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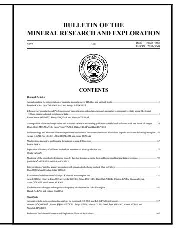

Separation efficiency of different methods in treatment of a low-grade iron ore

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Research Article

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ABSTRACT

In the present study, characterization and beneficiation tests were performed on an iron ore sample for the evaluation of separation efficiency (SE) of different methods. Results showed that the decrease in feed size fraction increases the SE irrespective of to beneficiation method. It was determined from the liberation analyses that the increase in SE values at finer size fractions is related with higher liberation. Calculated SE values revealed that operational parameters significantly affect the SE of all methods and the net forces acting on particles play an important role on SE of different size fractions. Mean SE of different size fractions showed that the separation efficiencies of gravity concentration and magnetic separation takes similar values above 1 mm, however, SE of magnetic separation is significantly higher than gravity concentration below 1 mm for the studied sample. For low grade ores, it is very crucial to develop a flow sheet to achieve the optimum grade and recovery while decreasing the cost likely by using optimum method. Therefore, SE calculations used in this research can be used as a basic method to compare the efficiency of different beneficiation methods. SE method has advantages as they provide fast evaluation of efficiency by using experimental results.

1. Introduction

The most important aim of different separation methods in minerals engineering has always been concentrating valuable minerals from gangue by using different properties of minerals. Separation methods produce different quality and quantity products (Drzymala, 2007). The quality of a concentrate or tailing is defined by the term grade. It can be defined as the valuable material in the final concentration. The recovery represents the ratio of concentration in weight of the total mineral or metal in an ore (Irannajad et al., 2018).

The grade and recovery are the most used performance evaluation parameters in beneficiation processes (Wills and Napier-Munn, 2006). To date, lots of parameters have been used by different researchers. Some of these parameters have been reported in the literature (Drzymala, 2006, 2007, 2008). Irannajad compared different indices and proposed a new approach in separation process evaluation. Authors reported that separation efficiency (SE), operation efficiency (OE) and selectivity index (SI) are the optimum parameter for assessment of mineral beneficiation methods (Irannajad et al., 2018). In addition, Mukherjee proposed an alternative method to SE evaluation of gravity concentration without the impact of feed properties (Mukherjee, 2009).

In iron ore beneficiation, efficiency determination of any concentration method is far more difficult, as heavy liquid tests for the materials are not possible

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due to higher specific gravities of the particles (Mukherjee, 2009). However, production of sinter/pellet grade concentrates by developing suitable and low cost flowsheets is crucial (Özcan et al., 2021). The gangue and iron ore minerals have significant differences in magnetic susceptibility and density. As a result, gravity concentration and magnetic separation are possibly the two most effective methods in concentration of iron ores. However, the finer particle size distributions of the valuable and gangue minerals and their insufficient liberation are the main limitations that prevents its effective concentration at coarser size fractions (Makhija et al., 2013).

Different methods can be applied to iron ore concentrations. These methods can be listed as, gravity and centrifugal concentration, froth flotation, low and high intensity magnetic separation. Magnetic separation is the most effective between these methods. Froth flotation has higher selectivity, but magnetic separation has lower operational cost than froth flotation. Gravity concentration has also the potential of lower operational costs, but it can be performed in smaller scale than magnetic separation (Xiong et al., 2015). There have been some significant results published about the effectiveness of gravity and magnetic concentration techniques for the beneficiation of low-grade iron (Seifelnassr et al., 2012; Suthers et al., 2014; Amiri, 2019).

The following equation (Equation 1) for the separation efficiency (SE) can be used in expressing the technical excellence of any separation that occurs in mineral concentration processes or processes of any nature that consist of two matter that are physically separated from one another:

$$SE = W(Cm(c-f))/f(Cm-f)) \qquad (1)$$

where, W is the percent amount of feed that reports to the concentrate, m is the maximum grade of valuable mineral (72.36% Fe in Fe_3O_4), f is the percentage of metal in the feed, and c is the percent metal in the concentrate (Schulz, 1979; Barari et al., 1979). Mukherjee studied various methods used in calculation of the SE. The author discussed 25 different equations and proposed a new method for calculation. In addition, the author reported that each of these 25 calculation method can be used with minor changes in the coal cleaning and gravity concentration plants (Mukherjee, 2009).

SE calculation is a useful method to identify various operating parameters. In addition, it can be used to compare performances of various concentration methods used in existing plants (Shivakumar et al., 2017). The values of SE vary between 0 and 100. SE index has been often used in technical evaluation of concentration methods (Irannajad et al., 2018).

Wills and Finch, (2016) have expressed that although separation efficiency can be useful in comparing the performance of different operating conditions, it does not take into account the economic factors, and is sometimes referred to as the technical separation efficiency. As discussed in the following chapters of this study, a high value of separation efficiency does not necessarily lead to the most economic return. Nevertheless, it remains a widely used measure to differentiate alternatives prior to the economic assessment. Sousa (2020) has also stated that, a plotted grade/recovery curve does not allow to distinguish the liberation efficiency (El) from the technical efficiency (Et). It is difficult to determine whether lower efficiency values are related to operational conditions or are a result of insufficient liberation. For this reason, the detailed material characterization can aid in understanding the process.

In the present, processing of low grade iron ore deposits has become high importance for economic and environmental preservation. Recovery of iron by using optimum separation method and operational conditions has grown in importance. In this study, detailed laboratory scale beneficiation studies were performed to determine the optimum beneficiation conditions of a typical low grade iron ore sample. For this purpose, separation efficiency values of various concentration methods were calculated by using chemical analysis of the test products. In literature, a significant amount of studies are found on iron ore beneficiation processes whereas studies on the evaluation and comparison of SE obtained from different methods are very limited. Therefore, the objective of this investigation is to find the fundamental effects of different operational parameters in dry and low magnetic separation, jigging and shaking table, on separation efficiency of a low grade iron ore and find out optimum method and operational parameters. In the present study, the author emphasizes the grade/

recovery curves and separation efficiency values in evaluation of beneficiation possibilities of a low grade iron ore.

2. Material and Method

The representative core samples were supplied from an ore potential area. The area is located in Kuluncak, one of the important areas having underground resources of iron and chromium stratum in the surrounding area of Hekimhan and Kuluncak towns in Malatya, located at Eastern Anatolia region of Türkiye. The sample acquired for this study was subjected to detailed characterization and laboratory scale testing. The core samples supplied from area were crushed below 30 mm and split into small amounts of representative samples for chemical, mineralogical and liberation analyzes, heavy liquid tests and beneficiation studies.

