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# Beneficiation and flowsheet development of a low grade iron ore: A case study

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**ABSTRACT**

In the present study a detailed characterization followed by beneficiation of low grade iron ore was studied. The Run of Mine (R.O.M) sample assayed 21.91 % Fe, which is very low grade in nature. The impurities are $SiO_2$ 26.25%, MgO 20.48%, CaO 5.85%, $Al_2O_3$ 1.86% and loss on ignition (LOI) 12.71%. A Davis Tube test was performed for the assessment of the separability of magnetic ores by low intensity magnetic separators. The heavy liquid test was carried out to evaluate the possible response of the sample by the gravity concentration technique. The samples were subjected to jigging, dry low intensity magnetic separation (DLIMS) and shaking table tests. Thus a sufficient concentrate could not be obtained in +1 mm by using jigging and DLIMS. The obtained results show that the a high grade iron concentrate (>65% Fe) with lower recoveries was obtained from shaking table tests by using -1 mm fraction. According to the results a flowsheet was developed. From the developed flowsheet, it is possible to obtain pellet grade concentrate with 65.41% Fe, 2.54% $SiO_2$, 2.79% MgO, 0.70% CaO and 0.32% $Al_2O_3$. with 21.42% weight recovery. The overall gangue rejection recovery of the circuit is over 95%.

## 1. Introduction

Basic raw material for iron and steel industry is iron ore which leads to world growing economy. With increasing global demand of iron ores due to the huge requirement of steel all over the world, countries have increased their production by initiating steps to utilize the low - grade iron ores, fines and slimes. Upgrading these low grade ores is becoming an attractive proposition today.

The high grade iron ore is depleting due to the increasing global demand of iron. In Turkey, a substantial quantity of low grade iron ore deposits is present. Hence, to increase the iron ore resources to meet the ever increasing demand of iron and steel, the use of the abundant low grade iron ore is inevitable.

Processing of iron ores generally depend on the size and the nature of impurities present in the ore body. Depending upon the origin and mineralogical characteristics of the ore, different beneficiation methods are being adopted for iron ore from simple crushing and screening to complex concentration processes (Singh and Mehrotra, 2007; Rath and Singh, 2007; Rath et al., 2010; Jyoti et al., 2010; Gundewar, 2011; Özcan and Çelik, 2016; Das and Sarkar, 2018). Therefore, it is essential to identify suitable beneficiation methods and develop flowsheets for different origin iron ores.

The most commonly used beneficiation methods for iron ores are the gravity and magnetic separation techniques (Seifelnassr et al., 2012; Wills and Finch, 2016). In addition to this, a lot of developments in

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iron ore processing have been taken place in recent years. The emphasis was on the development of a cost effective flowsheet to beneficiate the low - grade iron ores to produce concentrates suitable for blast furnace, sinter or pellet making. Some of the development features in the processing side are jigging, innovations in spiral concentrator, autogenous grinding, column flotation, high gradient magnetic separators (HGMS), fine screening, shaking table separation etc. (Rath et al., 2013). Physicochemical method i.e. agglomeration and selective flocculation has been taken for further utilization of the tailings and slimes (Panda et al., 2017).

Normally iron ores with 65 % Fe content and above are desirable to achieve better productivity either through blast furnace or direct reduction for the metal iron production. Iron ore with low Fe content and high Al:Si ratio cannot be used directly in any of the processes. The alumina to silica ratio that is typically greater than one possesses serious operational problems during sintering and subsequent smelting in the blast furnace (Srivastava et al., 2001; Muwanguzi et al., 2012). This has been mainly due to the presence of high levels of impurities such as silica and alumina in the raw materials (Dwari et al., 2014). Therefore, research on beneficiation and utilization of low grade iron ore to produce quality raw material is highly essential.

Iron ores usually contain a huge amount of silicates and its presence has been found to have a negative effect on the quality of the iron and also it complicates the process for the production of iron. Thus, it is important that the silicate content of the enriched iron mineral can be reduced as much as possible (Rath et al., 2013).

Detailed initial characterization of the samples were required before developing a suitable beneficiation flowsheet. Limited studies have been carried out based on earlier experience to develop conceptual flowsheet.

In the present work, an iron ore sample which has very low iron grade and high silica content was taken up for detailed material characterization and subsequent physical beneficiation studies. Iron ore is processed for production of a concentrate of an economic grade and recovery suitable for the sinter/ pellet. Different physical beneficiation methods were performed to ore in different size fractions. Effect of particle size and operational parameters on the performance was also evaluated.

## 2. Raw Material

The low - grade iron ore sample was taken from an iron ore mine, in Central Anatolia Region, Turkey. The representative samples were obtained from the open pit mine area (Figure 1). Approximately 10 tons of mine excavated and crushed down to 6 mm in the plant crushing circuit. Then, representative sample were transported to laboratory to perform detailed characterization and beneficiation tests.

## 3. Material Characterization and Previous Tests

The as - received iron ore sample was subjected to material characterization in terms of particle size analysis, XRD analysis, size wise chemical analysis. In addition, Davis tube test and heavy liquid test for were performed to evaluate the behavior of iron ore sample in magnetic separation, jigging and shaking table. These steps are described in detail in the following sections and corresponding observations are presented. A simplified flowsheet of experimental procedure is shown in Figure 2.

### 3.1. Particle Size Analysis

The particle size distribution of the iron ore was determined by using the Vibratory Laboratory Sieve Shaker (RETSCH AS 200 basic). According to results, the 80% of the sample ($d_{80}$) is finer than 3.44 mm and the $d_{50}$ value is 1.64 mm. Particle size distribution of iron ore sample is represented in Figure 3.

### 3.2. Qualitative Mineralogical Analysis and Ore Microscopy

Qualitative mineralogical analysis of the ore sample was performed to identify its mineralogical composition and textural properties. Qualitatively, the iron ore sample revealed a mineralogy composed carbonate minerals, mica minerals, silicate minerals, opaque minerals and trace amount of sphen.

Microscopic analysis was performed to identify the ore minerals in the sample. Analysis was performed by using optical microscope and thin sections of the representative ore sample. Analysis results was revealed that the ore contains mainly magnetite, minor amount of limonite, chromite, pyrite and trace amount of hematite as ore minerals.


Figure 1- Excavation of iron ore sample from open pit area.

