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ENRICHMENT OF LOW-GRADE MAGNETITE ORE BY MAGNETIC AND GRAVITY SEPARATIONS: EFFECT OF PARTICLE SIZE

DÜŞÜK TENÖRLÜ MANYETİT CEVHERİNİN MANYETİK AYIRMA VE YERÇEKİMİ İLE ZENGİNLEŞTİRİLMESİ: TANE BOYU ETKİSİ

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ABSTRACT

This study compares the efficiency of different methods in beneficiation of iron ore from Doğanşehir (Malatya) region. It is a low-grade ore containing 27.43 % Fe which requires concentration to meet the specifications of blast furnace feeds. The main mineral composition of ore is magnetite and also contains magnesioferrite, ferro-actinolite and calcite minerals. The collected samples were classified into different size fractions after size reduction and then subjected to different gravimetric and magnetic separation methods for concentration. The results showed that particle sizes affected the concentrations to a large extent and generally cleaner concentrates were obtained at finer sizes for a certain separation method. On the other hand, wet magnetic separation yielded comparably better results than gravimetric methods. A concentrate assaying 65.66 % Fe and 0.38 % K_2O+Na_2O was obtained with 78.11 % recovery by wet magnetic separation. It was concluded that concentrates meeting blast furnace specifications could be obtained from this low-grade iron ore. It was also concluded that the proposed separation flow sheet can be applied to similar low-grade iron ores in the region.

Anahtar Sözcükler:
Demir cevherleri,
Manyetit,
Manyetik ayırma,
Yerçekimi ile zenginleştirme,
Aşındırmalı yıkama.

ÖZ

Bu çalişmada Doğanşehir (Malatya) bölgesinden elde edilen demir cevherlerinin farklı yöntemlerle zenginleştirilmesini araştırmaktadır. Düşük tenörlü cevher % 27,43 Fe tenörüne sahip olup yüksek fırın beslemesi özelliklerini sağlaması için zenginleştirilmesi gerekir. Cevher içerisinde başlıca manyetit, ferro-aktinolit ve magneziyoferrit bulunmaktadır. Boyut küçültmeden sonra cevher farklı tane boylarına sınıflandırılmış ve sonra değişik yerçekimi ve manyetik ayırma testleri uygulanmıştır. Sonuçlar tane boyunun zenginleştirme sonuçlarını çok etkilediğini ancak manyetik ayırma testlerinin yerçekimi zenginleştirme testlerinden daha iyi sonuçlar verdiğini göstermiştir. Yaş manyetik ayırma yöntemi ile % 65,66 Fe ve % 0,38 K2O+Na2O içeren konsantre % 78,11 verimle elde edilmiştir. Sonuçlar düşük tenörlü cevherden yüksek fırın besleme şartlarını sağlayan konsantre elde edilebileceğini göstermiştir. Sonuçlardan önerilen zenginleştirme akış şemasının bölgedeki benzer cevherlere uygulanabileceği anlaşılmıştır.

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INTRODUCTION

World crude steel production grows continuously and increased to 1.808 billion tons in 2018. Demand for iron ore in iron and steel industry also increases and production increased to 2.167 billion tons in 2017 (Worldsteel Association, 2019). Turkey is among the top 10 crude steel producing countries in the world and produced 37.3 million tons crude steel in 2018. Industries (e.g., construction, transport and machinery) in the country are steel-dependent and used 30.6 million tons of steel products in 2018. On the other hand, Turkey produced only 6.2 and imported 10.9 million tons of iron ore in 2017 to meet the demand of iron and steel industry (Worldsteel Association, 2019). Due to low iron ore production and dependence on imports, steel production did not change significantly in recent years. The extraction and processing of iron ores are important to sustain steel production and economic growth. The iron ore deposits in Turkey are mainly low-grade and require processing to meet the specifications of iron and steel industry. The required specifications of iron ore pellets to be used as blast furnace feed is given in Table 1 (Sivrikaya and Arol, 2012).

