

Characterization of Sangan low-grade iron ore and its processing by dry low-intensity magnetic separation

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ABSTRACT

Nearly two million tons of low-grade iron ore has been extracted, deposited, and left intact in the Sangan mining site. On the other hand, the mining site is located in a semi-arid region, and wet processing has been restricted due to water shortage. In this research, the enrichment of Sangan low-grade iron ore from Mine B was performed using the dry low-intensity magnetic separation (DLIMS) technique to solve both problems of unprocessed low-grade iron ores and water scarcity. The X-Ray diffraction analysis showed that the ore minerals are magnetite and to less extent, hematite, and the main gangue minerals are quartz and calcite. The Fe, FeO, and sulfur contents of some collected samples were determined to be 36.86%, 8.1%, and 0.12%, respectively. The scanning electron microscopy equipped with energy dispersive X-ray analysis showed that the full liberation of the iron minerals is achieved in the particle size less than 30 μm . The Davis Tube tests in three different magnetic field intensities of 1420, 2340 and 3800 Gauss confirmed the good amenability of the low-grade iron ore to low-intensity magnetic separation. A concentrate of 47.15% Fe, with a yield of 68.56% was produced using DLIMS technique. The process development for the enrichment of the Sangan low-grade iron ore was conducted through the DLIMS approach, for which a flowsheet was proposed. The results showed that after two steps of DLIMS, it would be possible to produce a concentrate with iron grade more than 50%, which can be traded as high-grade iron ore or fed to the on-site processing plants.

Keywords : *Sangan mine, Low-grade iron ore, Characterization, Dry processing, Flowsheet*

1. Introduction

Steel is an essential alloy used by all countries, especially developing countries, for the development of infrastructures, road transport systems, and so forth. Iron ore is the primary material for the production of steel, and 98% of the extracted iron ore is used globally in steel-making [1]. The global reserve of iron ore in 2017 was near 170 billion tons, with an iron content of 83 billion tons [2]. The iron ore reserve of Iran is nearly 2.7 billion tons, which is 1.59 percent of the world's iron ore reserve [2]. The principal iron ore reserves of Iran are located in central (Choghart, Chadormalou, Chahgaz, Sechaohn, Saghand, Mishdivan), south-central (Gol Gohar) and north-eastern (Sangan) areas [3, 4].

The Sangan iron ore mine, with 1.2 billion tons of geological reserve, is one of the largest iron mines in Iran and the Middle East [5]. It consists of three western, central and eastern mining regions in an area of 22 \times 10 km². The largest reserves are located in the western region. This region consists of five iron ore deposits including A, Á, B, CN, and CS in an area of 2 \times 3 km². The extracted ore from mines A, B, and CN with Fe grade more than 50% is transported to the on-site processing plants to produce iron ore concentrate with Fe grade more than 65%. In these plants, the iron ore is first crushed and ground to particle sizes less than 100 μm . These particles are directed to the enrichment circuit, which consists of three or four consecutively wet low-intensity magnetic separation (WLIMS) steps.

Two concerns in the Sangan iron ore mine include the unprocessed low-grade iron ore and water scarcity. Currently, nearly two million tons of low-grade iron ore extracted from different mines has been deposited

and left untouched in the mining site. The processing of low-grade iron ores has received significant attention in recent years due to the increasing demand for steel and depleting high-grade iron ore deposits around the world [6]. The enrichment of low-grade iron ores is difficult due to the low iron content and mineralogical complexity [7-9]. The flotation and wet magnetic separation have been widely approved for the enrichment of low-grade iron ores [10-15]. The Sangan iron ore mine is located in an area where water is scarce and, understandably, local communities and authorities often oppose mines using groundwater aquifers [4]. Hence, dry separation methods are preferred over wet separation techniques. Tripathy et al. investigated the enrichment of a low-grade iron ore (Fe=35.9%, hematite nature, and particle size below 1 mm) by dry high-intensity magnetic separators. The maximum product grade of 53.1% Fe was achieved with a 19% yield as the magnetic product at optimum conditions of variables. Zhang et al. investigated the beneficiation of a low-grade hematite ore by dry high-intensity magnetic separation [16]. It was found that the drum rotation speed and the feed particle size have significant effects on the separation performance, and a concentrate of 36.22% Fe with 75.97% recovery is achievable from the ore assaying 29.14% Fe at a coarse particle size below 10 mm [16]. Liu et al. studied the enrichment of a low-grade titanomagnetite ore containing 18.52% Fe and 6.65% TiO₂ by dry and wet low-intensity magnetic separators [17]. The experiment resulted in an iron concentrate of 23.65% Fe at 73.88% recovery using the DLIMS technique [17].