3.3. Chemical Analysis

Chemical analysis of samples was conducted by using XRF method. Size wise chemical analysis of iron ore sample is presented in Table 1. The sample contains 21.91 % Fe, which is very low grade in nature. The impurities are $SiO_2$ 26.25%, MgO 20.48%, CaO 5.85%, $Al_2O_3$ 1.86% and loss on ignition (LOI) 12.71%.

It can be observed from Table 1 that the main impurities are silica and magnesia in the ore. According to results, total iron and silica grades of size fractions are close to each other. Increase in fineness increases the total iron grade and decreases the silica grade marginally. The finest size fraction of feed has the highest total iron grade. From the Table 1 and size - analysis data, it can be found that +0.212 mm fraction contains more than 80% of total iron and 85% of silica and magnesia All impurities are concentrated in the coarser size fractions. This ore cannot be used either in blast furnace or sponge iron making without a physical beneficiation.

3.4. Davis Tube Tests

A Davis tube (DT) is a laboratory instrument designed to separate small samples of magnetic ores into strongly magnetic and weakly magnetic fractions. It has become standard laboratory equipment used for the assessment of the separability of magnetic ores by low - intensity magnetic separators (Schulz, 1964; Svoboda, 1987). The Davis tube comprises a 25 mm glass tube that is gyrated at an angle between the poles of a high - intensity electromagnet. The magnetic intensity between the poles is controlled by means of an adjustable autotransformer. The tube is gyrated between the poles in a reciprocating motion at a frequency controlled by an adjustable driving motor.

A number of tests were conducted to determine the impact of magnetic field strength and effect of particle size. Tests at 425, 600, and 732 Gauss were conducted for a grinding size of -500 µm, -300 µm, -150 µm, -75 µm and -45 µm separately. The pulp sample is fed to the top of the Davis tube after which the oscillation motor and wash water are turned on.

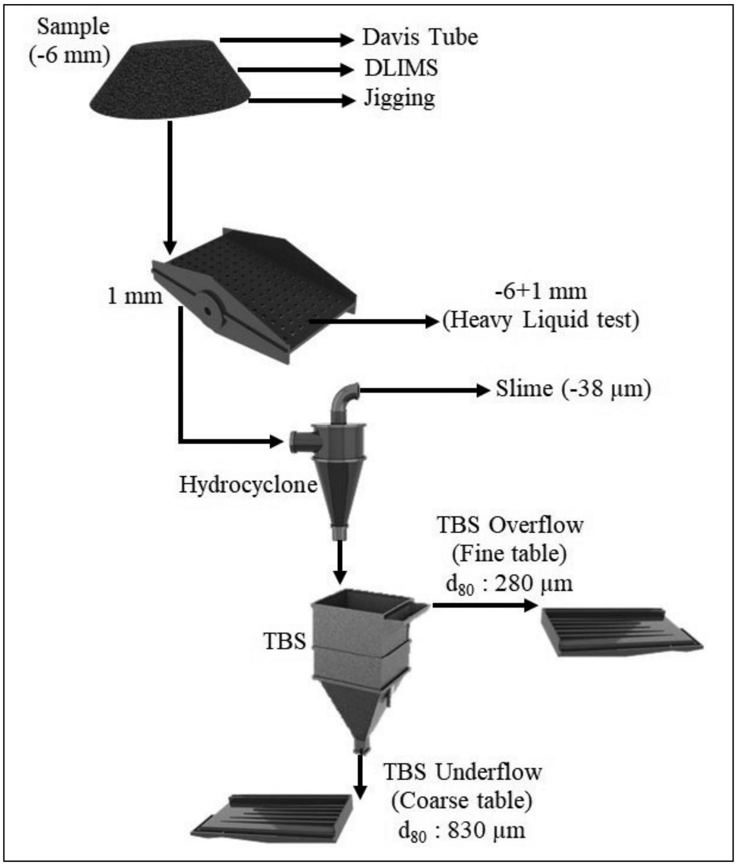


Figure 2- Simplified flowsheet of test procedure.

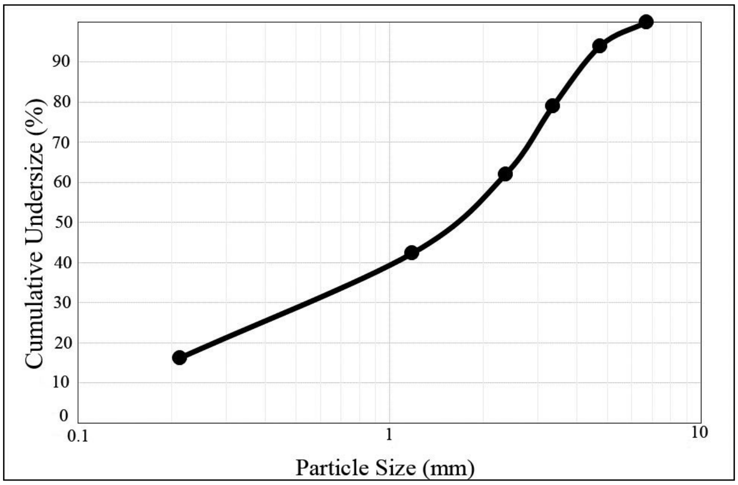


Figure 3- Particle size distribution of iron ore sample.

Nonmagnetic sample collection then commences from the tube outlet. The magnetic concentrate is removed from the tube at the end of each test by turning off the current to the magnets. Chemical analysis of the feed, magnetic and non - magnetic samples of each test was performed. Effect of magnetic field strength and particle size on the total iron grade of magnetic samples are shown in Figure 4.