The main difficulty in beneficiation of low-grade iron ores mainly results from their complex structure as they contain considerable amount and type of gangue minerals (e.g., gibbsite and kaolinite as aluminum sources) and their soft nature (Seifelnassr et al., 2012). Therefore, their concentration requires additional processes, (e.g., washing, desliming and fine grinding) as shown in Figure 1 (Yalçın and Ateşok, 1979). Presence of soft materials in the ore causes generation of fines during handling and can lead to slime coating on valuable minerals. Washing and desliming before concentration process may be required in such cases, which may cause valuable mineral loss. Liberation of the particles is one of the main parameters affecting separation efficiency and is mainly achieved at very fine sizes for low-grade ores (Seifelnassr et al., 2012). But, concentration of very fine particles, in turn, may result in inefficiency for most separation techniques and the obtained fine concentrates need pelletizing before being charged into blast furnace. Magnetic separation is mainly used for concentrating iron bearing ores by taking the advantage of distinctive magnetic response of minerals to magnetic fields (Sivrikaya and Arol, 2012). It is very efficient method for achieving high recovery but some problems may arise in obtaining clean concentrates from certain ore types (e.g., karstic and lateritic iron ore deposits). High-intensity magnetic separators are efficient in concentration of paramagnetic minerals (e.g., hematite, goethite, and limonite), on the other hand low-intensity magnetic separators are used

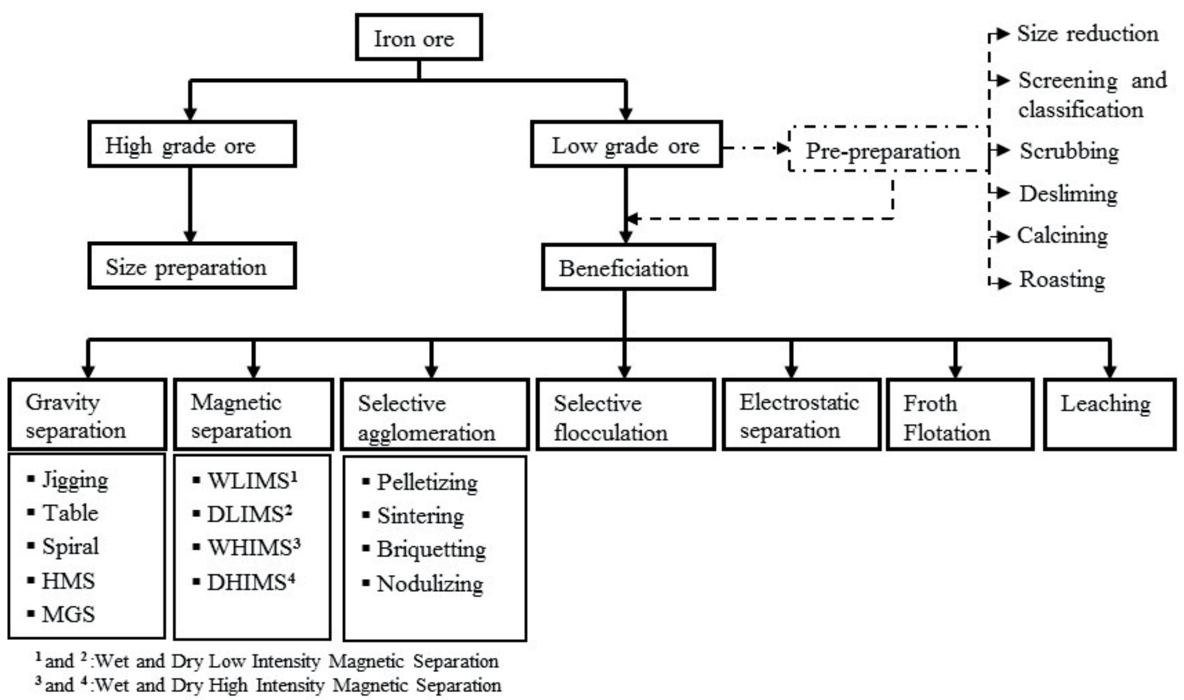

Figure 1. Beneficiation methods of high and low-grade iron ores (modified from Yalçın and Ateşok, 1979)

to separate ferromagnetic minerals from weakly or non-magnetic minerals (Özcan and Çelik, 2016). Froth flotation method is advantageous over other separation methods at very fine sizes. It is applied as the primary beneficiation method for non-magnetic iron ores and also used for upgrading fine size magnetic iron concentrate (Zhang et al., 2019).

