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CHARACTERIZATION AND PROCESSING OF LOW-GRADE IRON ORE FROM THE KHANGUET MINE BY ELECTROSTATIC SEPARATION

Purpose. Choice of a method for treating the iron ore of the Khanguet mine depending on its characterization.

Methodology. This work is focused on the study on physicochemical and mineralogical characterization of the poor iron ore of Khanguet mine, using multiple analysis techniques (X-ray diffraction, X-ray fluorescence, scanning electron microscope and optical microscope), to identify the chemical composition and mineral phases of the ore. The study also focused on the possibility of enrichment, using the electrostatic separation process. For this purpose, two main parameters are studied, such as, the voltage between the electrodes and the rotation speed of the roll.

Findings. The results of the characterization show the possibility of using the process of electrostatic separation for the enrichment of the Khanguet ore, which allows increasing the content of Fe_2O_3 up to 58.46 %.

Originality. The originality of this work is the possibility to use the electrostatic treatment process for the poor iron ore of the Khanguet iron mine.

Practical value. This study shows that the results obtained by the process of electrostatic treatment of ore are very significant; this technique makes it possible to obtain a concentrate with an iron content of 58.46 % and to bring an added value to the company and the steelmaking industry, on the one hand, and, on the other hand, to eliminate reserves of these poor iron ores stored near the mining site, which is harmful for the environment.

Keywords: *Khanguet mine, iron ore, enrichment, mineralogical analysis, electrostatic separation*

Introduction. The mining activity in Algeria is very important and the mining potentialities are much diversified. For the Algerian economy, the next decade will undoubtedly be the one of mining products. The knowing of the chemical and mineralogical composition of ores is essential to identify subsequent treatment solutions and to anticipate the difficulties which could appear in the process of the beneficiation of mineral resources.

The Khanguet deposit is one of the iron deposits in Algeria that were formed by a hydrothermal alteration process. The mine is characterized by five mineralized deposits: *A*, *B*, *C*, *D* and *E* close to each other, all of mineralized deposits are in the form of lenses. Currently, the mine exploits only the first three of these deposits.

Research studies on the structural and stratigraphic plan of the Djebel Djebissa area were carried out by Kowalski 1995 [1]. Other research studies on the characterization and processing of poor iron ores in Algeria are carried out by Idres [2–4] and by Chaabia [5].

Materials. The Khanguet mine is located in the North-Eastern part of Algeria, 16 km east of the city of Tebessa and 15 km South of El Kouif, it is bordered in the East by the Algerian-Tunisian border. On the regional setting, it is located at the North-East end of the Saharan atlas.

The deposit is located in the Djebel Djebissa massif, which forms an anticlinal structure oriented NE-SW, the heart of the structure is occupied by Triassic age terrains, extending over more than 15 km and 2 to 5 km wide. Figs. 1 and 2 illustrate the geographical location of the mine.

The Khanguet deposit is located in a large North-Eastern fault that passes through the central part of the Djebissa anticline. All the mineralized deposits are hosted in the same stratigraphic horizon related to the Aptian-Vraconian [6]. On the whole, the rocks of the bedding hosting the mineralization have a clayey-carbonate composition (Fig. 3).

Methods. In this experimental study, four representative samples with a total mass of 120 kg were taken from the different sites (*A, B, C*) and the waste rock stock (*S*), and were subjected to a detailed characterization study. The sampling points were picked out by GPS and the batches of samples were labeled and stored in plastic bags, then crushed to a size of less than 5 mm, air-dried, homogenized and milled to facilitate their subsequent handling.

The experimental techniques focus on physicochemical analysis by X-ray fluorescence (XRF), conducted at the Center for Scientific and Technical Research in Physical and Chemical Analysis of Bou Ismail, Tipaza and laboratory FUNDAPL, University of Blida 2.

The operations of dry sieve analysis are carried out at the laboratory of mining resources valorization and environment, University of Annaba on an electro-vibrating sieve of RETSCHtype: AS200 basic; Sercial No 22 2504 017 G; Voltage No: 230V 50 Hz. The analysis is carried out on samples of 200 g, the amplitude of vibration used is equal to 60 and the sieving time is equal to 20 minutes.