According to the material characterization, gravity concentration and magnetic separation studies were performed on different size fraction of run of mine ore. Grade/recovery curves for all methods were constructed and compared. The effects of material properties and operational parameters were evaluated.

For this aim, methods of jigging, flowing film concentration (shaking table), dry low intensity magnetic separation (DLIMS) and wet low intensity magnetic separation (WLIMS), were tested. Operational variables that may affect the performance of equipment, such as, magnetic field intensity in magnetic separation, tilt angle in shaking table, water velocity in jigging were taken into consideration in determining SE values. An explanatory diagram regarding the experimental procedure is given in Figure 1.

3. Material Characterization

Material characterization which gives information about the mineralogical, chemical and liberational attributes of the ore, is of crucial importance in studies of low grade ore deposits as it helps determining the most suitable method. The selection of suitable beneficiation method depends on the physical and textural properties of iron minerals and gangues. For this reason, the ROM sample and specific size fractions were subjected to various characterization studies such as determination of specific gravity, x-ray diffraction (XRD), Satmagan analysis, chemical analysis, liberation analysis and heavy liquid test. Specific size fractions have been chosen to be suitable for both coarse and fine fraction sized beneficiation tests.

3.1. Qualitative Mineralogical Analysis and Ore Microscopy

The mineral phases in the iron ore sample were determined by using XRD method. Diffractograms

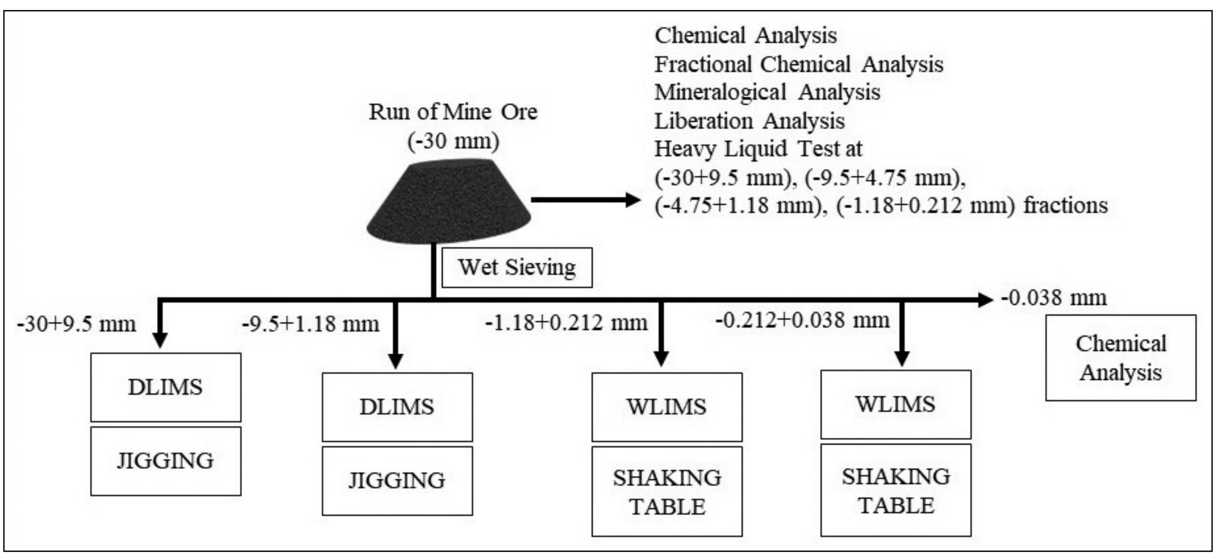

Figure 1- Simplified flowsheet of experimental studies.

were obtained from a Rigaku D/Max 2200 Powder X-ray Diffractometer, using a chrome anode. The Rigaku D/Max 2200 Powder X-ray Diffractometer is equipped with a horizontal goniometer capable of performing typical theta-2 theta scans. According to the results, the sample contains magnetite (Fe_3O_4). Additionally, the ore contains hematite (Fe_2O_3) and goethite $Fe^{3+}O(OH)$. Silicates, carbonates and clay minerals occur as the major gangue phases. The XRD pattern of the sample is given in Figure 2.

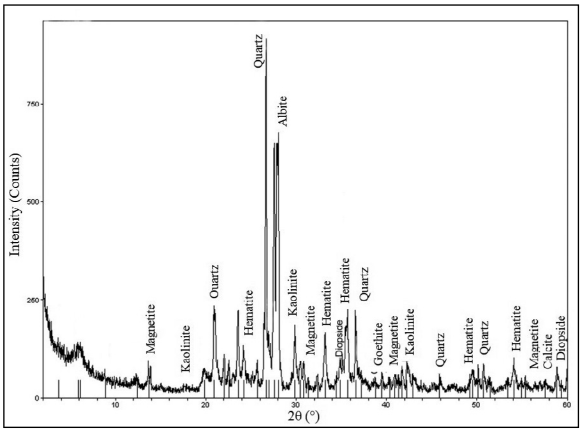

Figure 2- X-ray diffraction pattern of run of mine ore.

3.2. Fractional Chemical Analysis

The specific size fractions were analyzed for their major element composition by XRF (Table 1). It is indicated in Table 1 that iron ore contains 31.78% of total iron is low grade in nature, 17.52% silica as a major impurity, 14.26% CaO, 4.37% MgO, 0.56% Al_2O_3 with an LOI (Loss on Ignition) of 16.59%. Fractional analysis indicates that as the particle size decreased, iron content increased up to 38 µm, and below that, it decreased significantly. The -212+38 µm size fraction of feed has the highest total iron grade and lowest silica grade. Approximately 96% of total iron and 97% of silica are in the fraction are coarser than 0.212 mm. According to Table 1, -38 µm size fraction has highest alumina content (3.08%). Higher alumina and lower iron content (6.57%) of this fraction can be a marker of clay presence. XRD pattern shows the kaolinite presence in the ore.

3.3. Determination of Magnetite Content

Satmagan analyses have been performed by using Rapiscan Systems Satmagan 135 (Saturation Magnetization Analyzer) in order to determine the amount of iron originated from magnetite mineral.

Table 1- Fractional chemical analysis of iron ore sample.

