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FEASIBILITY ASSESSMENT OF LOW-GRADE IRON ORE FROM EL OUENZA MINE BY HIGH-INTENSITY MAGNETIC SEPARATION

Purpose. The objective of this work in the first stage is to characterize the poor iron ore from the El Ouenza mine. Then, in the second stage, it is a question of valorizing it by high intensity magnetic separation.

Methodology. The characterization of representative samples taken from the study area was carried out using several techniques, including X-ray fluorescence spectrometry (XRF), X-ray diffraction (XRD), scanning electron microscopy coupled with energy dispersive spectroscopy (SEM-EDS), thermogravimetric analysis and differential scanning calorimetry (TGA/DSC), and Fourier transform infrared spectroscopy (FTIR). Processes involving a combination of calcination and high-intensity dry magnetic separation were used to upgrade the poor iron ore to meet the requirements of the steel industry.

Findings. The results obtained show that the El Ouenza iron ore consists mainly of ferrous minerals, notably hematite and goethite, as well as a siliceous and calcareous gangue. The treatment results enabled us to achieve a grade of 51.94 % for the sample calcined at 900 °C using a magnetic field of 2.3 T on the size fraction (–0.5 +0.125) mm.

Originality. The originality of the work lies in the possibility of using combined methods, calcination and magnetic separation, to valorize poor iron ore from the Ouenza mine.

Practical value. This study shows that the results obtained by calcination and magnetic separation are very significant. These techniques enable us to obtain a concentrate with an iron content of 51.94 %, bringing value to the steel industry, eliminating the reserves of poor iron ore stored near the mine site and preserving the environment.

Keywords: *El Ouenza mine, enrichment, treatment, magnetic separation, calcination, environment*

Introduction. The continuous exploitation of ore deposits leads to the gradual depletion of raw materials, creating critical problems in the mining industry. This encourages the use of tailings generated during ore processing, rejects from mine workings, low-grade ores and processing fines [1]. However, iron has continually become in high demand as a result of technological and industrial development on a global scale. Reserves of high-quality iron ore that can be used directly in the steel industry are limited and are being depleted very rapidly [2]. In addition, the mining of iron ore deposits produces huge quantities of waste, constituting a major solid waste. It is estimated that several hundred million tons of waste, such as free-flowing waste rock and low grade iron ore, are dumped around the world every year [3]. Low-grade iron ore must be beneficiated before it can be used by the steel industry. The overall profitability and productivity of steelworks depends mainly on the quality of the ore fed into the blast furnace [3]. The main difficulty in processing low grade iron ore is the presence of gangue minerals such as calcite, alumina and silica, which must be removed by beneficiation [4].

Mining waste is defined as residues from the extraction and processing of ore, consisting mainly of crushed rock, chemicals, processing fines and water. Mine waste remains an environmental liability for the mining industry [5, 6]. Appropriate disposal of mine waste has become crucial for environmental preservation, hence the need to develop awareness mechanisms and find solutions to deploy technologies capable of minimizing the negative impacts of the mining industry [7]. Because of the limited availability of rich ores, beneficiation is directed towards other resources such as poor ores, mine tailings and processing residues to obtain the desired quality [8]. Mineral characterization is an integral part of mineral processing, as it is the key to choosing the most appropriate route for mineral recovery [9].

Mining activity in Algeria is very significant and the country's mining potential is highly diversified, which has led to renewed interest and new ambitions for growth after a prolonged period of stagnation. From 2020, the annual volume of iron ore production in Algeria will reach around two million tons. However, this is still not enough to meet the country's growing needs [10, 11]. The El Ouenza iron deposit is one of the main sources of iron ore, mainly of the hematitic type, with an average iron content of around 50 % for the Algerian steel industry. However, the mine produces thousands of tons of tailings every year, and reserves are estimated at over 100 million tons. This huge quantity of mine waste takes up a

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lot of space and poses a real threat to the environment, including low grade iron ore that is deposited on the surface in various dumps near the mine site [12].

In this context, the aim of this work is, on the one hand, to study the physico-chemical, mineralogical, thermal and structural characterization of low-grade iron ore, and on the other hand, to assess the feasibility of high-intensity magnetic separation of poor iron ore from El Ouenza in order to reduce the rate of rejects and preserve the environment.