Davis tube test results revealed that total iron grade of magnetic product can be increased from 21.91% to 65.33% at -75 μm grinding size. Also,

Table 1- Fractional chemical analysis of iron ore sample.

| | | GRADE (%) | | | | | |
|---|---|---|---|---|---|---|---|
| Size fraction (mm) | Weight (%) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ | LOI |
| -6+3.35 | 21.00 | 22.30 | 26.40 | 20.60 | 5.91 | 1.18 | 12.88 |
| -3.35+1.18 | 36.69 | 21.28 | 26.80 | 20.90 | 5.94 | 1.64 | 12.93 |
| -1.18+0.212 | 26.06 | 20.27 | 26.70 | 20.70 | 5.87 | 2.56 | 13.04 |
| -0.212 | 16.25 | 25.45 | 24.10 | 19.05 | 5.51 | 2.12 | 11.45 |
| Feed | 100.00 | 21.91 | 26.25 | 20.48 | 5.85 | 1.86 | 12.71 |
| | | DISTRIBUTION (%) | | | | | |
| Size fraction (mm) | Weight (%) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ | LOI |
| -6+3.35 | 21.00 | 21.37 | 21.12 | 21.12 | 21.23 | 13.31 | - |
| -3.35+1.18 | 36.69 | 35.64 | 37.46 | 37.44 | 37.29 | 32.33 | - |
| -1.18+0.212 | 26.06 | 24.11 | 26.50 | 26.33 | 26.17 | 35.84 | - |
| -0.212 | 16.25 | 18.88 | 14.92 | 15.11 | 15.32 | 18.51 | - |
| Feed | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | - |

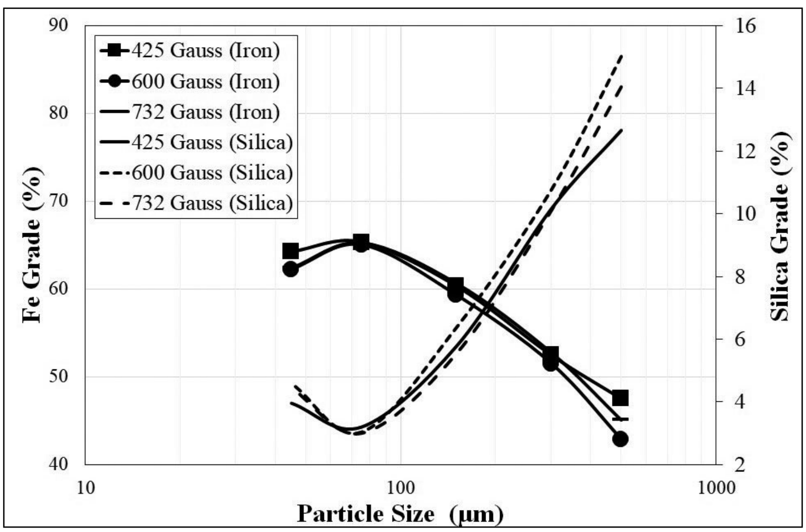


Figure 4- Effect of magnetic field strength and particle size on the total iron and silica grade of magnetic products.

silica grade of the magnetic product can be decreased from 26.25% to 3.20%. Increase in fineness increases the total iron grade of magnetic product significantly. However, magnetic strength field has a marginal effect on product quality. Liberation of iron ore particles is quite acceptable below 100 µm size fractions. According to Davis tube test results 26.33% of the feed material can be concentrated as a magnetic product with an 81.25% Fe recovery. Total iron content in the magnetic product decreasing from 65.33% Fe to 62% Fe with increasing fineness from -75 µm to -45 µm. As stated before, in this sample magnetite is the main iron - bearing phase. However, iron ore consists a portion of weakly magnetic minerals which are hematite and goethite. According to results, it can be concluded that the recovery of these weakly magnetic minerals decreases and can report to non - magnetic product at -45 µm size fraction. According to Davis tube test results the grades of the magnetic concentrates are quite acceptable between -100+45 µm. This may indicate that magnetite can be liberated from gangue sufficiently below 100 µm. It is indicating the suitability of the magnetic separation process only below 100 µm for the studied iron ore sample.

3.5. Heavy Liquid Test

Heavy liquid separation is also known as “sink and float separation” and commercial adaptations of the common laboratory procedure used for separating a mixture of two products having difference in specific gravity (Wills and Napier - Mun, 2006). Laboratory testing may be performed on ores to assess the suitability of dense medium separation (and other gravity methods) and to determine the economic separating density (Angadi et al., 2017). The sink and float studies of -6+1.18 mm fraction at two specific gravities viz. 2.85 g/cm$^3$, and 3.30 g/cm$^3$ were carried out to evaluate the liberation characteristics of iron and gangue particles in coarser size fractions.

Pure tungsten carbide and sodium polytungstate mixture was used to obtain high densities as described in the study of Aghlmandi (Aghlmandi et al., 2017). Then, sample was introduced into the liquid of highest density. The float product was removed and washed and placed in the liquid of next lower density. All the products were finally drained, washed, dried, weighed and analyzed, to assess the performance of the heavy liquid test. Results of heavy liquid test are tabulated in Table 2.

The high - weight percentage (89.03%) and low total iron grade of the float fractions (18.47%) of 3.30 g/cm$^3$ indicate the presence of liberated gangue in this density class. Approximately 95% of the silica can be rejected in float products. Even so, the silica grade of 3.30 g/cm$^3$ sink product is 11.20% $SiO_2$. This indicates that there is some locked gangue material associated with the sink product.

The results of the study at 3.30 g/cm$^3$ density indicated that a total iron of 47.46% Fe could be obtained at a recovery of 24.04%. Silica grade can be decreased from 26.65% $SiO_2$ to 11.20% $SiO_2$. However, total iron recovery in the sink product is quite low. Approximately 76% of the total iron rejects in the float products. The results obtained from the heavy liquid test indicate that the ore is not suitable for obtain a sinter/pellet grade concentrate in coarser size fractions. These results also show that liberation degree of +1 mm is quite insufficient. Coarse size gravity separation is not suitable for this ore.

## 4. Beneficiation Studies, Results and Discussion

It is evident from the detailed characterization of the low grade iron ore that liberation of the ore is insufficient in coarser size fractions (+1 mm). A high grade concentrate can be obtained below 75 µm with a low silica content. According to characterization, different beneficiation tests were designed and performed to obtain concentrates in different size fractions separately. Effect of operational parameters also evaluated.