Size (mm)	Weight (%)	Grade (%)				
		Fe	SiO_2	CaO	MgO	Al_2O_3
-30+9.5	48.47	30.54	18.73	15.14	4.37	0.51
-9.5+4.75	24.57	31.32	17.27	14.51	4.37	0.50
-4.75+1.18	12.54	34.55	16.06	13.26	4.55	0.53
-1.18+0.212	10.57	35.87	15.66	11.50	4.01	0.68
-0.212+0.038	2.82	38.66	9.50	9.96	3.62	0.75
-0.038	1.03	6.57	25.43	19.18	8.15	3.08
Head Sample	100.00	31.78	17.52	14.26	4.37	0.56
Size (mm)	Weight (%)	Distribution (%)				
		Fe	SiO_2	CaO	MgO	Al_2O_3
-30+9.5	48.47	46.58	51.82	51.46	48.43	43.90
-9.5+4.75	24.57	24.21	24.21	25.00	24.55	21.88
-4.75+1.18	12.54	13.63	11.49	11.66	13.06	11.92
-1.18+0.212	10.57	11.93	9.45	8.52	9.70	12.86
-0.212+0.038	2.82	3.43	1.53	1.97	2.33	3.76
-0.038	1.03	0.21	1.50	1.39	1.92	5.66
Head Sample	100.00	100.00	100.00	100.00	100.00	100.00

The Satmagan was designed specially to measure magnetite in iron ore concentrations. The principle behind the Satmagan 135 is to measure the force acting on the sample in a magnetic field with a spatial gradient. The magnetic field is strong enough to saturate the magnetic component in a sample. In this case all the magnetite in the sample gets measured regardless whether it can be separated by a magnet or not. Previous studies showed that particle size does not affect Satmagan measurements as it was expected (Amikiya, 2014). Therefore, representative samples were ground to -53 µm and analyses were performed. Magnetite content of the size fractions are tabulated in Table 2.

It is observed from Table 2 that magnetite is the main iron bearing mineral (98% wt) in the sample. Beside this ore consist minor amount of hematite (Fe_2O_3) and goethite $Fe^{3+}O(OH)$. Hematite and goethite contains only 2% of the total iron in the ore. These results are beneficial for determining the behavior of the ore in low intensity magnetic separators.

3.4. Liberation Analysis

Liberation analysis was performed below 1 mm by using a Nikon SMZ 1500 Stereo Microscope and Clemex Vision PE 3.5.025 image analysis software (Figure 3). The size fractions were analyzed under the microscope using the reflected light mode.

The liberation degree of the magnetite particles was determined by the point counting technique. Approximately 600 grains was counted for each size fraction. Then, both free and locked magnetite particles in the images were counted and liberation degree of each size fractions was calculated. Liberation degree of size fractions are shown in Figure 4.

Figure 3- Stereo microscope and image analysis software.

According to results, it is observed that the degree of liberation increases with a corresponding decrease in particle size. The liberation of magnetite particles are quite acceptable below 0.212 mm. Percentage of liberated particles increases from 49.18% to 89.05% in the -0.212+0.150 mm size fraction. The magnetite in the >95% liberated class can be regarded as free particles approximately. The magnetite in the

Table 2- Fractional magnetite content of size fractions.

Size (mm)	Weight (%)	Fe_3O_4 (%)	Fe from Analysis (%)	Fe from Satmagan (%)	Fe in Magnetite / Total Fe (%)
-30+9.5	48.47	41.15	30.54	29.78	0.975
-9.5+4.75	24.57	42.42	31.32	30.70	0.980
-4.75+1.18	12.54	47.07	34.55	34.06	0.986
-1.18+0.212	10.57	49.14	35.87	35.56	0.991
-0.212+0.038	2.82	52.35	38.66	37.88	0.980
-0.038	1.03	8.87	6.57	6.42	0.977
Head Sample	100.00	43.03	31.78	31.14	0.980

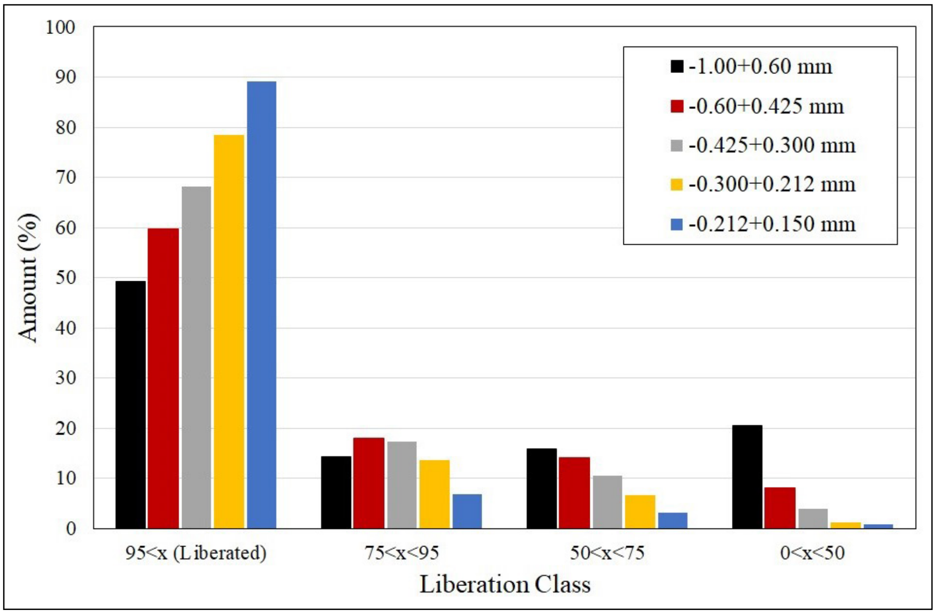

Figure 4- Liberation classes of magnetite mineral.

50>x>0% liberated (the magnetite in this class can be regarded as fully locked particles approximately) class is only 0.86% in 0.212+0.150 mm size fraction. This indicates that a grinding size finer than 212 µm is sufficient in separation of magnetite from gangue minerals.

3.5. Heavy Liquid Analysis

Heavy liquid analysis is an extremely useful tool in the determination of liberation characteristics of an ore. In this study, sized fractions of the ore were subjected to heavy liquid analysis. In a heavy liquid analysis theoretically, the liberated silicates and carbonates should concentrate in the float product, and iron minerals and locked particles (middling) of sufficient specific gravity should sink. In heavy liquid analysis, a tetrabromoethane (TBE) and acetone mixture was used to prepare the heavy liquids with densities of 2.70 g/cm^3 and 2.90 g/cm^3 separately. Then, each fraction was sunk into the 2.90 g/cm^3 heavy liquid. The float product was removed out, drained and sunk in the liquid of 2.70 g/cm^3 density. The all products were finally drained, washed, dried, weighed and analyzed. Heavy liquid analysis results are tabulated in Table 3.