The scanning electron microscope (SEM) has become a fundamental tool in scientific research, as it allows the study on morphology and chemical elemental composition of materials, which consists of bombarding a solid sample with a primary beam of electrons and then scanning the surface of the object to be observed [7]. The observations by SEM and analysis by energy dispersive X-ray spectrometry (EDS) are carried out at the laboratory of the National Higher School of Mining and Metallurgy Amar Laskri – Annaba, on a microscope of type QUANTA 250.

In addition, the X-ray diffraction analyses (XRD) are carried out at the University of Blida 2, Department of Chemistry, using a D2 PHASER, brand BRUKER device, where the samples are put in the form of powders. This method of analysis is based on the diffraction of X-rays by the material. The diffractogrammes are processed with the software HighScore PlusV3.0d.2013.

Results and discussions. The results of the physicochemical analysis by XRF of the representative samples from *A, B, C* cites and the *S* waste rocks stock are shown in Table 1. The XRF analysis shows that *A* and *B* sites are rich in useful substance;

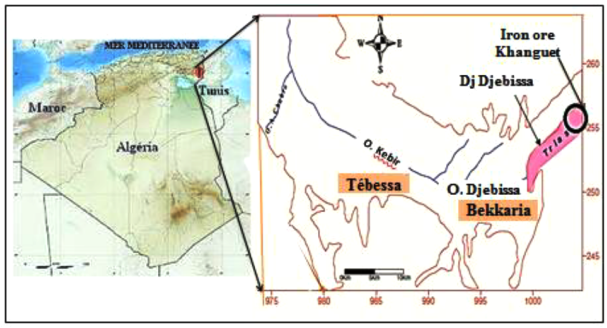

Fig. 1. Geographical location of the Khanguet mine

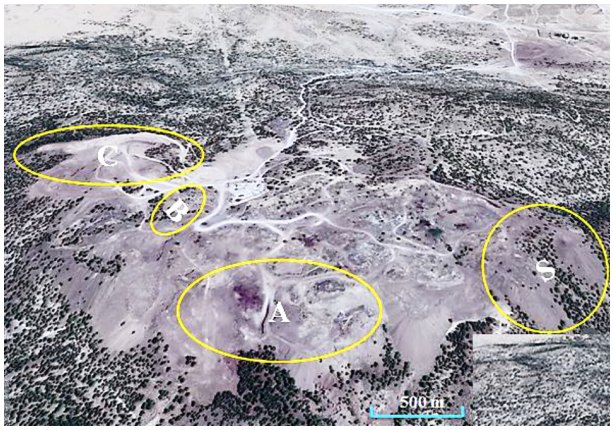

Fig. 2. Map of the location of sites (A, B, C) and the stock of waste rock (S) (Personal treatment by the author TIOUR F)

however, the *C* site and the *S* waste rocks stock are poor. Therefore, the research work will focus only on the latter two.

The different fractions resulting from the sieve analysis by dry sieving of the samples of the *C* deposit and the *S* waste

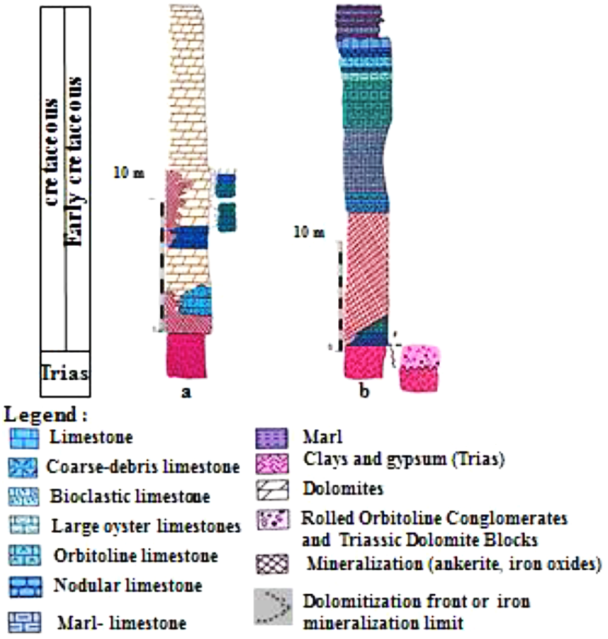

Fig. 3. Stratigraphic section of the Khanguet mine [6]:
a – Djebel Djebissa; *b – North East of Khanguet*