4.1. Dry Low Intensity Magnetic Separation (DLIMS) Studies

It is well known from the characterization tests that liberation of the ore is insufficient in coarser size fractions. To obtain different concentrates, a number

Table 2- Heavy liquid test results.

| | | GRADE (%) | | | | |
|---|---|---|---|---|---|---|
| Size fraction (mm) | Weight (%) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
| 2.85 g/cm$^3$ Float | 76.25 | 16.49 | 29.80 | 23.10 | 6.46 | 1.51 |
| 3.30 g/cm$^3$ Float | 12.78 | 30.31 | 21.12 | 16.65 | 4.96 | 1.45 |
| 3.30 g/cm$^3$ Sink | 10.97 | 47.46 | 11.20 | 9.56 | 3.37 | 1.21 |
| Feed (-6+1.18 mm) | 100.00 | 21.65 | 26.65 | 20.79 | 5.93 | 1.47 |
| | | DISTRIBUTION (%) | | | | |
| Size fraction (mm) | Weight (%) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
| 2.85 g/cm$^3$ Float | 76.25 | 58.07 | 85.26 | 84.72 | 83.07 | 78.42 |
| 3.30 g/cm$^3$ Float | 12.78 | 17.89 | 10.12 | 10.23 | 10.69 | 12.54 |
| 3.30 g/cm$^3$ Sink | 10.97 | 24.04 | 4.61 | 5.04 | 6.23 | 9.04 |
| Feed (-6+1.18 mm) | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |

of tests were conducted with variable current by using -6 mm sample. In the experiments, the feed rate was kept constant to create a mono particle layer. While the current was set to obtain a clean tail, magnetic field variation (732, 885 and 1200 Gauss) was examined whether it has an effect on grade and recovery. Test results are tabulated in Table 3 and Table 4 for magnetic and non - magnetic products respectively.

It can be seen from Table 3 that total iron grade of the magnetic concentrates decreases with increasing magnetic field intensity. The high recovery of impurities is due to the fact that a large portion of the locked particles reported to the magnetic fraction. The obtained results show that the DLIMS of the -6 mm sample reveals poor separation performance as the magnetic products still has high silica content (>22%) and iron losses in the non - magnetic product. This may be related to the low degree of liberation. Thus, a sufficient concentrate could not be obtained in +1 mm by using DLIMS.

4.2. Jigging

A laboratory scale mineral jig fitted with screen was used for the jigging studies. The cross sectional area of the jig is 10.5x10.5 cm. It has constant stroke lengths with a hutch which convincingly maintains pulsation of water flow for effective separation of light and heavies. The effects of water velocity on jigging was studied by using -6 mm iron ore sample. Two jigging tests were carried out in a batch mode. Each test was performed for 15 minutes. The samples were collected after allowing the jig to stabilize for a period of 5 minutes. The jig pressure varied from 0.1 to 0.2 bar. The effect of pressure on concentrate weight, grade and recovery was evaluated. The concentrates and tailings in jigging operations were collected, dried, weighed and analyzed. The chemical analysis results are tabulated in Table 5 and Table 6 for 0.1 and 0.2 bar respectively.

Jigging results shows that a higher grade concentrate can be obtained by using higher pressure.

Table 3- Magnetic products of DLIMS test.

| | | GRADE (%) | | | | |
|---|---|---|---|---|---|---|
| Magnetic Field (Gauss) | Weight (%) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
| 732 | 58.57 | 30.29 | 22.37 | 18.54 | 4.00 | 1.18 |
| 885 | 68.77 | 28.11 | 23.56 | 19.08 | 4.33 | 1.28 |
| 1200 | 76.85 | 25.98 | 24.71 | 19.90 | 4.86 | 1.41 |
| | | RECOVERY (%) | | | | |
| Magnetic Field (Gauss) | Weight (%) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
| 732 | 58.57 | 80.97 | 49.91 | 53.00 | 40.04 | 37.27 |
| 885 | 68.77 | 88.25 | 61.71 | 64.04 | 50.98 | 47.21 |
| 1200 | 76.85 | 91.14 | 72.35 | 74.65 | 63.95 | 58.03 |

Table 4- Non-magnetic products of DLIMS test.

| | | GRADE (%) | | | | |
|---|---|---|---|---|---|---|
| Magnetic Field (Gauss) | Weight (%) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
| 732 | 41.43 | 10.06 | 31.74 | 23.24 | 8.46 | 2.82 |
| 885 | 31.23 | 8.24 | 32.19 | 23.59 | 9.18 | 3.15 |
| 1200 | 23.15 | 8.38 | 31.36 | 22.43 | 9.10 | 3.37 |
| | | RECOVERY (%) | | | | |
| Magnetic Field (Gauss) | Weight (%) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
| 732 | 41.43 | 19.03 | 50.09 | 47.00 | 59.96 | 62.73 |
| 885 | 31.23 | 11.75 | 38.29 | 35.96 | 49.02 | 52.79 |
| 1200 | 23.15 | 8.86 | 27.65 | 25.35 | 36.05 | 41.97 |

Table 5- Jigging results of 0.1 bar test condition.

| | | GRADE (%) | | | | |
|---|---|---|---|---|---|---|
| Product | Weight (%) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
| Feed | 100.00 | 21.91 | 26.25 | 20.48 | 5.85 | 1.86 |
| Concentrate | 33.59 | 27.38 | 22.7 | 18.15 | 5.38 | 1.74 |
| Tail | 66.41 | 19.14 | 28.05 | 21.66 | 6.08 | 1.92 |
| | | RECOVERY (%) | | | | |
| Product | Weight (%) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
| Feed | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| Concentrate | 33.59 | 41.98 | 29.05 | 29.76 | 30.92 | 31.40 |
| Tail | 66.41 | 58.02 | 70.95 | 70.24 | 69.08 | 68.60 |

Table 6- Jigging results of 0.2 bar test condition.

| | | GRADE (%) | | | | |
|---|---|---|---|---|---|---|
| Product | Weight (%) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
| Feed | 100.00 | 21.91 | 26.25 | 20.48 | 5.85 | 1.86 |
| Concentrate | 10.45 | 33.10 | 19.20 | 15.60 | 4.96 | 1.60 |
| Tail | 89.55 | 20.60 | 27.07 | 21.05 | 5.95 | 1.89 |
| | | RECOVERY (%) | | | | |
| Product | Weight (%) | Fe | SiO2 | MgO | CaO | $Al_2O_3$ |
| Feed | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| Concentrate | 10.45 | 15.78 | 7.64 | 7.95 | 8.86 | 8.98 |
| Tail | 89.55 | 84.22 | 92.36 | 92.05 | 91.14 | 91.02 |

It is possible to obtain an iron concentrate of 33.10% Fe with 15.78% recovery. The jig tail contains 20.60% Fe, which is quite high. Thus a sufficient concentrate could not be obtained in +1 mm by using jigging as predicted by the results of the sink - float tests. Jig tail samples of 0.1 bar and 0.2 bar test conditions were subjected to fractional chemical analysis to know the distribution of iron in the fractions (Table 7 and Table 8).