It is indicated from Table 3 that the weight percentages of the sinks are increasing in finer size fractions. The total iron content in the sink product is higher than float products and varies between 51-55% Fe. Increase in fineness increases the total iron content and decreases the silica content in the sink product. The silica grade of float products is higher in the floats for all size fractions. The highest silica grade was observed at -30+9.5 mm size fraction. The results obtained from the heavy liquid test indicate that liberation of the iron and silica is insufficient. This observation was confirmed by visible and microscopic examination of heavy liquid analysis fractions. Heavy liquid test results also show that liberation degree of +4.75 mm is quite insufficient. These results mark that there are some locked gangue grains in the sink product.

4. Beneficiation Studies

A detailed test procedure was designed and performed in evaluation of separation efficiencies of magnetic separation and gravity concentration. Representative samples were taken during tests and chemical analyses of all samples were done to determine the performance of each test. Effect of feed size and some important operational parameters on separation efficiency were also evaluated. The grade/recovery curves of each test were constructed and evaluated. Details of experimental studies are discussed below.

Table 3- Heavy liquid analysis results.

Size Fraction (mm) / Product	(%)	Grade (%)				
	Weight	Fe	SiO_2	CaO	MgO	Al_2O_3
-30+9.5 / 2.7 Floats	30.09	9.95	24.44	18.93	5.75	0.53
-30+9.5 / 2.9 Floats	22.98	15.01	15.39	16.63	4.77	0.53
-30+9.5 / 2.9 Sinks	46.93	51.35	16.71	11.98	3.28	0.48
-30+9.5	100.00	30.54	18.73	15.14	4.37	0.51
-9.5+4.75 / 2.7 Floats	31.05	9.10	25.69	18.92	6.24	0.47
-9.5+4.75 / 2.9 Floats	19.59	15.06	19.92	17.74	4.44	0.66
-9.5+4.75 / 2.9 Sinks	49.36	51.74	10.91	10.45	3.16	0.45
-9.5+4.75	100.00	31.32	17.27	14.51	4.37	0.50
-4.75+1.18 / 2.7 Floats	24.76	6.71	30.75	22.99	7.42	0.69
-4.75+1.18 / 2.9 Floats	19.26	14.14	25.84	15.48	5.14	0.69
-4.75+1.18 / 2.9 Sinks	55.98	53.89	6.19	8.19	3.08	0.41
-4.75+1.18	100.00	34.55	16.06	13.26	4.55	0.53
Size Fraction (mm) / Product	(%)	Distribution (%)				
	Weight	Fe	SiO_2	CaO	MgO	Al_2O_3
-30+9.5 / 2.7 Floats	30.09	9.81	39.26	37.62	39.64	31.58
-30+9.5 / 2.9 Floats	22.98	11.29	18.88	25.24	25.10	24.01
-30+9.5 / 2.9 Sinks	46.93	78.90	41.86	37.13	35.25	44.41
-30+9.5	100.00	100.00	100.00	100.00	100.00	100.00
-9.5+4.75 / 2.7 Floats	31.05	9.02	46.20	40.50	44.37	29.55
-9.5+4.75 / 2.9 Floats	19.59	9.42	22.60	23.95	19.92	25.92
-9.5+4.75 / 2.9 Sinks	49.36	81.56	31.19	35.55	35.72	44.53
-9.5+4.75	100.00	100.00	100.00	100.00	100.00	100.00
-4.75+1.18 / 2.7 Floats	24.76	4.81	47.42	42.93	40.38	31.94
-4.75+1.18 / 2.9 Floats	19.26	7.88	31.00	22.49	21.75	24.96
-4.75+1.18 / 2.9 Sinks	55.98	87.31	21.58	34.58	37.87	43.10
-4.75+1.18	100.00	100.00	100.00	100.00	100.00	100.00

4.1. Magnetic Separation Studies

It is well known from the detailed characterization studies that the main mineral in the feed is magnetite. For this reason, low intensity magnetic separation tests were developed and conducted to investigate the effect of field intensity and feed size distribution on SE (Table 4). One stage low intensity magnetic separation was performed to different size fractions. A simplified schematic view of test procedure is shown in Figure 1. Magnetic separation tests were performed in a batch scale. Feed rate was adjusted manually to approximately 0.25 kg/min to generate a mono-particle layer on the surface of the type magnetic separator. The operational magnetic field intensity was measured by using a Gauss meter on the roller surface.

4.2. Gravity Concentration Studies

4.2.1. Jigging

Jigging tests were performed by using -30+9.5 and -9.5+1.18 mm size fractions to evaluate the effect of water velocity on SE. A laboratory scale Denver mineral jig was used which dimensions of 10.5x10.5 was used for the process. A constant duration of five minutes jigging was applied during each test (feeding 60 sec., jigging 240 sec.). All products (float and sink) were collected, and chemical analysis were performed.

Table 4- Low intensity magnetic separation test conditions.

Test No.	Feed Size (mm)	Test Type	Magnetic Intensity (Gauss)
1	-30+9.5	Dry	1000
2	-30+9.5	Dry	1200
3	-30+9.5	Dry	1400
4	-30+9.5	Dry	1600
5	-9.5+1.18	Dry	1000
6	-9.5+1.18	Dry	1200
7	-9.5+1.18	Dry	1400
8	-9.5+1.18	Dry	1600
9	-1.18+0.212	Wet	1000
10	-1.18+0.212	Wet	1200
11	-1.18+0.212	Wet	1400
12	-1.18+0.212	Wet	1600
13	-0.212+0.038	Wet	1000
14	-0.212+0.038	Wet	1200
15	-0.212+0.038	Wet	1400
16	-0.212+0.038	Wet	1600

It is reported in the literature that traditional jigging techniques become increasingly inefficient in finer size fractions (Dobbins et al., 2009). Therefore -1.18 mm fraction of iron ore sample was removed before jigging and WLIMS tests and shaking table test was conducted to this fraction. The jigging test conditions are tabulated in Table 5.

Table 5- Jigging test conditions.