Materials and methods. ***Geographical location of the study area.*** The El Ouenza iron ore deposit is one of the main sources of iron ore for the El Hadjar steel complex, enabling it to produce steel and cast iron that meet the requirements of modern steelmaking [13]. The El Ouenza mine is located around ten kilometers from the Algerian-Tunisian border, on the extension of the Aurès-El Kef corridor, 90 km North of Tebessa and 190 km South-East of Annaba (Fig. 1). It is linked to the steel complex by an electric railway used to transport iron ore [14].

In order to characterize this low-grade iron ore, a sample weighing around 40 kg was taken from the landfill stockpile and subjected to an in-depth characterization study. The samples were air-dried for 48 hours to remove any moisture. The material is then crushed using a FRITSCH jaw crusher. The crushed sample is thoroughly mixed and sampled by a RETSCH rotary separator to prepare representative samples.

Characterization of raw materials. The analytical methods used in this research work are laser granulometric analysis, X-ray fluorescence (XRF), X-ray diffraction (XRD), scanning electron microscopy with energy dispersive X-ray spectrometry (SEM-EDX), Fourier transform infrared spectroscopy (FTIR), and thermogravimetric analysis and differential scanning calorimetry (TGA/DSC).

A laser particle size analyzer of the Horiba LA960 is used to determine the particle size distribution of the sample in the range 0.01 to 1,000 μm. For this test, the sample is dispersed in an aqueous solution (water) and homogenized by a propeller using ultrasonic excitation.

Quantitative chemical analysis of the initial sample is carried out by X-ray fluorescence using a Bruker X-ray fluorescence spectrometer (S8 Tiger). Loss on ignition is obtained by heating the sample powder to 950 °C for 2 hours, and then analyzed.

Structural characterization of the various functional groups in the lean iron ore sample obtained was carried out using an FTIR spectrometer (Thermo Scientific iS5) over a range of 4,000 to 400 cm^{-1}. A quantity of 2 mg of sample was mixed with dry KBr powder (100 mg) and then compacted. The spectra obtained are analyzed in transmission mode.

Thermogravimetric analysis by differential scanning calorimetry (TGA/DSC) was carried out on a Perkin Elmer analyzer (STA8000) on a 20 mg sample. The samples were placed in platinum crucibles and examined over a temperature range from 50 to 1,100 °C, with a heating rate of 10 °C/min in a flow of synthetic air.

Fig. 1. Geographical location of the El Ouezna mine [14]

The microstructure of the lean iron ore is examined using a FTI QUANTA 250 scanning electron microscope (SEM) at an accelerating voltage of 25 kV. Elemental chemical analyses were also carried out using energy dispersive X-ray spectroscopy (EDS) equipped with the SEM system.

Enrichment of low-grade iron ore from the El Ouenza mine. Calcination. Samples of low-grade iron ore from the El Ouenza mine were first subjected to a calcination process in a Nbertherm GmbH muffle furnace (manufactured in Germany). A 300 g quantity of low-grade iron ore, with a particle size of between –2 and +0.125 mm, was calcined at three different temperatures: 800, 900 and 1,000 °C, for 15 minutes.

Dry high-intensity magnetic separation (HIMS). Based on the results of the characterization and the literature, high-intensity magnetic separation was recommended for upgrading iron ore from the El Ouenza mine.

Magnetic separation tests were carried out using a KHD HUMBOLDT WEDAG R40-VU0 separator (made in Germany), under the following conditions: magnetic flux density of 2.3 T, variable particle size, humidity of 2 % and ambient temperature of 25 °C. Magnetic separation tests were carried out on samples weighing 100 grams each. The tests are repeated three times to ensure reliable results.

Results and discussion. ***Characterization of low-grade iron ore. Particle size distribution.*** According to the results of the laser granulometry, the particle size distribution of the sample indicates a monomodal distribution, characterized by a single population. The D_{10} corresponds to particles of size 4.81 μm and the D_{50} corresponds to particles of size 13.69 μm. In addition, 90 % of the suspension contains grains with a diameter of 34.21 μm. The graph shows the existing population in the sample as a function of percentage by volume (Fig. 2).