rocks stock are analyzed by XRF and the results are reported in Tables 2 and 3.

X-ray fluorescence analysis. The chemical analysis shows that the main elements constituting the ore are: Iron, Silicon, Aluminum, Magnesium and Oxygen. Within *A*, *B*, *C* deposits and the *S* waste rock stockpile, the Fe_2O_3 contents are 55.13, 58.67, 36.15 and 32.37 % respectively. The results of chemical analysis (Tables 2 and 3) show that the Khanguet iron release size is between the following fraction class: (–0.5 + 0.063) mm.

Scanning electron microscope. The SEM allows us to make detailed observations, from the photomicrographs

Table 1

Chemical analysis results of the sample from site (*A, B, C*) and waste rock stock (*S*)

Deposit	Fe %	Fe_2O_3 %	CaO %	MnO %	SiO_2 %	MgO %	Al_2O_3 %	K_2O %	SO_3 %	P_2O_5 %	SrO %	CuO %	Na_2O %	TiO_2 %	LOI %	Total %
A	38.60	55.13	6.89	2.43	3.77	2.187	1.55	0.13	0.22	0.08	0.10	0.04	0.02	0.05	27.34	99.93
B	41.00	58.67	3.46	2.13	8.63	0.828	4.28	0.15	0.46	0.27	0.21	0.49	0.11	0.09	19.49	99.27
C	25.30	36.15	7.19	1.44	19.08	0.679	10.01	0.36	4.06	0.09	0.15	0.03	0.05	0.09	20.00	99.38
S	22.60	32.37	8.91	1.43	15.66	1.937	7.24	0.73	0.12	0.13	0.10	0.04	0.06	0.16	30.15	99.05

Table 2

Particle size chemical analysis of the sample from site (*C*)

Fraction (mm)	Refusal %	Fe_2O_3 %	SiO_2 %	Al_2O_3 %	CaO %	MgO %	MnO %	P_2O_5 %	CuO %	Na_2O %	SO_3 %	BaO %	K_2O %	LOI %
Initial	//	36.15	19.02	10.01	7.19	0.68	1.44	0.10	0.04	0.05	4.06	0.37	0.36	20.50
>2	22.905	32.48	20.33	9.02	6.41	1.30	1.50	0.30	0.06	0.08	4.10	0.40	0.41	23.55
–2 + 1	15.355	33.54	20.28	8.40	7.12	0.98	1.90	0.22	0.03	0.06	3.65	0.45	0.38	22.45
–1 + 0.5	12.57	35.01	19.45	7.50	8.50	1.20	1.30	0.31	0.02	0.04	3.45	0.51	0.34	22.22
–0.5 + 0.25	13.975	37.41	18.12	7.54	6.03	1.02	2.21	0.15	0.07	0.09	3.20	0.54	0.32	23.25
–0.25 + 0.125	26.76	38.25	16.72	6.82	6.04	1.58	1.02	0.09	0.04	0.05	4.21	0.33	0.38	24.32
–0.125 + 0.063	5.26	38.52	15.54	6.22	5.97	0.70	1.16	0.06	0.05	0.07	4.15	0.09	0.35	27.02
–0.063 + 0.045	2.065	37.10	17.70	8.91	6.13	0.80	1.55	0.15	0.08	0.06	2.86	0.08	0.30	24.15
<0.045	1.11	36.65	19.25	10.25	6.15	0.47	1.15	0.08	0.05	0.05	2.12	0.22	0.31	23.01