Test No.	Feed Size (mm)	Water velocity (cm/sec)
17	-30+9.5	5
18	-30+9.5	10
19	-30+9.5	15
20	-30+9.5	20
21	-30+9.5	25
22	-9.5+1.18	3
23	-9.5+1.18	6
24	-9.5+1.18	9
25	-9.5+1.18	12
26	-9.5+1.18	15

4.2.2. Shaking Table Tests

Shaking table tests were performed on the -1.18+0.212 mm and -0.212+0.038 mm size fractions to evaluate the effect of feed size fraction and table tilt angle on separation efficiency (SE). During the tests a shaking table with dimensions 500×1200 mm was used. Wash water rate (10 lpm) and feed pulp density (25% solid) were kept constant during the tests. Concentrate, middling and tailing samples were collected by using a special design sampler during each test. Shaking table test conditions are tabulated in Table 6.

Table 6- Shaking table test conditions.

Test No.	Feed Size (mm)	Table tilt Angle (degrees)
27	-1.18+0.212	2
28	-1.18+0.212	4
29	-1.18+0.212	6
30	-1.18+0.212	8
31	-0.212+0.038	2
32	-0.212+0.038	4
33	-0.212+0.038	6
34	-0.212+0.038	8

5. Discussion

Grade/recovery curves of separation methods were compared for different feed size fractions (Figure 5).

It is indicated from Figure 5 that total iron recovery of gravity concentration method is higher than the magnetic separation coarser than 1 mm. In contrast, total iron recovery of gravity concentration method is lower than the magnetic separation finer than 1 mm. Grade/recovery values are lowest in the -30+9.5 mm size fraction. Recovery and grades

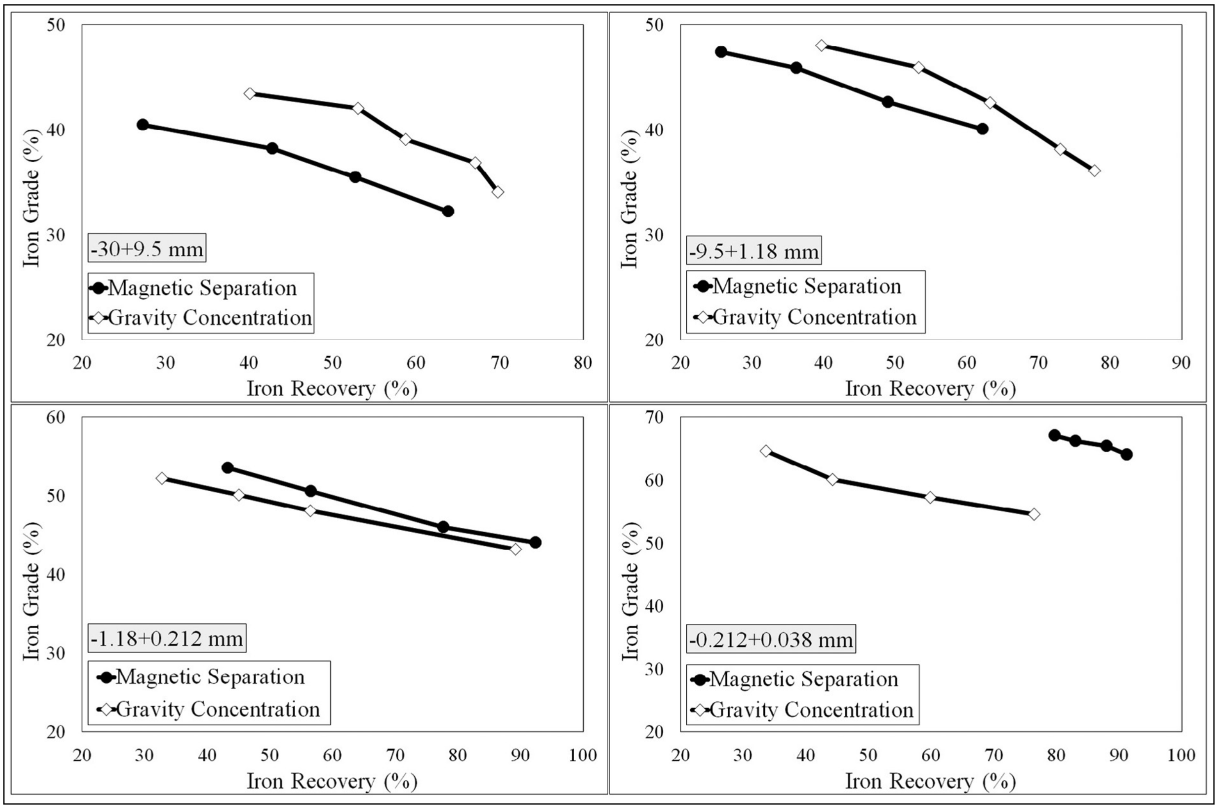

Figure 5- Grade/recovery curves of separation methods for different feed size fractions.

increase with decrease in feed size irrespective to separation method. The reason for lower recoveries of particles above 1 mm is mainly due to poor liberation of the magnetite mineral as discussed in heavy liquid analysis results.

In terms of process dynamics of jigging, concentration of coarser size fractions is relatively simpler than the finer size fractions (Mukherjee et al., 2006). However, in the current magnetic separation devices, an effective concentration occurs only when the magnetic forces exceed the gravitational forces, many folds (Lin et al., 1997). Hence, irrespective to the liberation of particles as the particle size increases, the gravity force will further increases and it may be also greater than the magnetic force. This can lead to a decrease in the recovery of coarse particles in magnetic separation. According to Figure 10 the jigging method can be beneficial as a pre concentrator above 1 mm. According to results, jig has a higher capability to treat coarser particles.

The liberation degree of magnetite increases significantly below 1 mm according to liberation analysis results. Therefore, an upwards and/or to the right shift of the curves shows an improvement in performance of shaking table and wet magnetic separator. Wet magnetic separation and shaking table gives a similar grade/recovery curve at feed size fraction -1.18+0.212 mm. However, magnetic separation produces a higher grade concentrate for the same recovery value. As a result of Satmagan analyses it is well described that the main iron bearing mineral is magnetite in the ore. The magnetite contains 98% of total iron. Magnetic susceptibility of these more liberated particles increases in finer size fractions. It is reported in the previous studies that magnetic forces become more dominant for the intermediate size ranges (Rayner and Napier-Munn, 2000; Vijayendra, 2001; Arol and Aydoğan, 2004; Mahmoud, 2010; Dworzanowski, 2012). Higher recovery of magnetic separation can be described with dominant magnetic forces on the intermediate size particles. However, similar grade/recovery curves of both wet magnetic separation and shaking table reveal that both method have the capability to treat intermediate particles with varying recovery values. In addition, neither magnetic separation nor shaking table can produce a high grade concentrate with higher recoveries at intermediate size ranges of the sample studied.