Chemical analysis by X-ray fluorescence (XRF). Table 1 presents the results of the chemical analysis of the crude sample and by particle size of the low-grade iron ore from the El Ouenza mine. Chemical analysis of the crude sample indicates that the ore contains mainly Fe_2O_3, SiO_2 and CaO, with concentrations of 41.04, 18.46 and 15.98 % respectively, representing approximately 75 % of the total. This indicates the presence of hematite, quartz and calcite in the ore. However, other minerals, such as MgO, Al_2O_3 and TiO_2, are present in low concentrations.

The Fe_2O_3 values are uniformly present in the different particle size ranges. As the particle size decreases, the iron content decreases and the silica content increases up to the slice (+0.063 mm). The CaO content is also uniformly present in all particle size fractions. The release mesh is circumscribed between (–2 +1 mm) and (–0.125 +0.063 mm). According to the results of the chemical analysis, this type of ore contains mainly a siliceous and calcareous gangue.

X-ray diffraction. The results of the XRD analysis of the raw sample and by particle size fractions, presented in Fig. 3,

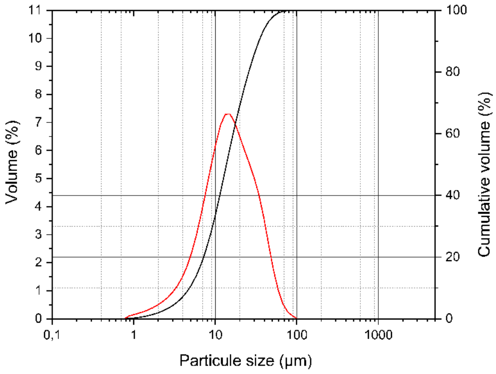

Fig. 2. Particle size distribution of initial low-grade iron ore

Table 1

Results of granulo-chemical analysis of low-grade iron ore from El Ouenza

Fraction, mm	SiO_2, %	Al_2O_3, %	Fe_2O_3, %	CaO, %	MgO, %	SO_3, %	K_2O, %	Na_2O, %	P_2O_5, %	TiO_2, %	MnO, %	PAF, %
Initial	18.46	1.82	41.04	15.98	1.77	0.12	0.09	0.07	0.06	0.06	1.43	19.35
>2	17.76	1.21	41.20	17.07	1.83	0.04	0.05	0.01	0.07	0.04	1.04	19.69
–2 + 1	17.30	1.40	42.09	16.75	1.63	0.07	0.05	0.01	0.06	0.03	1.13	19.49
–1 + 0,5	16.47	1.58	41.82	17.04	1.75	0.08	0.08	0.01	0.07	0.06	1.22	19.82
–0.5 + 0.250	16.63	2.01	38.79	18.34	2.17	0.20	0.09	0.13	0.08	0.05	1.30	20.21
–0.250 + 0.125	21.13	2.74	40.06	14.67	1.79	0.22	0.15	0.16	0.11	0.09	1.29	17.57
–0.125 + 0.063	24.91	3.11	41.28	11.69	1.69	0.20	0.18	0.11	0.10	0.09	1.26	15.39
<0.063	26.89	4.15	40.18	11.34	1.58	0.20	0.21	0.10	0.08	0.10	1.24	13.93

indicate that the main mineral phases in the ore are hematite and goethite as the main iron minerals, and quartz and calcite as the main gangue phases. The hematite, calcite and quartz peaks, with their strong, well expressed intensity, make them easy to identify in relation to the other peaks. The results of the XRD analyses of the different particle size classes show that all the mineral phases in the different particle size classes are similar to those in the raw sample. The main mineral phases of the different particle size fractions are hematite (Fe_2O_3) and goethite ($FeO(OH)$), associated with gangue minerals quartz (SiO_2) and calcite ($CaCO_3$). The intensity of the quartz peaks increases in the fine fractions.