Table 3

Particle size chemical analysis of the Khanguet waste rock stock (*S*)

Fraction (mm)	Refusal %	Fe_2O_3 %	SiO_2 %	Al_2O_3 %	CaO %	MgO %	MnO %	P_2O_5 %	CuO %	Na_2O %	SO_3 %	BaO %	K_2O %	LOI %
Initial	//	32.37	15.66	7.23	8.91	1.94	1.43	0.14	0.04	0.06	0.12	0.03	0.73	31.12
>2	25.98	29.02	17.22	7.88	7.50	2.18	1.35	0.16	0.06	0.09	0.10	0.03	0.65	33.65
−2 + 1	19.33	29.89	17.33	6.55	6.99	2.02	1.02	0.08	0.05	0.10	0.15	0.02	0.42	34.95
−1 + 0.5	13.765	31.02	16.86	8.01	7.22	1.44	0.98	0.16	0.05	0.05	0.14	0.04	0.66	32.98
−0.5 + 0.25	10.21	33.50	15.85	6.40	8.98	2.22	0.78	0.09	0.06	0.09	0.16	0.05	0.50	31.10
−0.25 + 0.125	11.675	35.09	15.60	6.52	7.81	1.89	0.68	0.08	0.07	0.08	0.11	0.04	0.71	30.58
−0.125 + 0.063	11.615	35.02	16.24	7.20	8.90	2.45	1.05	0.15	0.05	0.07	0.12	0.06	0.80	27.65
−0.063 + 0.045	3.82	34.56	17.80	8.66	9.02	1.54	1.70	0.88	0.07	0.06	0.09	0.07	0.91	24.52
<0.045	3.605	33.98	17.45	8.54	8.50	1.81	1.65	0.74	0.08	0.04	0.08	0.05	0.95	26.00

(Figs. 5 and 6), the existence of two main phases appears clear; the bright phase is mainly composed of iron, and the dark phase consists of carbonates. This observation coupled with a semi-quantitative chemical micro-analysis (EDS) showed a diversified chemical composition, mainly composed of the following elements: Fe, Si, Al, Ca, Mg, Mn and O. We also note the presence of several trace elements such as: S, Cl and C.

The important quantity of oxygen detected in all the samples is due to the fact that it occurs in the composition of several oxides, the presence of silica and alumina indicates the presence of a clayey fraction. Finally, the presence of Calcium and Magnesium means the presence of carbonates.

X-ray diffraction analysis. XRD is considered one of the most important methods for mineralogical characterization of ores. The results of the analysis of the deposit (*C*) and the waste rock stockpile (*S*) are shown in Figs. 7 and 8. The results of the XRD analyses show that the C deposit is similar to the *S* waste rock stockpile, they are constituted of quartz (45 and 43 %) as the basic mineral phase, associated to hematite Fe_2O_3 (28 and 24 %) and carbonates $CaCO_3$ (27 and 33 %).

Treatment of Khanguet ore by the electrostatic separation process. The exploitation of Khanguet mine generates, on the one hand, the depletion of iron rich reserves and, on the other hand, mining wastes which are not only an environmental problem, but also an economic loss. Therefore, this study focused on the processing of low-grade ore and the storage of waste rock.

Taking into account the characteristics of the Khanguet ore and waste rock, mineralogical composition, iron content, particle-size distribution, iron mineral release mesh from the gangue, as well as the arid climate of the region, tests were conducted on the treatment of this poor ore and the stock of waste rocks by the electrostatic separation process. The research was conducted on samples to determine the optimal parameters of the electrostatically tested corona effect; these parameters are the electrical voltage between the electrodes and the rotation speed of the roll.