Grade/recovery values of magnetic separation is significantly higher than shaking table below 0.212 mm. This fraction can be defined as fully liberated (Figure 4). Therefore, the difference of grade/recovery curves can be described by finer magnetite treatment capabilities of magnetic separation and gravity concentration. It is well known that the performance of conventional gravity equipment such as spiral and shaking table decreases significantly below 75 µm (Hearn, 2002). The particle movement in a fluid is affected by its specific gravity and particle diameter. The particles having larger diameter are affected more than the smaller diameter particles. Higher efficiency separation is more likely with coarser particles in gravity concentration. As a result, effect of magnetic forces on particles is higher than gravity and drag forces results a better recovery at feed size -0.212+0.038 mm (Chatterjee, 1998).

A SE based performance calculation is applied in the present study to determine the effect of operational parameters and feed size on magnetic separation, jigging and shaking table separately. The SE of each method calculated by using iron analysis in the feed and the products. SE of magnetic separation tests is figured in Figure 6. The SE of each feed size fraction is calculated by applying the Equation 1.

Figure 6 reveals that magnetic separation has lowest SE at the coarsest size. The separation efficiency gradually improves with increasing fineness for all magnetic field intensities. According to some authors, hydrodynamic forces, magnetic forces, gravity forces and drag forces are the main forces that lead the complete movement of particles in a magnetic separator (Arol and Aydoğan, 2004; Wills and Napier-Munn, 2006). Gravity and drag forces work against magnetic forces which attract magnetic particles. The magnitude of these forces is significantly affected by the size of particles. It is reported from the previous studies that; the hydrodynamic drag forces are proportional to the diameter of a particle. The magnetic forces and gravity forces are proportional to the second and third power of the particle diameter, respectively. Consequently, the gravity forces are effective on the coarse particles while the hydrodynamic drag forces are more effective on the fine particles (-38 µm), and magnetic forces are more effective on the intermediate particle sizes. Because the attraction is directly proportional to the particle mass, the larger particles require higher magnetic intensity than for the finer ones (Vijayendra, 2001). In magnetic separation of fine particles, magnetic forces must exceed that of the hydrodynamic drag forces. But, higher magnetic

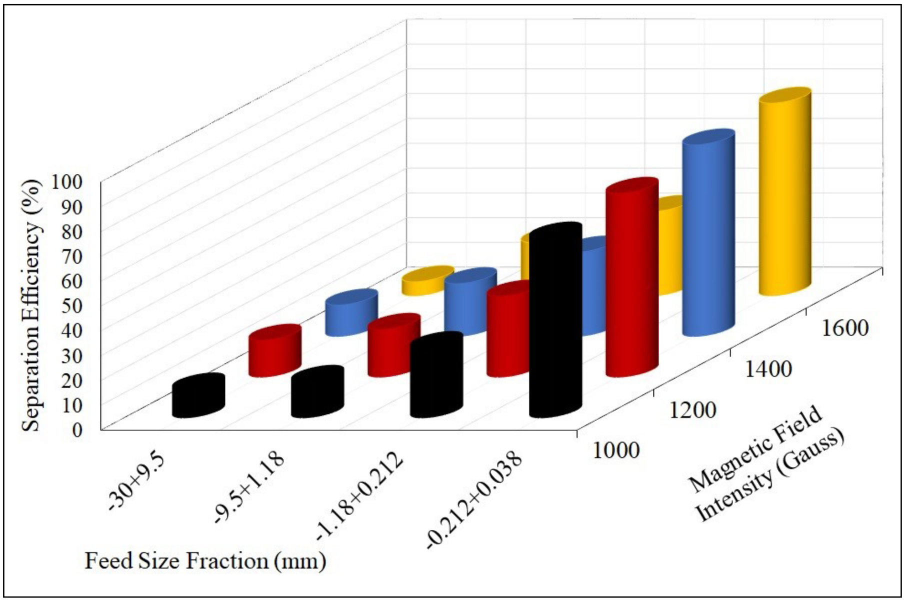

Figure 6- Separation efficiency of magnetic separation.

forces than gravity forces are required for the coarse mineral particles (Arol and Aydoğan, 2004). Hence, as the particle size increases, the gravity force will be further increased and it may be also greater than the magnetic force. This can lead to a decrease in the recovery of coarse magnetic particles and accordingly a decrease in separation efficiency of the same liberation level.

As the magnetic field intensity increases, magnetic minerals are normally captured efficiently by magnetic separators, resulting in an increase of magnetic particles, hence to a marginal increase in SE values. SE of coarsest size fraction (-30+9.5) are similar for all magnetic fields. It can be concluded that the effect of gravity forces on the coarse particles are higher as mentioned above. In addition, poor liberation of coarser size fractions can negatively affect the separation efficiency. The SE increases with the increasing field intensity for other size fractions. Highest separation efficiencies can be obtained at finest feed size. Therefore, the degree of liberation of the size fractions can be inferred as the main reason behind this effect. It should be noted that sufficient liberation is required for the separation efficiency to increase with magnetic field intensity.

SE values of jigging are presented in Figure 7.

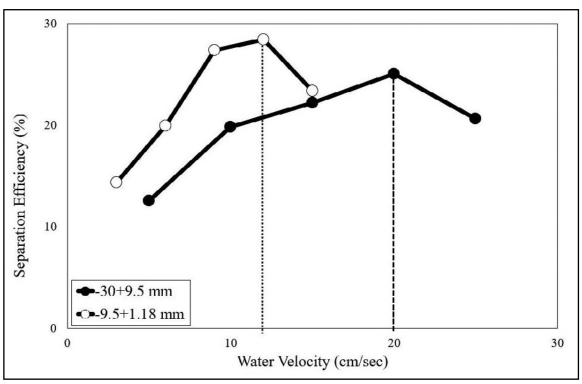

Figure 7- Separation efficiency of jigging.

It is visible from the Figure 7 that the SE is related with feed size and water velocity. Figure 7 shows that -9.5+1.18 mm size fraction has a higher SE. Higher SE value of this size fraction indicates the significant effect of better liberation. To increase the SE of both fractions, water velocity should be increased. A higher amount of water is required to increase SE of coarse size fraction. A water velocity of 12 cm/sec is necessary for the optimum separation of the magnetite mineral from the gangues at -9.5+1.18 mm size fraction. An increase in water velocity above 12 cm/sec has negative effect on SE. Similarly, the 20 cm/sec water velocity is acceptable for the optimum separation at -30+9.5 mm size fraction.