In this research, the enrichment of the Sangan low-grade iron ore is investigated using the DLIMS technique, which aims to solve both problems of the unprocessed low-grade iron ore and water scarcity in the Sangan mining site.

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2. Material and Methods

2.1. Sampling and ore preparation

A low-grade iron ore samples was taken from the Sangan iron ore

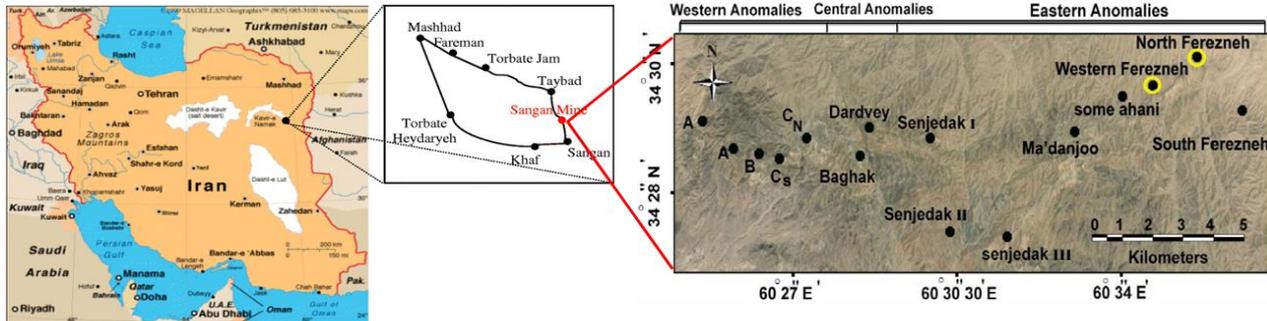


Fig. 1. The geographical location of the Sangan iron mine and its iron reserves [18].

. In the Sangan mine, the extracted iron ore is divided into two parts of high-grade and low-grade. The high-grade iron ore is transported to the on-site processing plants for the enrichment to produce an iron ore concentrate with an Fe grade more than 65%. The low-grade iron ore from mines A, B, CN, Baghak, Dardvay and Tape Ghermez is deposited

in the mining site separately. In this research, the low-grade iron ore was taken from the low-grade iron ore pile extracted from Mine B (Fig. 2). This is the most massive low-grade iron ore pile in the Sangan mining site with a tonnage of 523151, an iron grade of 34.74%, a sulfur grade of 0.07%, and an ore density of 3.62 g/cm³.



Fig. 2. A picture of the low-grade iron ore pile of Mine B with an iron grade of 34.74%.

Fig. 3 shows a schematic representation of the pile and the sampling network. As can be seen, the sampling procedure was conducted from the hillside of the pile. The sampling network consists of 12 profiles. Three sub-samples were taken from each profile, one from the top third, one from the middle third and one from the bottom third of the profile. Sampling was performed using a blade and a cylindrical vessel. Initially, the surface layer, which is probably weathered, was removed by the cylindrical vessel. Afterward, the blade was placed on the upstream slope to prevent the particles from collapse. Then, the sample was collected using the cylindrical vessel. The minimum sub-sample weight was determined based on the Gay's formula.

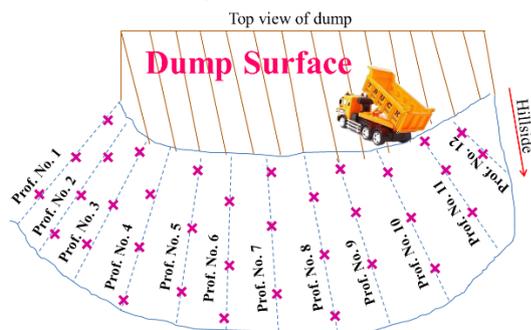


Fig. 3. Schematic representation of the low-grade iron ore dump of Mine B and the sampling grid.