Electrostatic separation takes advantage of the difference in electrical conductivity that exists between materials to accomplish separation [8]. There are several types of separators and the difference is due to the charging method. A system of

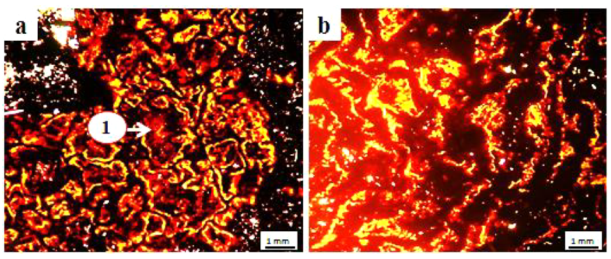

Fig. 4. Microphotographs of thin section:
a – sample of site (*C*); *b – sample of waste rock stock* (*S*) *1 –Hematite nodule*

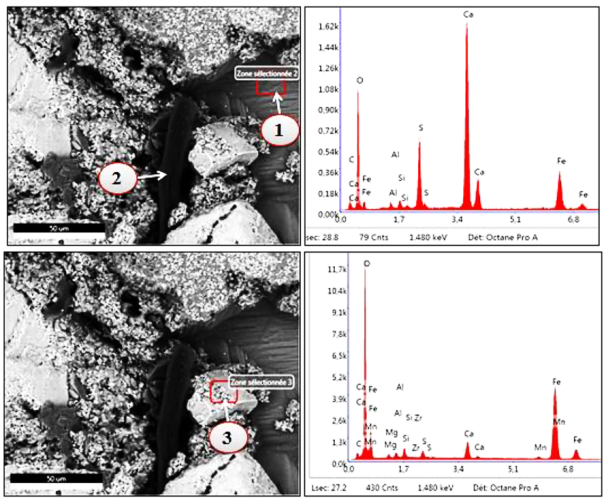

Fig. 5. Microphotographs taken on the sample from site C:
1 – Calcite; 2 – organic matter; 3 – Hematite

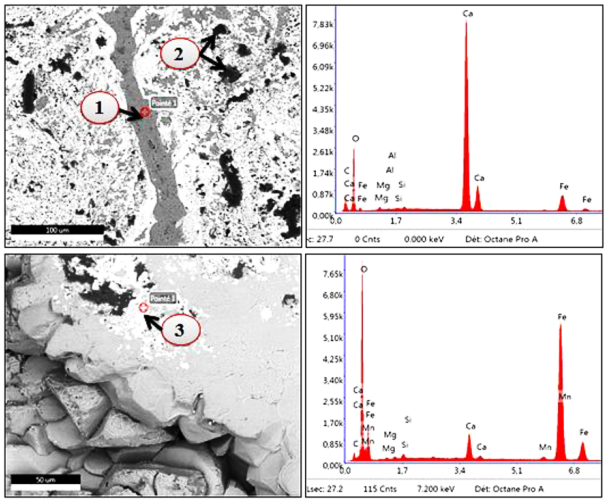

Fig. 6. Microphotographs taken on the sample of the waste rock S:
1 – Calcite venule; 2 – Pores; 3 – Hematite

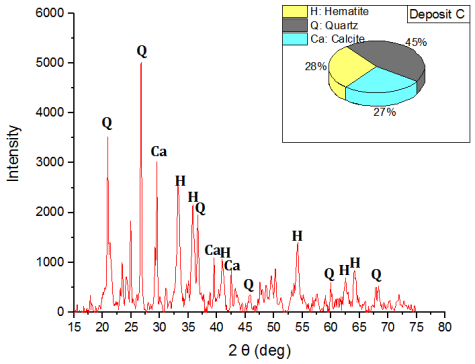

Fig. 7. X-ray diffraction pattern of site C

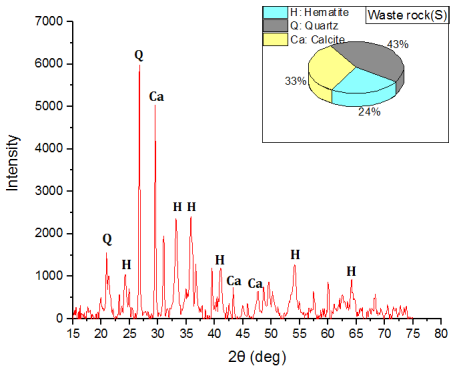

Fig. 8. X-ray diffraction pattern of the waste rock S

attraction or repulsion proportional to this charge allows their separation.