Fourier transform infrared spectroscopy (FTIR). Fig. 4 shows the infrared spectrum of the low-grade iron ore sample. The broad band located at 3,296 cm^{-1} is associated with the vibrations of the O—H bonds of the bonds of the water molecules adsorbed on the surface of the sample, characteristic of goethite [15]. A more intense and better resolved peak at 2,521 cm^{-1} corresponds to an OH crystallization band. The range between 1,030 and 1,435 cm^{-1} is related to the vibration of the Si—O bond [16]. The range observed between 879 and 779 cm^{-1} corresponds to the symmetrical vibration of the Si—O—Si bond, as well as providing information on the extent of Al substitution in the goethite structure [4, 17]. The most characteristic infrared absorption bands of hematite are present in the low frequency region (< 600 cm^{-1}) [5]. A small band around 530 cm^{-1} can be associated with the stretching vibration of the Fe—O bond [18].

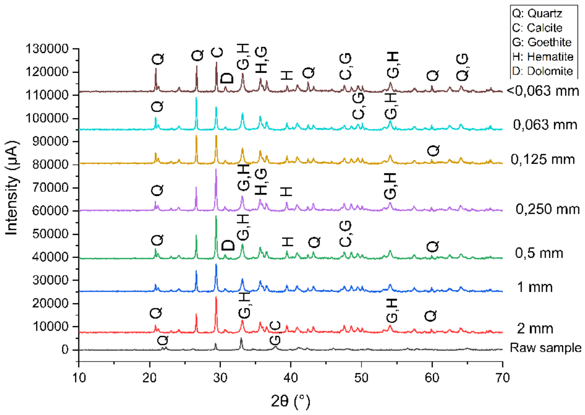

Fig. 3. X-ray diffractogram of the initial sample and the different particle size fractions

Thermogravimetric and differential scanning calorimetry (TGA/DSC) analysis. The thermal behavior of the low grade iron ore sample is shown in Fig. 5. According to the TGA/DSC curve, heating below 200 °C causes a mass loss of 0.7 %, due to the loss of adsorbed water or surface water present in the sample, characterized by an endothermic peak at around 73.53 °C. Mass loss between 200 and 320 °C is 1.73 %, characterized by an endothermic peak recorded at 305.96 °C, associated with structural O—H by a dehydroxylation reaction of poorly crystallized goethite, transforming into hematite [19]. The temperature increase in this endothermic is associated with crystal size and is influenced by the amount of Al—Fe substitution and structural defects [20]. Between temperatures of 300 and 500 °C, a mass loss of 0.92 % is observed due to the transition from α-quartz to β-quartz. In the temperature range from 500 to 850 °C, mass loss is 14.54 %, characterized by an endothermic peak at 759.23 °C, due to the elimination of constitutional water and the decomposition of certain clay minerals, such as quartz and kaolinite.

Scanning Electron Microscope (SEM-EDS) analysis. Fig. 6 shows the micrograph of the low-grade iron ore sam-

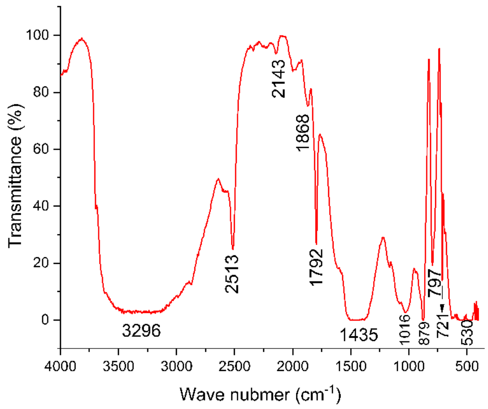

Fig. 4. FTIR spectrum of initial low-grade iron ore sample

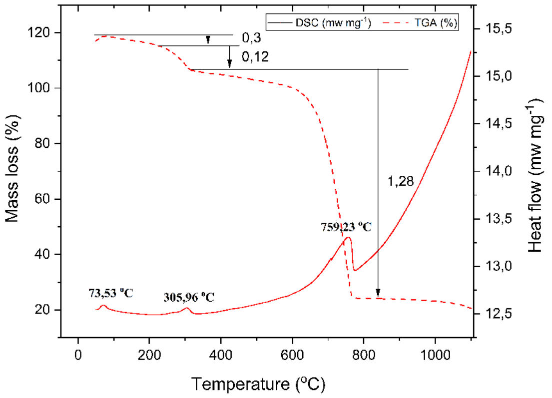

Fig. 5. Thermogravimetric and calorimetric analysis of initial low-grade iron ore sample