The sub-samples were mixed and dried in an oven at 105°C for two days. The total weight of the sample before and after drying was 200 and 186.26 kg, respectively, indicating that the moisture content of the sample was 7.2%. After drying, the sample was crushed by two laboratory jaw crushers with a minimum throat of 25 mm and 10 mm, respectively. Sample homogenization was performed after crushing, and then, several sub-samples were prepared by riffle splitter.

2.2. Analysis methods

The mineralogical composition of the sample was determined by Philips-Xpert Pro X-ray diffraction (XRD) analyzer. Philips PW 1400 X-ray Fluorescence (XRF) analyzer was used for determining the chemical composition of the sample. The Fe and FeO contents of the sample were chemically determined by titration with potassium dichromate according to the ASTM E246 [19] and ASTM D3872 [20] standard test methods, respectively. The sulfur content of the sample was determined by Leco instrument. Different phases of the iron sample were determined through high-resolution imaging using scanning electron microscopy (LEO, 1450 UP, Zeiss; Oberkochen, Germany). The chemical composition of these phases was also determined by an Energy Dispersive X-ray (EDX) analyzer connected to it (INCA ENERGY 350 accessory).

Davis Tube tests were carried out by Eriez' Davis Tube Tester Model EDT. Davis Tube is a standard laboratory equipment used for the evaluation of the separability of magnetic ores by low-intensity magnetic

separators. It separates small amounts of strongly magnetic ores into strongly magnetic and weakly or non-magnetic fractions. Davis Tube consists of an inclined tube of 25 mm in diameter, placed between poles of an electromagnet. Material to be separated is passed through the tube; the magnetic field holds the strongly magnetic fraction while the weakly magnetic material is washed down the tube. The sample mass, water flow, and engine speed were constant for all tests, being equal to 10 g, 20 mL/S, and 4 m/s, respectively. At the end of the test, the magnetic fraction was dried, weighed, and the mass recovery was determined. The Davis Tube tests were conducted in three magnetic field intensities of 1420, 2340 and 3800 Gauss.

2.3. DLIMS tests

DLIMS was performed by a drum type magnetic separator of 30 cm long with a diameter of 20 cm, equipped with a vibrating feeder from Coal and Minerals Technology GmbH Co., Germany. The magnetic field intensity of the drum separator was determined to be 1389 Gauss by Japan's powerful KANETEC gauss meter TM-701. The sample weight was 5 kg. The speed of the feeder motor was kept constant at 60 rpm. The rotation speed of the drum was set at two different values of 30 and 60 rpm. Fig. 4 a and b show the feeding operation and the working status of the dry low-intensity magnetic separator, respectively.

2.4. Flowsheet development for enrichment of low-grade iron ore by DLIMS

At this step, the flowsheet development for the enrichment of Sangan low-grade iron ore sample was investigated using a low-intensity dry magnetic separator. Three sub-samples with a total weight of 11.740 kg were mixed, homogenized, and fed to the dry low-intensity magnetic separator. In the dry magnetic separation, both the drum rotation speed and the feeder vibration speed were set at 60 rpm. In order to increase the Fe grade of the concentrate, it was directed consecutively to the second and third magnetic separation steps. The concentrate of the third step of magnetic separation and the tailing of the first step of magnetic separation were ground using a laboratory ball mill under dry condition.