Gravity separation is widely used in mineral beneficiation practices for its low-cost, ease of operation and control, and eco-friendly nature (Seifelnassr et al., 2012; Akbari et al., 2018; He et al., 2019). Conventional gravity separation methods (e.g., jigging, spirals and shaking tables) find wide application in the processing of iron ores, but their major limitation is the treatment of fine size particles. In fine size ranges, viscous forces dominate gravity forces and in turn affect the separation efficiency. However some gravity separators (e.g., Knelson, Falcon, Kelsey jig and Multi-gravity separators) generate higher gravity force by employing centrifugation and are capable of concentrating fine particles (He et al., 2019). Specific gravity, size and shape of particles affect the gravity separation and efficiency of the separation increases with increasing differences in these factors.

This study describes beneficiation of a low-grade iron ore by various gravimetric and magnetic separation methods carried out at various particle sizes. The experimental results obtained from different methods were compared in terms of recovery, grade (% Fe) and the impurities associated with concentrates.

1. MATERIALS AND METHODS

1.1. Materials

The iron ore deposit is located at Beğre region of Doğanşehir town on the southwest of Malatya city (Turkey). About 250 kg of sample was representatively collected from the fresh seams of ore. The sample was crushed below 3 cm with a jaw crusher and classified with 2.36 mm standard laboratory sieve. The coarser fraction was further crushed again by a hammer crusher combined with screen of 2.3 mm opening. All crushed fractions were combined and blended well to ensure homogeneity. Using a riffle splitter, the homogenous sample was then split into six parts (fractions) as needed for each separation method. Each fraction was later ground to the desired fineness (sizes) in ball mill to use in separation tests. The classified and weighted samples were kept in sealed plastic bags until testing. Sizing was made dry by utilizing ASTM standard laboratory sieves and using a sieve shaker.

1.2. Methods

1.2.1. Characterization and Analysis

The iron content of the samples (raw materials and products) was determined by wet chemical method described by Harris (2010). The analysis was repeated three times for each sample and the average was presented as final value. The impurities in the raw ore and concentrates were determined by ICP-MS instrument in ACME-Labs (Bureau Veritas Minerals, Vancouver Office in Canada). The results, given in Table 1, showed that the raw ore contains 27.43 % Fe. It also includes high amount of siliceous materials (30.23 %SiO_2) and alkaline materials (e.g., Na_2O and K_2O), but low amount of aluminous materials (% 1.85 Al_2O_3).The mineralogical analysis was made by XRD instrument (Rigaku Geigerflex D-Max/B, Japan). XRD results indicated that the major component of raw ore is magnetite with some magnesioferrite, ferro-actinolite and calcite minerals (Figure 2). The highest intensity peaks of these minerals showed up at 2θ values of about 35.5, 35.5, 10.3 and 29.4, respectively.

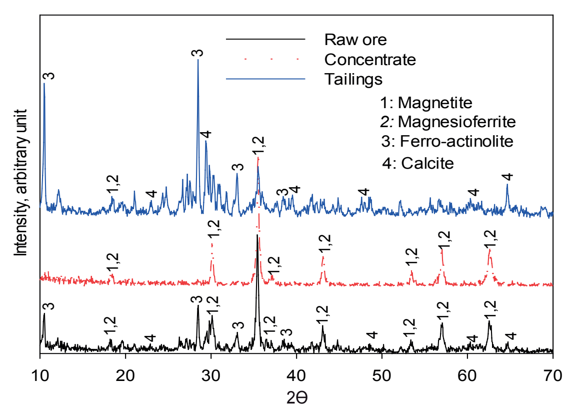

Figure 2. XRD analysis of raw iron ore and separation products

1.2.2. Separation (Concentration) Tests

Beneficiation of extracted iron ore for steel industry consists mainly of size reduction, classification and concentration in sequence.