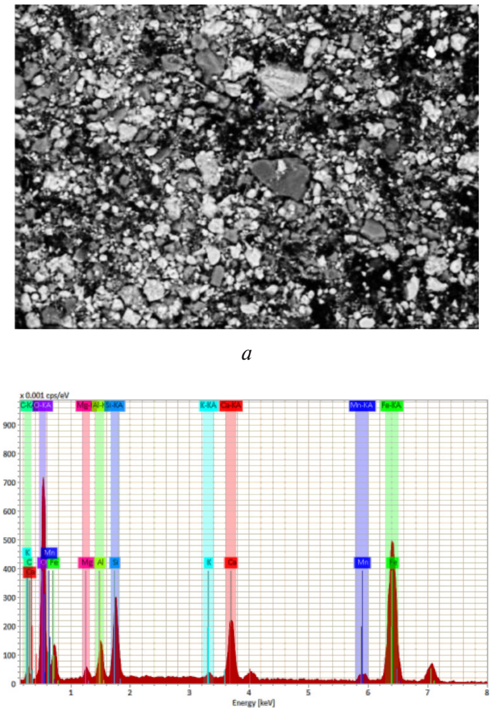

Fig. 6. SEM observation of initial low-grade iron ore sample:
a – micrographs; b – EDS

ple, obtained by scanning electron microscopy coupled to EDS. Different phases are distinguished according to their density, size, shape and orientation angle. The results show that the minerals are separated from each other during grinding. The ferrous minerals (hematite and goethite) appear in the SEM images with a light color and more luminosity, while goethite is identified by a grey color. The presence of greyish-black quartz as the dominant compound, linked to the iron oxides, and grey calcite (dark phase) is also noted [10].

The EDS diffractogram shows two larger peaks represented by oxygen and iron at 77.76 %, indicating that the sample is predominantly composed of iron oxides (hematite and goethite). In comparison, other elements in the sample, such as calcium and silicon (9.01 %), can be attributed to the presence of quartz and calcite. This trend indicates that the poor ore from the El Ouenza mine is mainly rich in quartz. In addition, the EDS result also confirmed and correlated with the XRD result, revealing that the main mineral phases in the poor ore are goethite, hematite and quartz.

Proposed processing method for El Ouenza iron ore. The chemical and mineralogical characterization of the ore characterizes the content of useful mineral components and gangue, are used to determine the processing method. High intensity dry magnetic separation among the commonly used techniques, for the separation of paramagnetic minerals, while based on the difference between magnetic susceptibility, texture of the minerals to be separated, granulometry and marketing and ecological issues [21]. Several studies have been carried out on the valorization of rejects and poor iron ores by high-intensity magnetic separation. [22] studied the valorization of poor iron ore from the Rouina mine, by high-intensity magnetic separation, followed by pre-treatment by washing in order to obtain a pre-concentrate with a content of 38.05 %. They found that magnetic separation makes it possible to obtain a concentrate with an iron content of 54.09 %, with an extraction degree of 84.52 % and a yield of 57.81 %. [23] proved the feasibility of magnetic separation of poor iron ore at high intensity by dry method. It was found that the rotation speed of the drum and the feed particle size have a significant influence on the separation efficiency, and that it is possible to obtain a magnetic concentrate grading 36.22 % Fe with a recovery of 75.97 % at a particle size of less than 10 mm. Fahem et al. showed that the beneficiation of Khanguet ore by high-intensity magnetic separation has a significant profitability, the hematite (Fe_2O_3) content in the concentrate reached 66 %. The results of this study show that high-intensity magnetic separation has proven to be the most efficient and advantageous solution when it comes to the treatment of low-grade iron ore and tailings from the Khanguet mine.

According to the results of the in-depth characterization obtained, it is proven that the iron ore of El Ouezna is composed of valuable mixtures of weakly magnetic iron oxides (goethite and hematite) and non-magnetic gangue (silica and calcite). The association of iron ores and silica is essential. The high-intensity dry magnetic separation process is the proposed recovery method associated with a preliminary process by calcination, in order to reduce the rate of associated gangues and leads to an increase in the iron content [11].