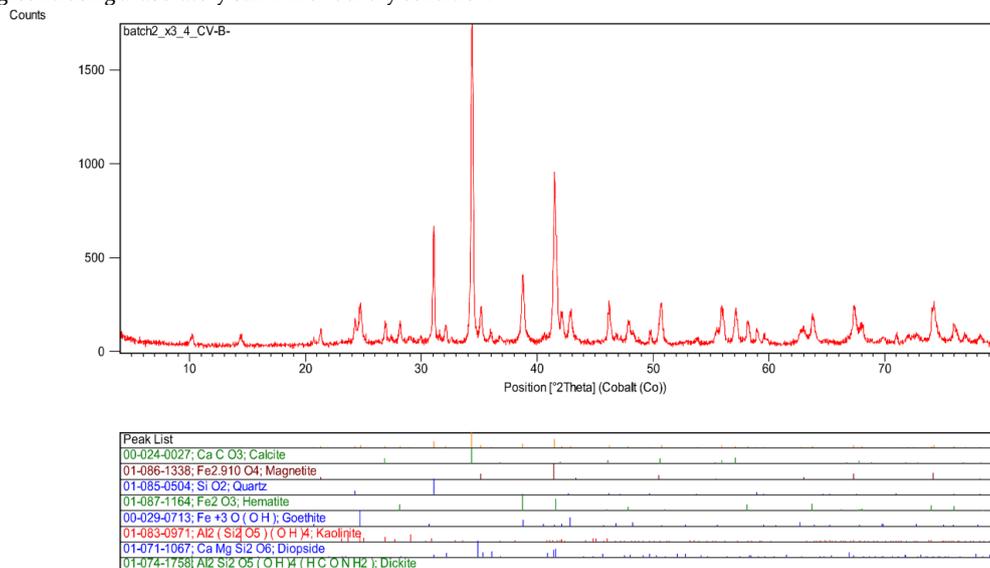


Fig. 5. XRD spectrum of the low-grade iron ore.

Table 1 shows the chemical composition of the sample using the XRF analysis. As seen, iron oxide (Fe_2O_3) grade is 52.23%, which is the dominant oxide phase in the sample. The other constituents of the sample are CaO 14.2%, SiO_2 13.6%, Al_2O_3 4.98%, K_2O 0.93%, MgO 0.66%, SO_3 0.4% and MnO 0.38%.

The total Fe content of the sample was determined to be 36.86%, indicating that the sample is in the range of low-grade iron ores. Furthermore, the FeO content of the sample was determined to be 8.1%. The sulfur content of the sample was determined to be 0.12%, which is

The grinding process was performed in a closed circuit with a 425 μm screen. Afterward, they were fed to the magnetic separator.



Fig. 4. a. Feeding operation, and b. Working status of the dry low-intensity magnetic separator.

3. Results and Discussion

3.1. Ore characterization

Fig. 5 shows the XRD spectrum of the low-grade iron ore sample. As seen, magnetite and to a lesser extent hematite are the ore minerals of the low-grade iron ore sample. There is also a small amount of goethite. The main peak for magnetite, hematite, and goethite is observed at 2θ equal to 41.8, 38.8, and 24.8, respectively. The dominant gangue minerals of the sample are calcite and quartz. The main peak of calcite and quartz is observed at 2θ equal to 34.5 and 31, respectively. Kaolinite, diopside, and dickite were detected in the XRD spectrum as minor gangue minerals.

below the standard limit of 0.2% for iron concentrates, and therefore, there is no need for desulfurization.