Table 1. Chemical analysis of raw iron ore and required specifications

Material	Fe, %	SiO_2 % ø	MgO % ø	CaO % ø	Al_2O_3 % ø	Na_2O % ø	K_2O % ø	TiO_2 % ø	MnO % ø
Raw ore	27.43	30.23	13.01	10.85	1.85	1.32	0.12	0.11	0.07
Requirement*	>65.50	<6.00	<1.50	<3.00	<1.00	<0.05	<0.05	<0.05	<3.87

* Required by Iskenderun Iron and Stell Co. (ISDEMIR) for iron ore pellets (Sivrikaya and Arol, 2012)

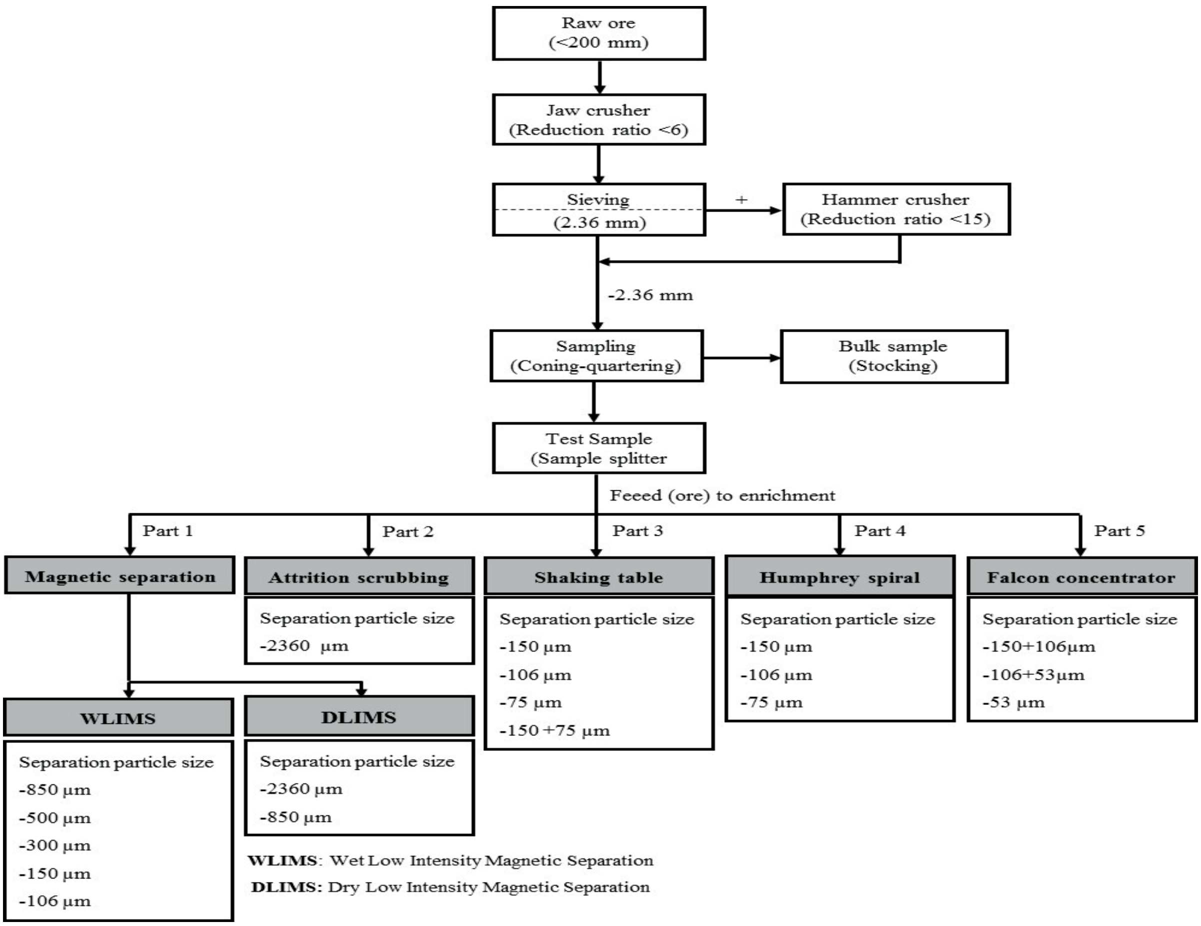

Figure 3. Flow sheet for sample preparation and applied separation methods

The classified samples were then subjected to concentration tests by magnetic separators (dry and wet), Falcon concentrator, shaking table and Humphrey spiral as explained in Figure 3. The best operating conditions of each equipment were determined by trial test and presented in Table 2. The variables, such as, rotating speed and solids % by weight were kept constant for the tests. Each separation test was repeated at least two times to ensure reproducibility, but only average result was presented for the sake of brevity.