The variable parameters of the electrostatic drum separation process can be mechanical (vibro-transporter, cylinder and collector), material (particle conductivity, particle shape and size, bulk density), environmental (Temperature, humidity and dust) and electrical (active electrode, neutralization electrode and high voltage) [9].

Fig. 9 shows the mechanism of discharge of particles in the corona discharge field. With the increase in the voltage between the electrodes there occurs intense gas shock ionization with the appearance of the corona electrode, then it decreases more and more with the electric field intensity in the direction of the conductive electrode [10].

The charging of a particle grows until the ions do not couple to each other. With increasing charging time and numbers

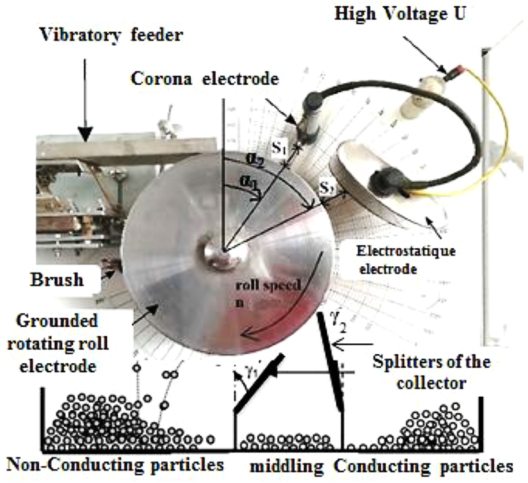

Fig. 9. Laboratory electrostatic separator [11, 12]

Table 4

XRF analysis results, before and after treatment

Product	Fe_2O_3 (%)	CaO (%)	SiO_2 (%)	MgO (%)	Al_2O_3 (%)	MnO (%)	BI
Conductor	58.46	6.48	5.51	0.01	3.29	1.05	1.18
Non conductor	7.41	18.9	27.4	0.18	5.47	2.07	0.69
Initial sample ($C+S$)	41.25	8.25	17.5	0.05	4.20	1.39	0.47

of ions deposited on the particle, the increase in field strength created by the charged particle is directed towards the external main field strength. When these intensities become equal, the particle stops receiving new ions. Therefore, it stops charging. At this moment, the particle has the maximum possible charge [13].

The enrichment tests by electrostatic separation were conducted at the laboratory applications of plasma, electrostatics and electromagnetic compatibility of the University of Sidi Bel Abbes, with the following parameters:

1. Type of active electrode: Wire electrode with a position $\alpha_1 = 10°$.
2. Type of neutralization electrode: static electrode with a position $\alpha_2 = 45°$.
3. Electrical voltage: Variable.
4. Roll rotation speed: Variable.
5. Particle size: (–1 + 0.125) mm.
6. Temperature: 25 °C.
7. Humidity: 2 %.
8. Roll radius: 15 cm and the separator valves are set so that the initial product will be divided into conductive and non-conductive.

According to the tests carried out by electrostatic separation with corona effect, it can be seen from Tables 4 and 5 that the best results are obtained with the following parameters: Rotation speed 50 r/min and an electric voltage of 20 kV, iron content 58.46 %, recovery of 93.94 % and with a basicity index (BI) equal to 1.18. The enrichment tests of the iron ore and the waste rock of Khanguet mine by the electrostatic separation process allow reaching very satisfactory results.

Conclusion. The results of XRF analysis show that, on the one hand, *A* and *B* deposits are rich in useful substances; on the other hand, *C* deposit and *S* waste rock stock are poor. On the whole of *A, B* and *C* deposits and *S* waste rock stock, the Fe_2O_3 contents are respectively: 55.13; 58.67; 36.15 and 32.37 %. The results of particle-size analysis show that the iron release mesh is between (–0.5 + 0.063) mm.

From the microphotographs obtained from optical observations and SEM, it clearly appears that two main phases exist: the light phase, which is mainly composed of iron, and the dark phase, which consists of carbonates.