In literature, certain studies in detail can be found on the jigging process. The authors of such studies report two important finding about SE of jigging in these studies (Mukherjee et al., 2005*a, b*; Mukherjee et al., 2006; Mukherjee and Mishra, 2006; Mukherjee, 2009). According to their results the SE increases with increase in water velocity, achieves a maximum point and then decreases. In addition, coarse size feed material needs a higher maximum water velocity for optimum efficiency (Mukherjee and Mishra, 2006). Maximum water velocity term as an important term and parameter in defining optimum SE value of the jigging method is reported by Mukherjee. According to author, the efficiency of jigging is related to the water velocity (Mukherjee et al., 2006). Figure 7 clearly indicates that maximum water velocity values were also observed in this study.

According to Das et al. (2008), the SE of jigging is higher at finer sizes and the 4-5 cm/sec water velocity is sufficient to concentrate the iron particles from the gangues at a size fraction of -5+1 mm. A water velocity value above these values did not result in much positive effect on SE. In the present study, similar results to those of previous studies were obtained. According to results, maximum water velocity of -30+9.5 mm can be given as 20 cm/sec, and maximum water velocity of -9.5+1.18 mm can be given as 12 cm/sec for studied low grade iron ore. The results of all studies show that maximum water velocity term is valid and important for jigging process. However, the maximum water velocities to treat different types of iron ore should be determined to obtain optimum SE. SE values can vary according to the feed size.

Separation efficiency of the coarser size fraction suggests poor liberation characteristics. This inference was verified through optical analysis. The heavy liquid tests revealed that a concentrate grade of maximum

54% Fe is attainable for -30+1.18 mm fraction with an overall recovery of 82%. The concentrate grade obtained during jigging tests nearly met the analysis grade while the recovery was around 66% of the analysis value.

Separation efficiency of shaking table is figured in Figure 8.

It can be observed from Figure 8 that shaking table performed best especially at finer particle sizes and at an angle of 2°. The SE of both size fractions increases significantly with decreasing the tilt angle. It is observed from the test results that table tilt angle effects the SE significantly. So it is clear that feed size, liberation degree and deck tilt angle have a major influence on SE of the shaking table process.

Lower separation efficiencies of -1.18+0.212 mm size fraction can be explained with insufficient liberation obtained from liberation analyses. The average liberation degrees of -1.18+0.212 mm size fraction and -0.212 mm size fraction are calculated as 64% and 89.05% respectively.

It is observed from shaking table test results the lowest angle should be used to obtain highest SE. Above 2°, separation efficiency of shaking table decreases significantly. The decrease of SE can be explained by residence time of particles. Residence time of particles in the flowing film decrease with increasing angle. In this short period of time, transportation of the very fine magnetite particles to middling and tailing can decrease the selectivity. In addition, it can be concluded that desliming (removing of -38 μm) has positive effects on overall efficiencies. Relationship between iron recovery and separation efficiency values of separation methods is shown in Figure 9.

It can be revealed from Figure 9 that an increase in recovery increases the SE of magnetic separation. The SE of jigging and shaking table increases with increasing recovery up to a certain value. Then, SE of gravity concentration methods decreases significantly. This can be explained with the limited effect of gravity forces on the magnetic particles. In addition, higher iron recoveries can be obtained with sufficient liberation of magnetite particles. The poor liberation characteristic of +1 mm can negatively affect the SE of jigging and DLIMS. In contrast, liberation of magnetite increases below 1 mm. An increase in SE of shaking table and WLIMS can be the result of this better liberation. Figure 9 clearly shows that SE of wet magnetic separation is significantly higher than shaking table and jigging approximately 80% iron recovery. It can be concluded from Figure 9 that SE of WLIMS is better than various gravity separation techniques for iron ore beneficiation. The lower efficiency of DLIMS can be described with the effect

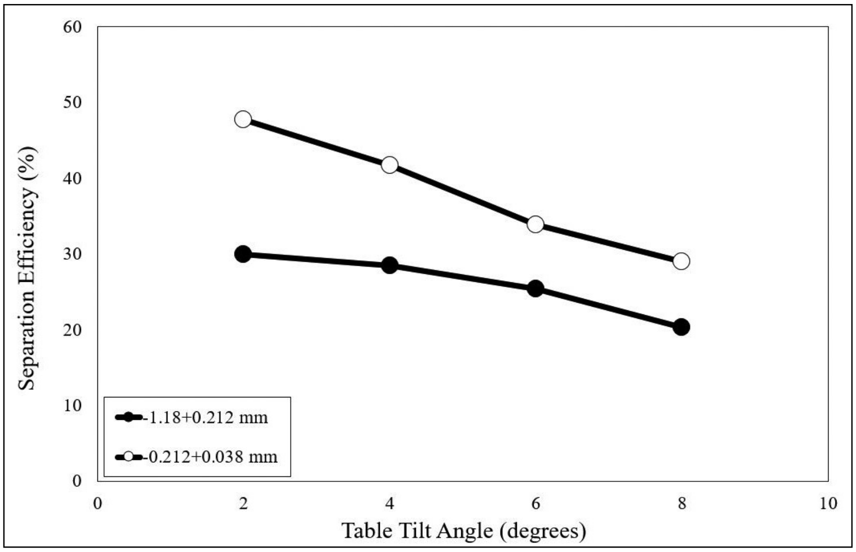

Figure 8- Separation efficiency of shaking table.

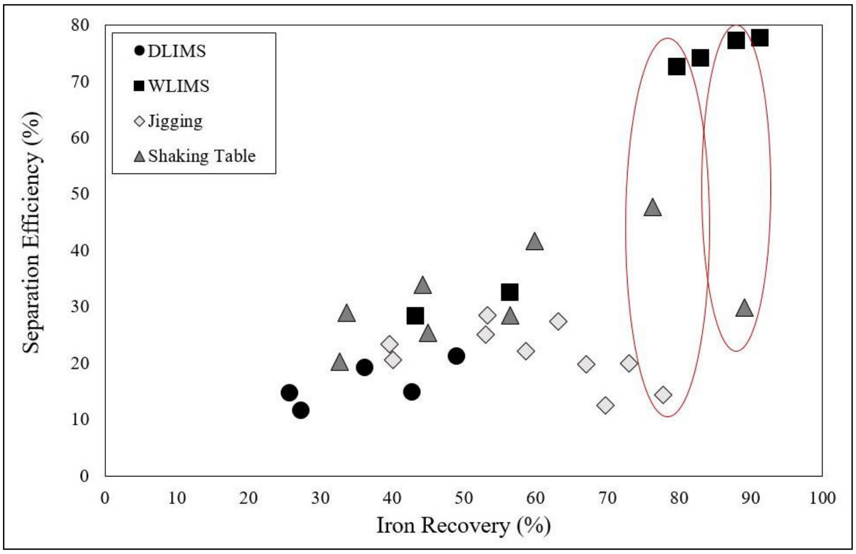

Figure 9- Relationship between iron recovery and separation efficiency.

of gravity forces on coarser particles and mainly with poor liberation.