In order to reduce the size effect in gravity separation, a closely sized feed was prepared and tested in most methods. Knowing that gravity separators are extremely sensitive to the presence of slimes (especially fine aluminous and siliceous materials), the effect of desliming was also investigated. The feed and products from the tests were dried at 60 °C in an oven and the dry weights were used to calculate recovery (R) by using Equation 1. In the equation, F and C represent dry weights of feed and concentrate whereas f and c represent Fe grades of feed and concentrate, respectively.

$$R = \frac{Cxc}{Fxf} x100 \quad (1)$$

Table 2. Operational conditions for separation tests

Equipment	Model	Operational conditions
Shaking table	Wilfley Mining Machinery	Slope (tilt angle): 8°
		Motor speed: 110 rev/min
		Stroke length: ~15 mm
Humphrey spiral	Denver	Solids by weight: 15%
		Splitting angle: 20°
Falcon concentrator	Sepro Mineral Systems	G Forces: 20G, 30G, 40G and 60G
Low-intensity dry magnetic separator	Boxmag Rapid	Drum rotational speed: 36 rev/min
		~3.0 kg solids (each test)
Low-intensity wet magnetic separator	Boxmag Rapid	Drum rotational speed: 24 rev/min
		~3.0 kg solids (each test)
		Solids by weight: 10%
Scrubbing and de-sliming	Modified Denver flotation machine (in 2 dm^3 cell with baffle)	Solids by weight: 70%
		Mixing speed: 1100 rev/min
		Duration: 15, 30, 60 and 120 min

2. RESULTS AND DISCUSSIONS

2.1. Gravity Separations Results

Humphrey spiral, Wilfley shaking table and Falcon concentrator were used as gravity separators. Two-stage separation processing was applied by re-cleaning spiral rougher concentrate to obtain clean concentrate. Three different feed sizes of -150, -106 and -75 μm were tested and the results are presented in Table 3. The recovery decreased from 67.45 to 56.01 % with decreasing particle size from -150 to -75 μm, but the grade increased in reverse order from 41.37 to 49.93 % Fe. The liberation of particles with decreasing feed size increased and yielded cleaner concentrates, but no satisfactory results were obtained in terms of recovery and grade. As seen from the table, 30.23 % SiO_2 and 1.85 % Al_2O_3 contents in the feed could not be reduced below 14.01 and 0.69 % in the concentrate, respectively. In literature, different findings were achieved in the concentration investigations of iron ores by various methods. Akbari et al. (2018) compared beneficiation methods of iron ores (mostly hematite) and found that spiral separation yielded higher separation efficiency than other methods, including magnetic separation. In their study, combination of spiral and multi-gravity methods gave a clean concentrate with 58.7 % Fe at 55.6 % recovery. It is considered that separation results are mainly affected by the origin and type (e.g., hematite versus magnetite) of ore.

Shaking tables make separation based on weight and size of particles by asymmetric reciprocating motion. The concentration tests were carried out at four different particle sizes of -150 μm, -106 μm, -75 μm and -150+75 μm. The feed material was first conditioned at 20 % solids by weight in a vessel and fed homogenously as slurry to the table together with wash water. Since the amount of middlings was very small in the table, only two products (i.e., cleaner concentrate and tailings) were obtained from each test as illustrated in Figure 4. Cleaning of rougher concentrates and scavenging of rougher tailings were performed to obtain cleaner concentrate with high recovery. The results presented in Table 3 showed that the highest recovery (82.72 %) was obtained with sized feed of -150+75 μm but with a relatively lower grade (55.03 % Fe).