The results of X-ray diffraction analysis of Khanguet iron ore show that *C* deposit is like that of *S* waste rock stock; they consist of quartz as the basic mineral phase, associated with hematite Fe_2O_3 and carbonates $CaCO_3$.

The exploitation of Khanguet mine generates an environmental problem related to the mining waste stored near the mine. The latter also represents an economic loss for the company.

The tests carried out on samples of particle-size (-1 +0.125) mm, by the electrostatic process gave significant results with regards of iron content and recovery which are 58.46 and 93.94 % respectively.

Acknowledgement. *The treatment process and the characterization analyses were carried out in several scientific research laboratories. The authors would like to thank all the directors and*

Table 5

Tests by high-tension electrostatic separation (*C* and *S*)

Speed (r/min)	Tension (kV)	Conductivity	Weight (%)	Fe_t (%)	Fe_2O_3 (%)	Performance (%)	Recovery (%)
40	14	Conductor	77.98	31.92	45.58	50.33	55.61
		Nonconductor	22.02	25.82	36.88	49.67	44.40
	17	Conductor	70.26	32.36	46.21	66.28	74.24
		Nonconductor	29.74	22.07	31.52	33.72	25.76
	20	Conductor	65.46	33.87	48.37	49.70	58.26
		Nonconductor	34.54	23.97	34.23	50.30	41.74
50	14	Conductor	66.12	32.20	45.98	71.76	79.98
		Nonconductor	33.88	20.48	29.25	28.24	20.02
	17	Conductor	74.28	38.02	54.30	66.59	87.64
		Nonconductor	25.72	10.69	15.27	33.41	12.36
	20	Conductor	81.18	41.00	58.46	66.30	93.94
		Nonconductor	18.82	5.20	7.41	33.71	6.06
60	14	Conductor	71.38	32.16	45.92	67.50	75.13
		Nonconductor	28.62	22.10	31.56	32.50	24.87
	17	Conductor	66.72	33.23	47.45	62.40	71.76
		Nonconductor	33.26	21.69	30.97	37.61	28.24
	20	Conductor	63.82	36.13	51.59	73.48	91.89
		Nonconductor	36.16	8.83	12.61	26.52	8.11

engineers of the laboratories for their assistance. We would like also to thank Prof. Dr. Tilmatine Amar from Sidi Bel-Abbes University, Prof. Dr. Hadj Zobir Soraya from Annaba University and Dr. Benselhoub Aissa for their precious help.

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Характеристика й переробка електростатичною сепарацією низькоякісної залізної руди рудника Хангет

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Мета. Вибір методу переробки залізної руди рудника Хангет в залежності від її характеристики.

Методика. Дана робота спрямована на вивчення фізико-хімічних і мінералогічних характеристик бідної залізної руди рудника Хангет з використанням декількох методів аналізу (рентгенівської дифракції, рентгенофлуоресцентного аналізу, скануючого електронного мікроскопа та оптичного мікроскопа) з метою визначення хімічного складу й мінеральних фаз. У фокусі дослідження також була можливість збагачення з використанням процесу електростатичного поділу. Для цього досліджуються два основні параметри, такі як напруга між електродами та швидкість обертання валка.

Результати. Результати аналізу характеристик показують можливість використання процесу електростатичної сепарації для збагачення руди родовища Хангет, що дозволяє збільшити вміст Fe_2O_3 до 58,46 %.

Наукова новизна. Новизна даної роботи полягає в можливості застосування процесу електростатичної обробки бідної залізної руди рудника Хангет.

Практична значимість. Дане дослідження показує, що результати, отримані у процесі електростатичної обробки руди, дуже значущі; цей метод дозволяє отримати концентрат із вмістом заліза 58,46 % і принести додаткову користь компанії та металургійній галузі, з одного боку, а з іншого боку, ліквідувати запаси цих бідних залізних руд, що зберігаються поруч із місцем видобування, що шкідливо для навколишнього середовища.

Ключові слова: *рудник Хангет, залізна руда, збагачення, мінералогічний аналіз, електростатична сепарація*

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