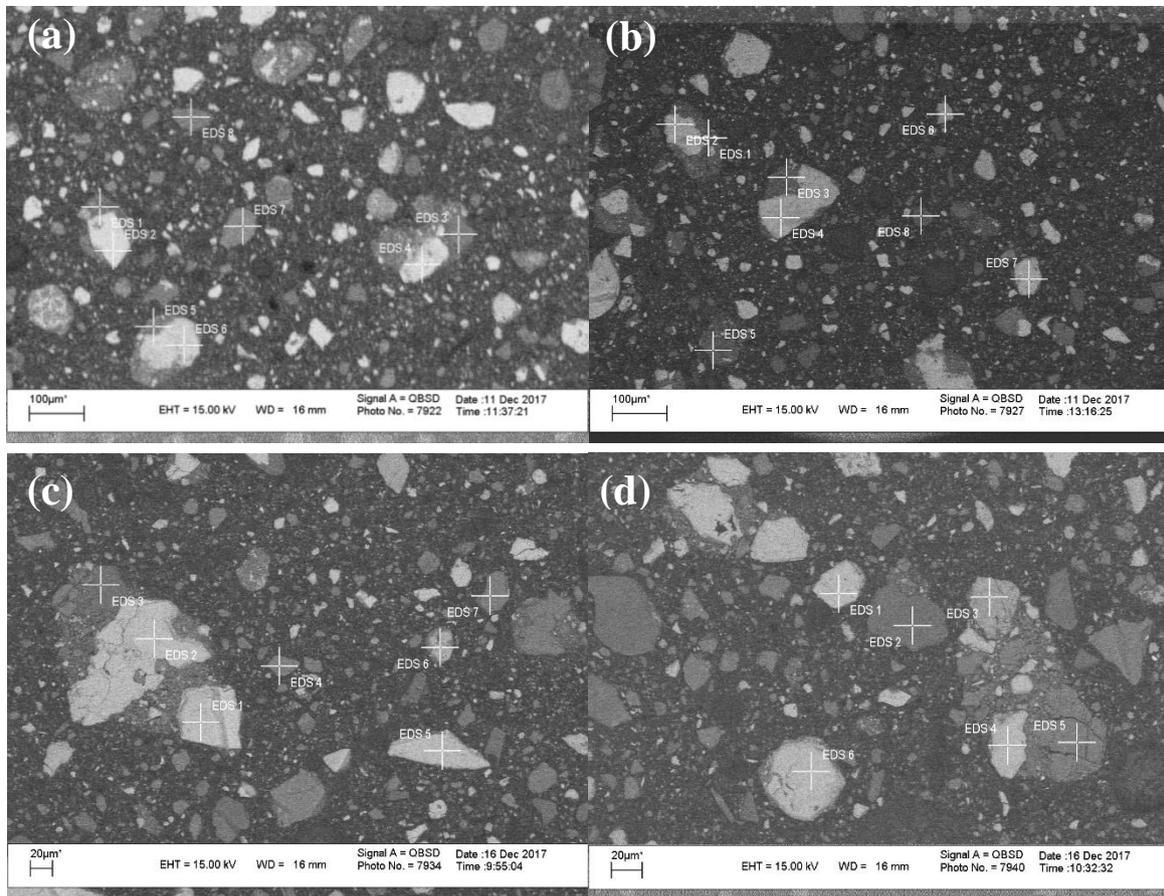
Table 1. Chemical composition of the sample determined by XRF method.

Oxides	SiO_2	Al_2O_3	CaO	MgO	TiO_2	Fe_2O_3	MnO	SO_3
%	13.6	4.98	14.2	0.66	<0.1	52.33	0.38	0.4
Oxides	P_2O_5	Na_2O	K_2O	As_2O_3	PbO	CuO	Cl	L.O.I.
%	<0.1	<0.1	0.93	<0.1	<0.1	<0.1	<0.1	12.42

In the SEM images in the backscattered electron (BSE) imaging mode, different phases are distinguished based on the difference in their density so that high-density phases appear with more brightness. Several SEM images of the low-grade iron ore sample from the Sangan iron ore mine are shown in Fig. 6. In these images, various phases with different brightness can be distinguished. According to the mineralogical composition of the sample and their corresponding density, it can be said that iron-bearing minerals are observed in the SEM images with more brightness. In order to validate this issue, an energy dispersive X-ray (EDS) analysis was performed on several points in the SEM images. The results are presented in Fig. 6. An EDS analysis is an analytical technique used for the elemental analysis or chemical characterization of a sample. It can detect the elements with an atomic number above the atomic number of Na. Hence, the oxygen element cannot appear in the EDS spectrum of a sample. As Fig. 6a shows, in points 2, 4, and 6, only the iron element was detected, which is related to the phases with more brightness. This is also observed in Fig. 6b (points 2, 4, 6, and 7), Fig. 6c (points 1, 2, 5, and 6) and Fig. 6d (points 1, 3, 4, and 6). Therefore, it can be concluded that iron ore minerals (hematite or magnetite) are observed with more brightness in the SEM images of the sample in the

BSE imaging mode. In these images, the phases with less brightness are related to the gangue minerals. In Fig. 6a (points 3, and 8), Fig. 6b (points 5, and 8), Fig. 6c (point 3), and Fig. 6d (point 4) only silicon was detected. Accordingly, the mineralogical phase of these points is quartz. In Fig. 6b (point 1), Fig. 6c (point 7), and Fig. 6d (point 5) only the Ca element was detected. Therefore, the mineralogical composition of these points is calcite.