Table 3. Recovery and chemical analysis separation concentrates

Feed size, μm	Recovery Fe, %	Fe, Fe, %	SiO_2, Fe, %	MgO, Fe, %	CaO, Fe, %	Al_2O_3, Fe, %	Na_2O, Fe, %	K_2O, Fe, %	TiO_2, Fe, %	MnO, Fe, %
Spiral separation										
-150	67.45	41.37	14.01	8.73	7.52	2.30	0.78	0.14	0.11	0.08
-106	65.98	46.72	13.00	7.56	6.65	1.32	0.79	0.18	-	-
-75	56.01	49.93	14.84	5.80	5.20	0.69	0.36	0.04	0.13	0.12
Shaking table										
-150	75.22	57.75	6.09	3.31	3.08	1.13	0.38	0.053	0.11	0.08
-106	60.77	56.56	7.08	3.43	2.90	0.32	0.26	0.025	0.11	0.08
-75	67.84	58.08	7.53	4.09	3.68	1.00	0.79	0.019	-	-
-150+75	82.72	55.03	8.49	3.99	3.19	0.42	0.24	0.023	0.11	0.08
Falcon concentrator (separation at 20 G)										
-150+106	67.43	49.16	20.96	8.98	7.38	1.19	0.15	0.05	0.11	0.08
-106+53	53.97	48.78	13,78	8,46	7,14	1,53	0,83	0,19	-	-
-53	40.09	49.43	17.37	6.89	6.69	0.77	0.06	0.04	0.13	0.12
Dry magnetic separation										
-2360	85.55	45.95	17.32	9.30	5.44	0.82	0.15	0.03	0.09	0.07
-850	83.30	47.69	15.16	8.25	4.72	0.77	0.13	0.02	0.09	0.07
Dry magnetic separation followed by wet magnetic separation										
-2360	77.17	59.25	7.76	5.64	2.69	0.87	0.73	0.02	-	-
-850	79.01	61.15	7.16	5.06	2.39	0.83	0.67	0.02	-	-
Wet magnetic separation										
-850	77.38	55.33	9.16	5.66	2.54	0.40	0.09	0.02	0.10	0.07
-500	79.83	60.39	7.36	4.74	1.94	0.33	0.06	0.01	0.10	0.07
-300	76.68	61.59	6.16	4.05	1.68	0.30	0.05	0.01	0.11	0.07
-150	78.11	65.66	3.40	2.43	0.98	0.26	0.02	0.01	0.10	0.07
-106	78.36	64.96	3.56	2.54	0.97	0.25	0.02	0.01	0.11	0.07

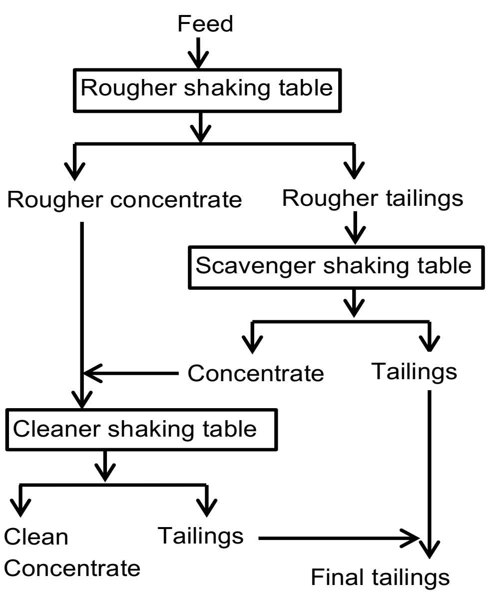

Figure 4. Schematic representation of concentration by shaking table

Obtaining cleaner concentrates with finer sizes must result from further liberation with size reduction. Generally, better results in terms of grade and recovery, were achieved by shaking table than spiral separation at the same feed sizes. Still, concentrates meeting blast furnace specifications could not be achieved by shaking table alone as the Fe grades remained below 58.08 % (Sivrikaya and Arol, 2012). Seifelnassr et al. (2012) studied concentration of low-grade hematite ore by shaking table and high-intensity wet magnetic separators. They obtained best results by using shaking table followed by magnetic separator. They exhibited that the concentrate grade could not be increased above 44.9 % Fe by shaking table alone, but table concentrates could be upgraded up to 65.5 % Fe with 69.0 % overall recovery by magnetic separation.