It is observed from Table 7 and Table 8 that total iron grades of size fractions are close to each other in both tailing samples. The distributions of total iron, silica and magnesia in the tailings are also very similar. These results show that the total iron losses in both jig pressures is caused by locked particles.

## 4.3. Shaking Table Test

Shaking table tests were performed on the -1 mm size fraction by using laboratory scale hydrocyclone, 100x100 mm teetered bed separator (TBS), and shaking table (500×1200 mm). The -1 mm sample was first classified in a 50 mm hydrocyclone to remove the ultra - fines. A number of tests were conducted by varying spigot and inlet pressure. Desliming tests were aimed to rejecting ultrafine particles and obtaining a highest iron recovery in the hydrocyclone underflow. Then, the best sample was fed to TBS to obtain narrow size fractions for shaking table tests (Figure 2). To obtain a high grade final concentrate, wash water rate adjusted 15 liters per minute (lpm) for coarse table test and 10 lpm for fine table test. Tilt angle (5°) was kept at maximum during the shaking table tests. Feed solid content was 25%. Approximately 200 kg of sample were used during shaking table tests. During the tests a large number of samples were taken to obtain grade recovery relationship and to determine table performance. The view of shaking table test is given in Figure 5. All samples obtained in each step of shaking table tests were dried, weighed and analyzed, to assess the performance of the beneficiation. Desliming test results are tabulated in Table 9.

The best result was obtained by using a 1 mm spigot opening and 0.5 bar cyclone feed pressure. As

Table 7- Fractional chemical analysis of jig tail (0.1 bar).

| | | TENNÖR (%) | | | | |
|---|---|---|---|---|---|---|
| Size Fraction (mm) | Weight (%) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
| -6+3.35 | 12.58 | 19.82 | 28.55 | 21.52 | 5.83 | 1.46 |
| -3.35+1.18 | 31.48 | 18.57 | 28.82 | 22.33 | 6.14 | 1.69 |
| -1.18 | 55.94 | 19.31 | 27.50 | 21.32 | 6.11 | 2.16 |
| | | DISTRIBUTION (%)) | | | | |
| Size Fraction (mm) | Weight (%) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
| -6+3.35 | 12.58 | 13.03 | 12.81 | 12.50 | 12.06 | 9.59 |
| -3.35+1.18 | 31.48 | 30.54 | 32.34 | 32.44 | 31.78 | 27.66 |
| -1.18 | 55.94 | 56.43 | 54.85 | 55.06 | 56.16 | 62.75 |

Table 8- Fractional chemical analysis of jig tail (0.2 bar).

| | | GRADE (%) | | | | |
|---|---|---|---|---|---|---|
| Size Fraction (mm) | Weight (%) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
| -6+3.35 | 16.07 | 18.70 | 28.41 | 22.11 | 6.28 | 1.25 |
| -3.35+1.18 | 33.98 | 19.43 | 28.01 | 21.81 | 6.23 | 1.51 |
| -1.18 | 49.94 | 22.01 | 26.00 | 20.20 | 5.65 | 2.36 |
| | | DISTRIBUTION (%)) | | | | |
| Size Fraction (mm) | Weight (%) | Fe | SiO2 | MgO | CaO | $Al_2O_3$ |
| -6+3.35 | 16.07 | 14.59 | 16.87 | 16.88 | 16.96 | 10.59 |
| -3.35+1.18 | 33.98 | 32.05 | 35.16 | 35.20 | 35.57 | 27.22 |
| -1.18 | 49.94 | 53.36 | 47.97 | 47.92 | 47.48 | 62.20 |

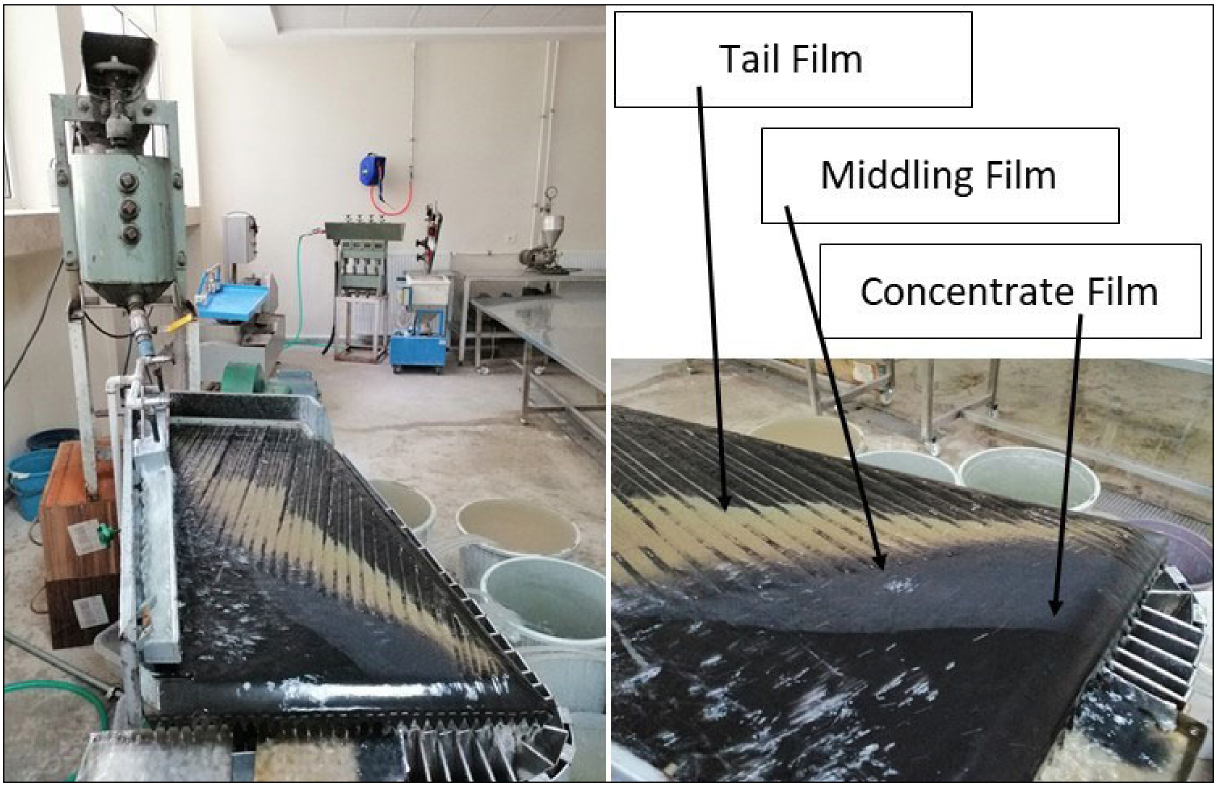


Figure 5- Shaking table test and sampling apparatus.