The SEM images can be used to determine the liberation of iron minerals. As can be seen from Fig. 6, the liberation of iron minerals with particle size less than 30 μm is nearly complete. However, the iron minerals with particle size more than 80 μm are not fully liberated. It can be also observed that the iron minerals even with microscopic dimensions (less than 10 microns) are completely enclosed in gangue minerals. The presence of such minerals confirms the loss of recovery in the enrichment circuits. There are also some iron minerals to which the gangue minerals are attached from one direction. These iron minerals can participate in the magnetic part during the magnetic separation, which is the main reason for the loss of iron grade of the magnetic concentrate.



Element	A								B								C							A					
	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	1	2	3	4	5	6
Ca	*				*				*		*										*		*					*	
Si	*		*		*		*	*			*		*		*				*	*						*			
Fe	*	*		*	*	*				*	*	*		*	*	*	*		*	*	*			*		*	*	*	*
K								*												*									
Al								*												*									
Mg											*																		

Fig. 6. SEM images of the sample and the EDX analysis results.

Iron and sulfur grades and Fe/FeO ratio in various size fractions of the low-grade iron ore are shown in Fig. 7. As shown, the iron grade of various size fractions is approximately equal. This suggests that iron has been uniformly distributed in all size fractions. As can be seen, the sulfur grade in all size fractions is less than 0.2%, which is in the desirable range, and therefore, there is no need for desulfurization. The FeO grade is considered as a criterion for differentiating the hematite or magnetite nature of an iron ore so that the Fe/FeO ratio is less than 4, in the range of 4-7, and more than 7 for an iron ore with magnetite nature, magnetite-hematite nature, and hematite nature, respectively. As can be seen in Fig. 7, the Fe/FeO ratio is in the range of 4 to 7 for all size fractions. Therefore, iron in all size fractions of the low-grade iron ore has a magnetite-hematite nature.

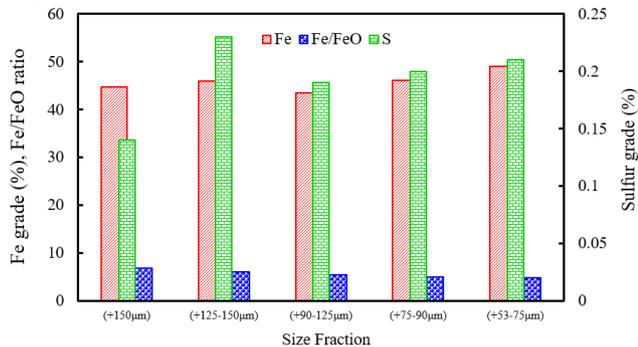


Fig. 7. Fe and Sulfur grade and Fe/FeO ratio in different size fractions of the low-grade iron ore.

The Davis tube test was performed on various size fractions at three different magnetic field intensities of 1420, 2340, and 3800 Gauss. The weight percent of the strongly magnetic fraction was determined in each test, and the results are presented in Fig. 8. As seen, the weight percent of the strongly magnetic fraction at various size fractions is in the range of 55-60%. Therefore, the low-grade iron ore is amenable to low-intensity magnetic separation even at large particle sizes. The weight percent of the strongly magnetic fraction in 53-75 µm size fraction is higher than that of the others. It may be due to a higher degree of freedom in smaller size fractions. Fig. 8 also shows that the increase of the magnetic field intensity from 1420 to 3800 Gauss has no significant effect on the weight percent of the strongly magnetic fraction in all size fractions. Therefore, the magnetic susceptibility of the low-grade iron ore is high. It further confirms the good amenability of the low-grade iron ore to low-intensity magnetic separation.