Falcon concentrator enhances gravity by employing centrifugal field. Increased gravity dominates over drag, frictional and buoyancy forces and hence accelerates sedimentation of particles which causes differential settling of particles that lead to separation (or concentration). They are usually used in the separation of fine particles. The feed materials were prepared at three different size ranges of -150+106 μm, -106+53 μm and -53 μm. A 150 g of sample was used for each test and the tests were carried out at four different gravitational forces of 20 G, 30 G, 40 G and 60 G. Preliminary tests showed that almost all of the feed material reported to concentrate at gravitations above 60 G. The obtained recovery and grade results given in Table 3 indicates a decreasing grade with increasing recovery which increased with particle size and centrifugal gravitation. Similar results were obtained by authors who worked on concentration of iron ores utilizing Falcon concentrator (Vapur et al., 2020; Nayak and Pal, 2013). The increased concentrate grade with decreasing size was obviously due to further liberation of particles. On the other hand, the increased recovery with particle size can be attributed to more acceleration of heavier particles than lighter particles at fixed gravitation. The cleanest concentrate with 49.43 % Fe was obtained with 67.43 % recovery for -53 m material at 20 G conditions (Table 3). The grades of other concentrates remained fairly below 50 % Fe, hence no impurity analysis was carried out on them.

2.2. Low-intensity Magnetic (dry and wet) Separation

Magnetic separators concentrate ores by separating minerals having different susceptibilities in magnetic field. Ferromagnetic minerals (e.g., magnetite) and paramagnetic minerals (e.g., hematite) are widely treated by low and high-intensity magnetic separators, respectively (Sivrikaya and Arol, 2012). Different size fractions were separated by drum type dry and wet magnetic separators. Approximately 3.0 kg of dry solids was used for each test and the rougher concentrates were subjected to cleaning stage under the same conditions to obtain clean concentrates. Dry magnetic separation was applied to relatively larger sizes than wet magnetic separation as explained in Figure 3. The position of the splitters of dry separator was adjusted and fixed to obtain only two products (i.e., concentrate and tailings). Rotational drum speed of the dry separator was kept low to avoid centrifugation and slip over of particles (especially large particles) from the drum surface (Seifelnassr et al., 2012).

As seen from Table 3, clean concentrates could not be obtained by dry magnetic separation. The recoveries were 85.55 and 83.30 % for -2360 and -850 μm sizes, respectively, with corresponding 45.95 and 47.69 % Fe grades. Only slight differences were observed in the recovery and grade of the concentrates despite the large difference in the feed sizes. The concentrate grades were far from meeting blast furnace feed specifications, thus the concentrates were additionally subjected to one stage wet magnetic separation. As seen from Table 3, the concentrate grades instantly increased to 59.25 and 61.15 % Fe for -2360 and -850 μm sizes, respectively, but the overall recoveries decreased to 77.17 and 79.01 %. Significant increase in grade and slight decrease in recovery showed the requirement of wet magnetic separation even for large sizes.

The wet magnetic separation tests were carried out on relatively finer size (-850, -500, -300, -150 and -106 μm) materials. As seen from Table 3, the cleanest concentrates (up to 65.66 % Fe) were obtained by wet magnetic separation with high recoveries (> 76 %). The amount of Al2O3, SiO2 and alkali (Na_2O+K_2O) content of concentrates was as low as 3.56, 0.26 and 0.11 %, respectively. The worst result was obtained at the largest particle size of -850 μm. A general increase in the grade and slight variations in recovery was seen with decreasing particle size. When the separation methods were compared (Table 3), it is seen that at fixed recoveries cleaner concentrates was obtained by wet magnetic separation. The separation result exhibits the necessity of liberation of particles by fine grinding (Sivrikaya and Arol, 2012) as well as utilization of wet magnetic separation for efficient concentration of low-grade magnetite type iron ores.

The effect of size and fine particles on separation was further investigated by scrubbing of feed material and then removal of fine material before wet magnetic separation. As illustrated in Figure 5, the -2360 μm samples were first subjected to scrubbing for various times (15, 30, 60, 120 min.) and then -75 μm size was removed as fine material. The results plotted in Figure 6 showed that after removal of fines, feed and concentrate grades increased from 30.96 to 36.95 % Fe and from 52.78 to 55.47 %, respectively, with increasing scrubbing time. The recovery did not change notably with scrubbing time as remained around 80 %.