Table 9- Desliming test results (Best condition).

| | | GRADE (%) | | | | |
|---|---|---|---|---|---|---|
| Product | Weight (%) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
| Cyclone Feed (-1 mm) | 100.00 | 22.26 | 25.70 | 20.07 | 5.73 | 2.39 |
| Cyclone Overflow | 12.13 | 7.97 | 34.40 | 25.50 | 7.60 | 1.85 |
| Cyclone Underflow | 87.87 | 24.23 | 24.50 | 19.32 | 5.47 | 2.47 |
| | | DISTRIBUTION (%)) | | | | |
| Size Fraction (mm) | Weight (%) | Fe | SiO2 | MgO | CaO | $Al_2O_3$ |
| Cyclone Feed (-1 mm) | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| Cyclone Overflow | 12.13 | 4.34 | 16.23 | 15.41 | 16.08 | 9.38 |
| Cyclone Underflow | 87.87 | 95.66 | 83.77 | 84.59 | 83.92 | 90.62 |

seen from Table 9, 87.87% of the feed material by weight was collected as an underflow a total iron grade of 24.23% Fe and a total iron recovery of 95.66%. Only 4.34% of the total iron in the hydrocyclone feed was rejected in slime fraction. According to particle size analysis 100% of the slime fraction was finer than 38 µm.

It is well known that ultrafine entrainment to the gravity concentration processes results in relatively lower efficiency value. The alumina bearing minerals particularly, the clay containing impurities are very finely disseminated in the iron ore matrix. Therefore, it can be concluded that an efficient desliming positively effects the shaking table performance.

In addition to this, if particles are fed to a shaking table in narrow sizes, the effect of size over density is eliminated, and besides beneficiation will also be enhanced (Das et al., 2009). Hydrocyclone underflow sample was divided to two narrow size fractions by using TBS. The effect of size on the shaking table performance was also evaluated. TBS test results are tabulated in Table 10.

It can be seen in Table 10 that approximately 60% of the TBS feed material was reported to underflow (coarse) fraction. In terms of chemical analyses of TBS product, no significant difference can be determined. TBS products were used in shaking table tests separately. Shaking table test results of TBS underflow and TBS overflow are tabulated in Table 11 and Table 12 respectively.

According to Table 11 a high grade concentrate can be obtained from coarse table test. As it can be seen in Table 11 that only 7.37% of the feed material can be obtained as a concentrate with a total iron grade of 65.72% Fe and 2.46% $SiO_2$. Approximately 19% of the total iron in the feed can be recovered in the

Table 10- TBS test results.

| | | | GRADE (%) | | | | |
|---|---|---|---|---|---|---|---|
| Product | Weight (%) | $d_{80}$ (mm) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
| TBS Feed | 100.00 | 0.70 | 24.23 | 24.50 | 19.32 | 5.47 | 2.47 |
| TBS Underflow | 60.02 | 0.83 | 25.49 | 23.49 | 18.29 | 5.32 | 2.34 |
| TBS Overflow | 39.98 | 0.28 | 22.34 | 26.02 | 20.86 | 5.71 | 2.66 |
| | | | DISTRIBUTION (%)) | | | | |
| Product | Weight (%) | $d_{80}$ (mm) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
| TBS Feed | 100.00 | 0.70 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| TBS Underflow | 60.02 | 0.83 | 63.14 | 57.54 | 56.83 | 58.31 | 56.90 |
| TBS Overflow | 39.98 | 0.28 | 36.86 | 42.46 | 43.17 | 41.69 | 43.10 |

Table 11- Shaking table test results of TBS underflow (Coarse fraction).

| | | GRADE (%) | | | | |
|---|---|---|---|---|---|---|
| Product | Weight (%) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
| Table Feed | 100.00 | 25.49 | 23.49 | 18.29 | 5.32 | 2.34 |
| Concentrate 1 | 3.37 | 67.64 | 1.52 | 2.01 | 0.35 | 0.31 |
| Concentrate 2 | 2.00 | 66.46 | 2.36 | 2.69 | 0.65 | 0.39 |
| Concentrate 3 | 1.99 | 61.71 | 4.16 | 4.14 | 1.41 | 0.52 |
| Middling 1 | 46.86 | 28.18 | 21.30 | 16.80 | 5.51 | 2.00 |
| Middling 2 | 26.75 | 19.17 | 27.20 | 21.00 | 6.23 | 2.43 |
| Tail 1 | 13.45 | 13.61 | 30.50 | 23.30 | 5.81 | 3.08 |
| Tail 2 | 5.58 | 8.71 | 34.90 | 26.20 | 4.21 | 5.51 |
| | | RECOVERY (%) | | | | |
| Product | Weight (%) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
| Table Feed | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| Concentrate 1 | 3.37 | 8.96 | 0.22 | 0.37 | 0.22 | 0.45 |
| Concentrate 2 | 2.00 | 5.21 | 0.20 | 0.29 | 0.24 | 0.33 |
| Concentrate 3 | 1.99 | 4.82 | 0.35 | 0.45 | 0.53 | 0.44 |
| Middling 1 | 46.86 | 51.80 | 42.49 | 43.04 | 48.55 | 40.09 |
| Middling 2 | 26.75 | 20.12 | 30.98 | 30.72 | 31.34 | 27.81 |
| Tail 1 | 13.45 | 7.18 | 17.46 | 17.13 | 14.69 | 17.72 |
| Tail 2 | 5.58 | 1.91 | 8.29 | 7.99 | 4.42 | 13.15 |