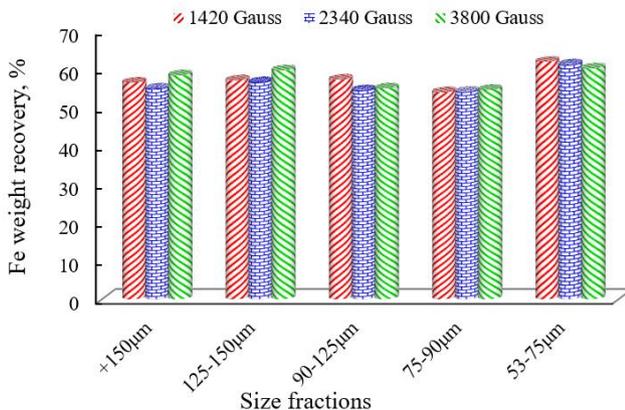


Fig. 8. The results of Davis Tube tests for various size fractions and at three different magnetic field intensities.

3.2. Magnetic upgrading

The results of dry magnetic separation tests showed that a concentrate with Fe grade of 45.2% and yield of 70.68% is attainable at drum rotation speed of 30 rpm. By increasing the drum rotation speed to 60 rpm, the Fe grade of concentrate increases to 47.15% and the yield

decreases to 68.56%.

3.3. Process development for dry processing of low-grade iron ore

The initial tests confirmed the ability of the DLIMS for enrichment of low-grade iron ore. On the other hand, water scarcity in the Sangan area is considered as an important issue. It was decided to develop a process for enrichment of low-grade iron ore by DLIMS method.

The particle size distribution curve of the low-grade iron ore after two stages of crushing with jaw crushers is shown in Fig. 9. As shown, the value of d_{80} for this sample is 2.4 mm. After homogenizing, 11,740 kg of the sample with $d_{80}=2.4$ mm was taken and fed to the dry low-intensity magnetic separator. The vibration feeder speed and the drum rotation speed were set at 60 rpm. The drum magnetic field intensity was determined to be 1389 Gauss. A concentrate of 46.7% Fe with a yield of 62.93% was produced. It was further enriched utilizing the low-intensity magnetic separator, and a concentrate of 47.59% Fe and a yield of 89.33% was obtained. The magnetic separation was repeated in the third step, and the Fe grade of concentrate increased from 47.59% to 48.42%, with a yield of 93.86%. These results indicate that the repetition of magnetic separation in the second and third steps had no significant effect on the increase of the iron grade of concentrate. In order to improve the iron grade of the concentrate, it was initially ground using a dry ball mill to a particle size less than 425 µm and then it was fed to the magnetic separator. A concentrate of 50.28% Fe with a yield of 89.13% was produced in this step. This concentrate can be considered as the final concentrate since its grade is in the range of high-grade iron ores. It can be traded as a high-grade iron ore or fed to the iron ore processing plants for further processing.

The yield of the first magnetic separation step was 62.93%. Therefore, it produced 4,352 kg tailing of 20.16% Fe. In order to increase the total iron recovery, it was decided to enrich the tailing of the first magnetic separation step. Hence, it was initially ground in a dry ball mill to particle sizes less than 425 µm and then it was fed to the magnetic separator. A concentrate of 38.58% Fe, with a yield of 8.31% was produced. The iron grade of this concentrate is near the iron grade of the initial low-grade iron ore. Therefore, it can be returned to the beginning of the circuit.

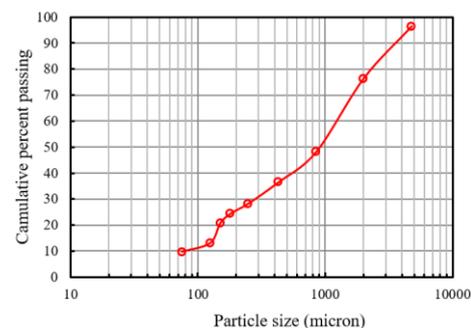


Fig. 9. The particle size distribution curve of the low-grade iron ore after two stages of crushing.