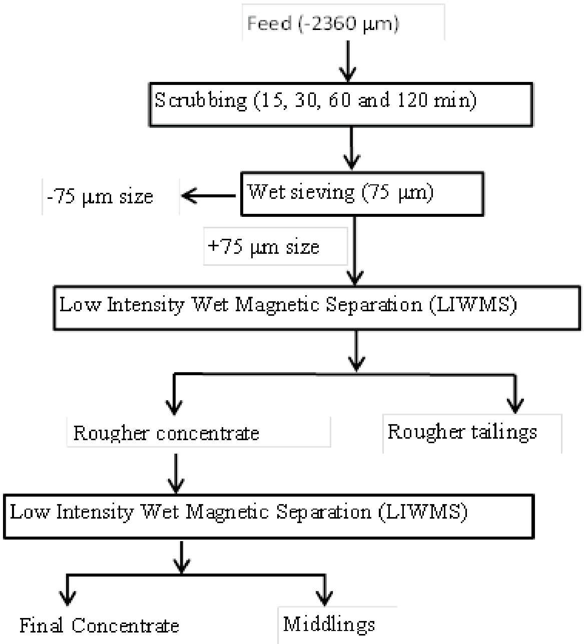

Figure 5. Concentration flow sheet by wet magnetic separation following scrubbing and desliming.

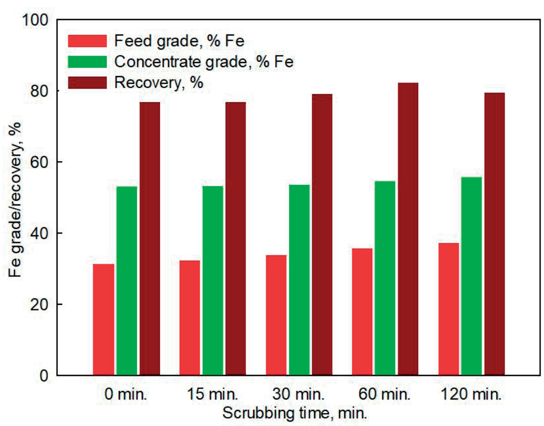

Figure 6. Effect of scrubbing time and desliming on feed grade and wet magnetic separation

It is seen that simple scrubbing and removal of fines (desliming) could not increase the grade satisfactorily as similar results were obtained in the separation of -850 µm size feed by the same method. But, when compared to finer sizes discernibly lower grades were obtained at certain recoveries. When the size reduction at long scrubbing times was taken into account, the results can be explained by additional liberation of particles rather than deleterious effect of fine sizes. It can be concluded that liberation is more important than the presence of fine materials in low-intensity wet magnetic separation. The reason is attributed to presence of low amount of aluminous minerals in the ore that can cause severe slime problems. Concentrates containing significantly low amount of alkali (i.e., Na_2O, K_2O) could be obtained by wet magnetic separation alone.

CONCLUSION

Beneficiation of low-grade iron ore from Doğanşehir (Malatya, Turkey) region was studied by utilizing gravimetric and magnetic separation methods. The ore containing mainly magnetite as valuable mineral was classified into different size fractions for concentration and the results were compared in terms of iron grade and recovery. The following conclusions were drawn from the tests;

1. Separation tests carried out for various sizes showed that the results depended largely on particle size, and hence liberation of particles, as cleaner concentrates was generally obtained at finer sizes.

2. Wet magnetic separation yielded much cleaner concentrates than dry magnetic separation and gravimetric methods at fixed recoveries. The presence of fine size particles did not cause slime problem in the low-intensity wet magnetic separation.

3. The concentrates from wet magnetic separation generally meet blast furnace feed specifications. A concentrate assaying 65.66 % Fe, 3.40 % SiO_2, 0.26 % Al_2O_3 and 0.38 % K_2O+Na_2O was obtained with 78.11 % recovery by wet magnetic separation.

4. The suggested wet magnetic separation flow sheet can be applied to similar low-grade iron ores in the region.

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