, depending on the field intensity

The share of the concentrate in the sample			Basalt. The concentrate output Q, %				
			The voltage of the electric field E, kW				
d_1	d_2	d_3	10	15	20	25	30
0.4	0.36	0.24	1.90	3.04	4.18	5.32	6.46
0.5	0.30	0.20	2.02	3.27	4.53	5.78	7.04
0.6	0.24	0.16	2.14	3.51	4.88	6.25	7.62
0.7	0.18	0.12	2.26	3.75	5.23	6.72	8.21
0.8	0.12	0.08	2.38	3.98	5.59	7.19	8.79

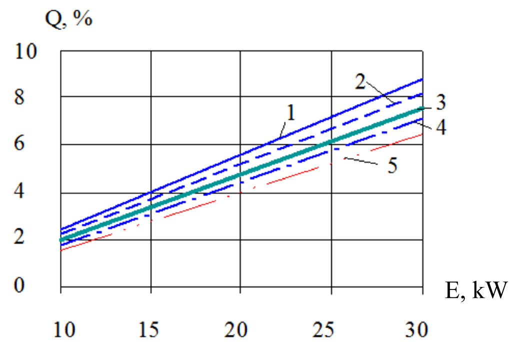

Fig. 2. The dependence of the concentrate output on the electric field voltage at varying the content of different particle size for basalt: 1 — d_1=0.4; 2 — d_1=0.5; 3 — d_1=0.6; 4 — d_1=0.7; 5 — d_1=0.8

Fig. 2 shows that at a low electric field voltage the ratio structure of the sample size has little effect on the amount of the concentrate output due to low extraction efficiency at E=10 kW. As the field voltage increases, different particle-size classes behave differently. Therefore, when d_1 increases from 0.4 to 0.8, the concentrate output increases; at E=30 kW, the output difference is 36 % (8.796/6.461=1.36). Thus, if a lot of rock mass in the flow contains over-ground solids, it reduces the efficiency of the process of extracting the copper concentrate from the rock formation [10].

5. The discussion of the results of researching the efficiency of a complex processing of basalt raw material aimed at extracting native copper

The results have showed the following:

– it is useful to involve electronic separation in the technological scheme of processing basalt raw material for all the three copper-bearing solids (basalt, lava-breccia, and tuff) of the Rafalovsky basalt quarry. The quality of the concentrate as a result of electric separation is improved if the feed size for the separators ranges from –0.25 +0.05 mm to –1.0 +0.63 mm;

– it is possible to develop the basic requirements for carrying out industrial trials in the Rafalovsky basalt quarry;

– it is necessary to carry out more field tests and to create an industrial site for a complex processing of basalt raw material so that technical specifications could be devised to construct a large enterprise or a factory for the development of copper deposits;

– it is essential to undertake research as a necessary element of a non-waste technology of processing the basalts of the Rafalovsky basalt deposits that contain native copper and a silicate portion; it implies extracting strategically valuable raw materials and improving the ecological situation in the region;

– it is obvious from the obtained results that a complex processing of basaltic raw materials (basalt, tuff, and lava-breccia) is feasible; it includes the use of electric separation to recover the silicate part for the construction industry and the metals, including native copper, the amount of which in the basaltic raw materials is of commercial interest.

6. Conclusions

1. The study has revealed a linear dependence of the native copper output on the electric field intensity of the separator, which must be taken into account in the development of the technological scheme of extracting native copper from basaltic raw materials.

2. It has been proved that a significant effect on the outcome of extracting copper is produced by the particle size distribution in the basalt raw material fed into the electric separator; when it changes from –0.25 +0.05 mm to –1.0 +0.63 mm, the percentage yield of native copper increases from 0.7 % to 10.37 %.

3. It has been shown that all the three components of the basalt raw material contain some percentage of copper that is of industrial interest: basalt – 10.370 %; lava-breccia – 5.741 %; tuff – 4.074 %; thereby, the particle size class of the feedstock is –1.0 +0.63 mm, and the electric field voltage is 30 kW.

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