Table 12- Shaking table test results of TBS overflow (Fine fraction).

| | | GRADE (%) | | | | |
|---|---|---|---|---|---|---|
| Product | Weight (%) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
| Table Feed | 100.00 | 22.34 | 26.02 | 20.86 | 5.71 | 2.66 |
| Concentrate 1 | 3.74 | 65.72 | 1.68 | 2.23 | 0.34 | 0.17 |
| Concentrate 2 | 8.59 | 64.18 | 2.37 | 2.82 | 0.77 | 0.22 |
| Concentrate 3 | 9.27 | 48.86 | 8.91 | 8.14 | 3.65 | 0.81 |
| Middling 1 | 7.92 | 19.73 | 24.18 | 20.16 | 8.54 | 2.10 |
| Middling 2 | 17.35 | 13.27 | 29.68 | 24.08 | 7.42 | 2.93 |
| Tail 1 | 35.85 | 11.30 | 33.57 | 26.52 | 6.58 | 3.34 |
| Tail 2 | 17.28 | 11.18 | 33.73 | 26.01 | 5.61 | 3.96 |
| | | RECOVERY (%) | | | | |
| Product | Weight (%) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
| Table Feed | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| Concentrate 1 | 3.74 | 10.99 | 0.24 | 0.40 | 0.22 | 0.24 |
| Concentrate 2 | 8.59 | 24.66 | 0.78 | 1.16 | 1.16 | 0.71 |
| Concentrate 3 | 9.27 | 20.27 | 3.18 | 3.62 | 5.93 | 2.84 |
| Middling 1 | 7.92 | 6.99 | 7.36 | 7.65 | 11.85 | 6.25 |
| Middling 2 | 17.35 | 10.30 | 19.79 | 20.03 | 22.55 | 19.12 |
| Tail 1 | 35.85 | 18.13 | 46.25 | 45.59 | 41.31 | 45.06 |
| Tail 2 | 17.28 | 8.65 | 22.40 | 21.55 | 16.97 | 25.78 |

concentrate. However, approximately 75% of the feed material by weight reports to middling. 71.92% of the total iron in the feed losses in the middling stream. Total iron losses in the tail stream is quite low (9.09%) for coarse fraction.

A high grade concentrate can be obtained from fine table test as well. According to results, 12.32% of the feed material can be obtained as a concentrate with a total iron grade of 64.65% Fe and 2.16% $SiO_2$. Approximately 35% of the total iron in the feed can be recovered in the concentrate. In the fine table test approximately 35% of the feed material by weight reports to middling. 37.57% of the total iron in the feed losses in the middling stream which is lower than coarse table test. Total iron losses in the tail stream is 26.78% for fine fraction.

Construction of grade/recovery curves is one of the well - accepted methods of assessing performance of separation units in mineral processing. Grade/recovery curves were constructed to evaluate the effect of size on the table performances (Figure 6).

It can be observed from Figure 6 that shaking table can produce a high grade iron concentrate (>65% Fe) with lower recoveries independent to feed size. The grade/recovery curve obtained from coarse table was truncated and flat in appearance as it generated concentrates with marginal total iron recoveries. Figure 6 shows that there are high grade products in the range of 20 - 70% recovery for the fine shaking table, while there is no data in the same range for the coarse shaking table. These data show that there are no possibilities to produce a high or intermediate grade product (middling) on coarse shaking table. This result can be explained by insufficient liberation of coarser size fractions. The grade/recovery relationship for the fine table followed a characteristic curve extending the arc along the ordinate, which indicates the ability of this size fraction to generate high - grade concentrates with higher recovery of total iron values than coarse table. The grade/recovery curve method presented in Figure 6 indicates that the performance of fine table was better than the coarse table. It can be concluded that the higher liberation degree of finer fraction can result in a better separation efficiency on the fine table test.

## 5. Flowsheet Development Studies

It is evident from the beneficiation studies of the low grade iron ore that a sinter/pellet grade product cannot be produced in coarser size fraction (+1 mm) by using gravity and/or magnetic separation methods. Therefore, a flowsheet for -1 mm has been considered. A 80 tph grinding and concentration circuit was developed. Flowrates of each stream were calculated by using experimental data. JKSimmet software was used to flowsheet development, mass balance and simulation of circuit. The developed flowsheet

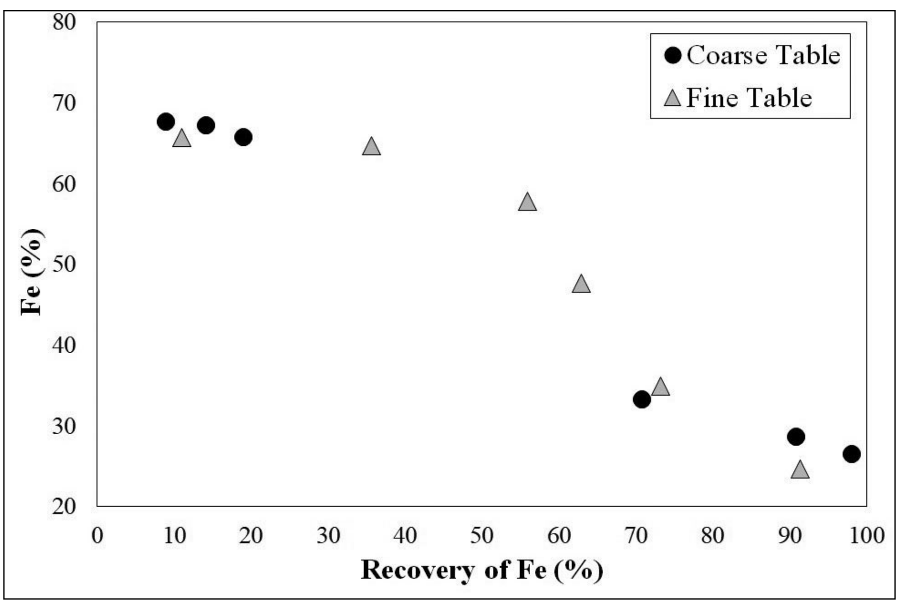


Figure 6- Grade/recovery curves of shaking table tests.

includes a crushing - grinding circuit and two stages of gravity concentration circuit to obtain a high grade concentrate. The middling of the gravity circuit regrinds and concentrated in the three stage magnetic separation. Figure 7 shows the simplified view of developed flowsheet.