High intensity magnetic separation by dry goose (HIMS). Calcination test results. The granulometric fractions prepared by sieving were subjected to calcination tests.

The result of the chemical analysis of the different particle size classes before and after calcination are presented in Table 2.

According to the results obtained, an increase in iron content was observed for all the granulometric fractions and for the total sample (–2 + 0.125 mm) at firing temperatures of 800 and 900 °C. However, the iron content decreases as the calcination temperature rises to 1,000 °C. There was also a significant increase in silica and alumina content for the different particle size fractions at 800, 900 and 1,000 °C.

Analysis of magnetic products. ***Chemical analysis by XRF.*** A series of tests was carried out on a total sample and samples of different particle size classes calcined at different temperatures (800, 900 and 1,000 °C). The results of the XRF analysis of the magnetic fractions are presented in Table 3.

The results of tests on different granulometric fractions, separated on the high-intensity dry magnetic separator, are encouraging, with a significant increase in iron ore content. The best result was obtained for the granulometric fraction

Table 2

XRF analysis of calcined and non-calcined sample

Fraction, mm	Temperature, °C	Fe_2O_3, %	SiO_2, %	Al_2O_3, %	CaO, %	MgO, %
(–2 + 0.5)	Brut	43.67	14.62	1.71	17.82	0.96
	800	44.06	15.81	2.14	17.68	1.13
	900	44.92	15.01	2.42	16.71	0.93
	1,000	42.53	19.61	2.64	16.33	1.03
(–0.5 + 0.125)	Brut	42.32	17.38	2.02	16.74	0.94
	800	42.86	19.45	2.45	16.84	1.02
	900	43.84	16.85	1.76	17.91	1.27
	1,000	42.13	19.53	2.37	16.96	1.08
(–2 + 0.125)	Brut	42.48	16.13	1.83	17.36	0.99
	800	44.04	15.10	1.75	17.17	0.98
	900	43.24	16.71	1.92	17.99	1.14
	1,000	42.12	17.36	1.83	16.82	1.05

Table 3

Results of magnetic separation test

Fraction, mm	Temperature, °C	Fe_2O_3, %	SiO_2, %	Al_2O_3, %	CaO, %	MgO, %
(–2 + 0.5)	Brut	46.80	15.87	1.93	16.94	0.94
	800	49.75	13.22	1.84	17.21	0.98
	900	51.02	11.51	1.68	18.06	1,18
	1,000	49.53	15.41	2.44	16.89	1.05
(–0.5 + 0.125)	Brut	50.40	11.85	1.98	17.91	1,27
	800	49.34	19.45	2.45	16.84	1.02
	900	51.94	10.75	1.76	13.55	0.73
	1,000	48.53	16.51	2.44	19.89	1.04
(–2 + 0.125)	Brut	49,80	14.87	1,93	16,94	0.98
	800	46.04	15.59	1.75	16.71	0.94
	900	47.24	15.71	1.92	18.17	1.14
	1,000	46.42	16.94	2.41	16.82	1.05

(–0.5 + 0.125 mm) calcined at 900 °C, where the iron content rose from 43.84 to 51.94 %. The increase in iron content in the fine fraction is due to the increase in the degree of liberation.

Technological schema of low grade iron ore. The obtained processing results allowed developing a treatment plan of low grade iron from the El Ouenza mine (Fig. 7).

The proposed scheme shows a significant improvement in the iron content compared to the initial sample. For example, the sample calcined at 900 °C allowed reaching an iron concentration of 51.94 %. These results show the effectiveness of the tests (calcination and magnetic separation) to valorize the poor iron ore of the El Ouenza mine.

Conclusion. Chemical analysis showed that the initial sample collected at the mine site dump is a low-grade iron ore with a content of 41.04 % Fe_2O_3 and 18.46 % SiO_2 collected at the mine site dump is a low-grade iron ore with a content of 41.04 % Fe_2O_3 and 18.46 % SiO_2.