Based on the results, a flowsheet was proposed for the enrichment of the low-grade iron ore. The flowsheet is shown in Fig. 10. As seen, the low-grade iron ore (total Fe=36.86%) with a d_{80} value of 2.4 mm is fed to the first magnetic separation step. The magnetic separation was performed by a drum type dry low-intensity magnetic separator. The tailing of the first magnetic separation after dry milling in a closed circuit with a 425 µm screen is fed to the dry magnetic separator. The tailing of this magnetic separation step can be considered as the final tailing, and its concentrate can be returned to the beginning of the circuit. The concentrate of the first magnetic separation step after dry milling in closed circuit with a 425µm screen is fed to the second step magnetic separation. The concentrate of this magnetic separation step with iron grade more than 50% can be considered as the final concentrate. It can be traded as a high-grade iron ore or fed to the iron ore processing plant for producing an iron concentrate with iron grade more than 65%.

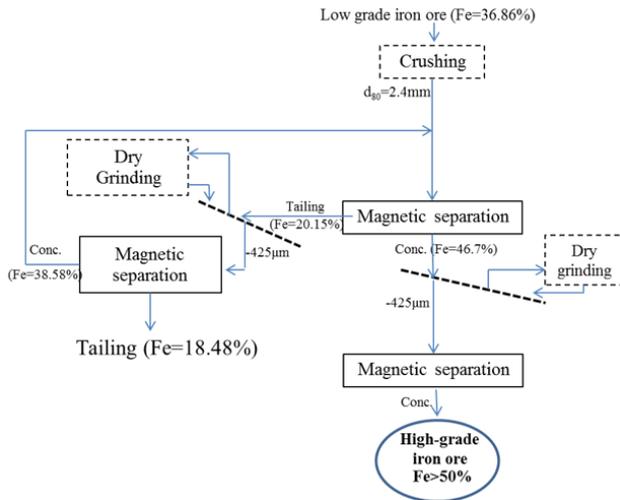


Fig. 10. The suggested flowsheet for the enrichment of the low-grade iron ore using the DLIMS technique.

4. Conclusion

The chemical composition of the low-grade iron ore in the Sangan iron mine using the XRF analysis showed that the sample contained 52.33% Fe_2O_3 , 14.2% CaO , 13.6% SiO_2 , and 4.98% Al_2O_3 . Also, the total Fe and FeO content of the sample were determined to be 36.86% and 1.8%, respectively. The Fe/FeO ratio of the sample was 4.55, indicating a magnetite nature for the sample. The sulfur content of the sample was determined to be 0.12%, which was below the standard limit of 0.2%, and therefore, there was no need for desulfurization. The mineralogical composition of the sample was determined using XRD analysis, which showed that the primary ore minerals of the sample were magnetite and hematite, and the main gangue minerals of the sample were calcite and quartz. Also, the sample contained kaolinite, diopside, and dickite as minor gangue minerals. The SEM-EDS analysis showed that the iron minerals were fully liberated in the particle size less than 30 μm . The liberation degree of iron minerals decreased at particle sizes larger than 30 μm . This suggested that the maximum iron grade of DLIMS concentrate would be lower than that of the WLIMS concentrate since the particle size of DLIMS feed was larger than that of the WLIMS (smaller than 10 mm versus smaller than 100 μm). The weight percent of the strongly magnetic fraction of Davis tube test was more than 50% at a magnetic field intensity of 1420 Gauss and increasing the magnetic intensity to 3800 Gauss had no significant effect on it. Therefore, the amenability of the low-grade iron ore to LIMS was good. The grade of Fe and FeO and the weight percent of strongly magnetic fraction of Davis tube test in various size fractions were nearly equal, suggesting the excellent amenability of the low-grade iron ore to DLIMS. The initial tests showed that the concentrate with the Fe grade of 47.15% and weight recovery of 68.56% could be produced by DLIMS from the low-grade iron ore at the particle size less than 4.75 mm. A flowsheet was proposed for the DLIMS of the low-grade iron ore, based on which the low-grade iron ore with particle size smaller than 4.75 mm would enter the first DLIMS step. Its concentrate, after grinding to a particle size of smaller than 425 μm , was fed to the second DLIMS step. The concentrate of the second DLIMS step can be considered as the final concentrate with an iron grade more than 50%, which can be traded as a high-grade iron ore or fed to the on-site processing plants.

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