Average separation efficiencies of gravity concentration and magnetic separation were calculated for average feed sizes by using statistical analysis. The results of gravity concentration and magnetic separation are tabulated in Table 7 and 8, respectively. The mean separation efficiencies of gravity concentration and magnetic separation are shown in Figure 10.

It can be revealed from Figure 10 that separation efficiency values of magnetic separation vary between 11.19% to 75.34%. Similarly, separation efficiency values of gravity concentration vary between 20.05% to 38.07%. A decrease in average particle size increases the separation efficiency of both methods. Separation efficiencies of gravity concentration and magnetic separation takes similar values above 1 mm, however, separation efficiency of magnetic separation is significantly higher than gravity concentration below 1 mm.

Table 7- Average separation efficiencies (SE) of gravity concentration.

Feed Size Fraction (mm),	Mean Feed Size (mm)	Mean SE (%)	Median	Standard Deviation	Standard Error
-30+9.5	19.75	20.05	20.62	4.65	2.08
-9.5+1.18	5.34	22.68	23.39	5.76	2.57
-1.18+0.212	0.70	26.03	26.94	4.26	2.13
-0.212+0.038	0.13	38.07	37.80	8.27	4.13

Table 8- Average separation efficiencies (SE) of magnetic separation.

Feed Size Fraction (mm)	Mean Feed Size (mm)	Mean SE (%)	Median	Standard Deviation	Standard Error
-30+9.5	19.75	11.19	12.13	3.95	1.98
-9.5+1.18	5.34	19.17	20.26	3.14	1.57
-1.18+0.212	0.70	32.21	33.27	2.67	1.34
-0.212+0.038	0.13	75.34	75.34	2.48	1.24

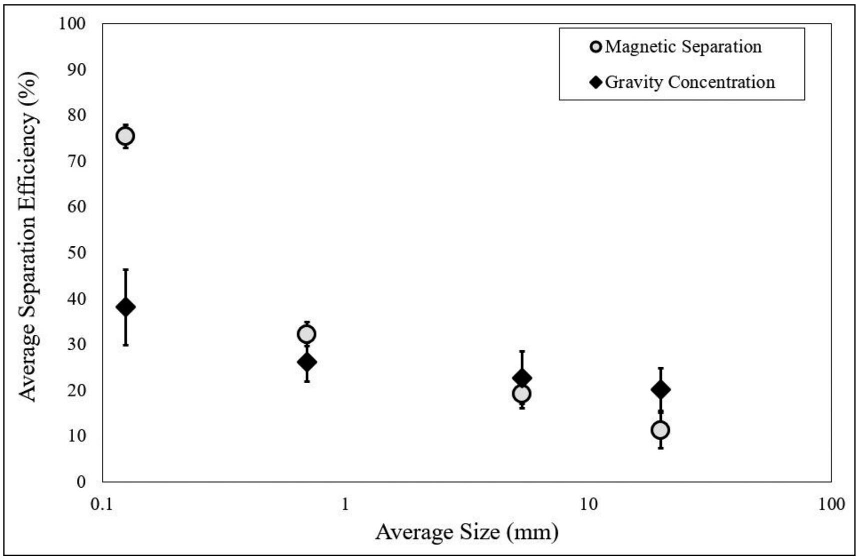

Figure 10- Separation efficiency (SE) of magnetic separation and gravity separation.

6. Results

An iron ore sample which is low grade in nature from the Eastern Anatolian, Turkey, has been subjected to detailed material characterization and various concentration methods with the objective to evaluate grade/recovery relationships and the SE of different physical beneficiation methods. Detailed beneficiation tests including dry and wet low intensity magnetic separation, jigging, and shaking table were performed to coarser, intermediate and finer size fractions of the ore. The effect of most significant operational parameters which are, magnetic field intensity, water velocity and table tilt angle on the separation efficiency values were evaluated and discussed.

Performance evaluation of beneficiation methods have been performed by calculating SE. Calculated separation efficiencies revealed that operational parameters significantly affect the separation efficiencies of all methods. According to results decrease in feed size fraction increases the separation efficiency irrespective of the beneficiation method. This result clearly shows that better liberation in finer size fraction positively affects SE. The strict relationship between size dependent iron recovery and SE can be beneficial finding potential reasons of lower SE values at higher recoveries for iron ore concentration.

Mean SE of different size fractions showed that separation efficiencies of gravity concentration and magnetic separation takes similar values above 1 mm, however, separation efficiency of magnetic separation is significantly higher than gravity concentration below 1 mm for studied iron ore sample.

According to SE calculations it can be concluded that Test 16 gives the best efficiency value (77.61%). In this test wet magnetic separation has been applied to -212+38 µm size fraction. According to test results a magnetic concentrate can be obtained with 64.01 %Fe and 91.27% total iron recovery. However, the presented results are independent of economic considerations, and can only compare the technical efficiency of different beneficiation methods. It is difficult to know whether a lower separation efficiency of any beneficiation method is related to operational conditions or a result of insufficient liberation. In the present study a strictly controlled test program was performed. The variation of the SE values can be explained according to nature of the beneficiation methods and material properties.

For low grade ores; especially for iron ores, it is very crucial to develop a flow sheet to achieve the optimum grade and recovery while decreasing the cost likely by using optimum method. Therefore, the grade/recovery curves and separation efficiency calculations used in this research can be used as a qualitative method to compare the efficiency of different beneficiation methods and choose the best technically. Both grade/recovery curves and separation efficiency methods have advantages as they are fast and basic methods for the efficiency evaluation by using experimental results. To apply these techniques to DLIMS, WLIMS, jigging, and shaking table and other potential methods can help in acquiring a good comprehension of the plant dynamics and the optimization.

To technically determine the best process condition with respect to operational parameters and beneficiation methods these basic calculations can be useful and give advantages to researchers. One of the advantages of this method is the determination of the best process among several ones. The presented results are one of the strategical methods for any separation process evaluation in no economic terms but process performance. The grade/recovery curves and relationship between recovery and SE will separately present useful results based on the needs of the users.

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