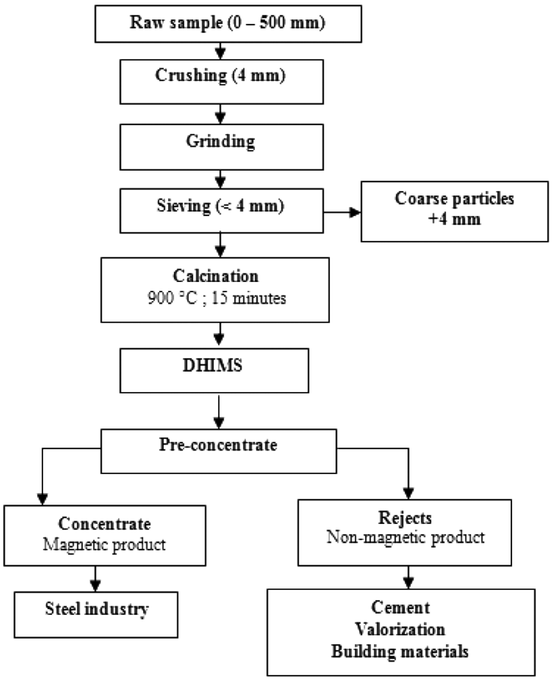

Fig. 7. Technological schema for processing of low grade iron ore from the El Ouenza mine

The mineralogical composition of the total sample and by particle size confirms the presence of ferrous minerals such as goethite and hematite. However, quartz and calcite are the main gangue phases.

The results obtained after the calcination process for different particle size classes show a significant increase in iron content, followed by an increase in alumina and silica content. This confirms the significant results obtained by this pre-concentration via calcination.

High-intensity magnetic separation by the dry process produced a good-quality concentrate. The best result was obtained for the granulometric fraction (–0.5 + 0.125) at a temperature of 900 °C, where the iron content increased from 40 to 51.94 %.

As a result, the results of calcination followed by dry magnetic separation of low-grade iron ore from the EL Ouenza mining complex are encouraging, show significant valorization potential and produce a good quality concentrate that meets the requirements of the steel industry. However, further research on the sustainability of the process and the long-term environmental impact needs to be conducted for a successful industrial implementation.

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Оцінка можливості збагачення низькосортної залізної руди із шахти Ель Уенза методом високоінтенсивної магнітної сепарації

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Мета. Метою цієї роботи на першому етапі є визначення характеристик низькосортної залізної руди із шахти Ель Уенза. Потім, на другому етапі, йдеться про її збагачення за допомогою високоінтенсивної магнітної сепарації.

Методика. Характеризація репрезентативних зразків, відібраних із досліджуваної території, була проведена з використанням декількох методів, включаючи рентгенофлуоресцентну спектрометрію (РФС), рентгенівську дифракцію (РФА), растрову електронну мікроскопію в поєднанні з енергодисперсійною спектроскопією (РЕМ-ЕДС), термогравіметричний аналіз і диференціальну скануючу калориметрію (ТГА/ДСК), а також інфрачервону спектроскопію з перетворенням Фур'є (ІЧ-спектроскопію Фур'є). Процеси, що включають поєднання класифікації, прожарювання й високоінтенсивної сухої магнітної сепарації, були використані для збагачення низькосортної залізної руди до рівня, що відповідає вимогам металургійної промисловості.

Результати. Отримані результати показують, що залізна руда із шахти Ель Уенза складається в основному із залізистих мінералів, зокрема гематиту й гетиту, а також крем'янистої та вапняної породи. Результати обробки руди з метою збагачення дозволили нам досягти вмісту заліза 51,94 % для зразка, прожареного при 900 °С з використанням магнітного поля 2,3 Тл на фракції розміром (–0,5 + 0,125) мм.

Наукова новизна. Оригінальність роботи полягає в можливості використання комбінованих методів, прожарювання та магнітної сепарації, для збагачення низькосортної залізної руди із шахти Уенза.

Практична значимість. Це дослідження показує, що результати, отримані за допомогою прожарювання та магнітної сепарації, мають важливе значення. Ці методи дозволяють отримати концентрат із вмістом заліза 51,94 %, що приносить користь металургійній промисловості, усуваючи запаси низькосортної залізної руди, яка зберігаються поблизу місця видобутку, та зберігаючи навколишнє середовище.

Ключові слова: *шахта Ель Уенза, збагачення, обробка, магнітна сепарація, прожарювання, навколишнє середовище*

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