A rod mill and a 1 mm aperture screen were used in grinding circuit. Plant feed fed to 1 mm aperture screen. The screen oversize reports to the rod mill. Rod mill discharge and screen undersize streams are fed to desliming cyclone. Cyclone overflow stream reject as slime and cyclone underflow stream fed to spiral concentration circuit. Spiral concentration circuit includes rougher and scavenger stages. Spiral concentration circuit aims to obtain a pre concentrate by using small number of equipment. In the spiral circuit design, the weight, grade and efficiency values obtained from the desliming studies were used. The amount of concentrate to be obtained from the spiral circuit is the amount of TBS feed obtained from experimental studies. For the concentrates to be obtained from the rougher and scavenger stages, possible grade values were predicted and the grade and recovery calculations were completed. The performance of the spiral circuit has been determined based on these values.

In the spiral circuit rougher tail fed to scavenger spiral. Concentrates of rougher and scavenger spirals

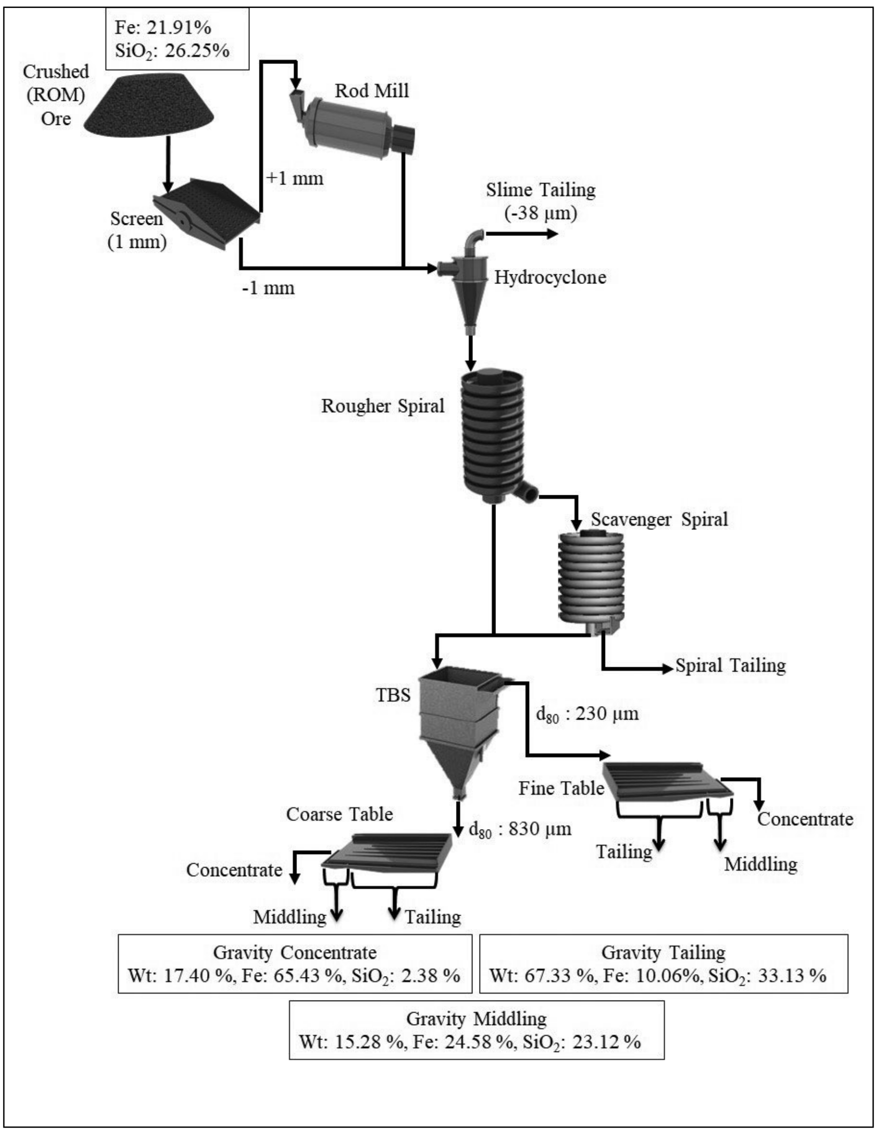


Figure 7- Simplified view of developed flowsheet.

are fed to TBS. TBS separates the stream into two size fractions as coarse and fine. Final concentrate is obtained in shaking tables. Mass balance, water balance and solid content of the beneficiation circuit is tabulated in Table 13.

Table 13- Flowrates of developed flowsheet after mass balance.

| STREAM | Solid Tonnage (tph) | Water Tonnage (tph) | Solid Content (%) |
|---|---|---|---|
| Feed | 80 | 80 | 50 |
| Rod Mill Discharge | 51.70 | 17.23 | 75.00 |
| Water 1 (rod mill feed) | - | 15.63 | - |
| Water 2 (cyclone feed) | - | 0.00 | - |
| 1mm Screen Undersize | 28.30 | 78.40 | 26.52 |
| 1mm Screen Oversize | 51.70 | 1.60 | 97.00 |
| Cyclone Feed | 80.00 | 95.63 | 45.55 |
| Cyclone Overflow (slime) | 12.38 | 72.68 | 14.56 |
| Cyclone Underflow | 67.62 | 22.95 | 74.66 |
| Rougher Spiral Concentrate | 24.96 | 10.14 | 71.10 |
| Rougher Spiral Tail | 42.66 | 91.28 | 31.85 |
| Water 3 (Cyclone Underflow) | - | 78.47 | - |
| Scavenger Spiral Concentrate | 15.14 | 9.13 | 62.39 |
| Scavenger Spiral Tail | 27.51 | 82.15 | 25.09 |
| TBS Feed | 40.10 | 32.81 | 55.00 |
| TBS Underflow (coarse) | 22.38 | 4.92 | 81.97 |
| TBS Overflow (fine) | 17.72 | 27.89 | 38.86 |
| Coarse Table Concentrate | 10.23 | 8.37 | 55.00 |
| Coarse Table Middling | 5.59 | 6.83 | 45.00 |
| Coarse Table Tail | 6.56 | 37.01 | 11.16 |
| Fine Table Concentrate | 3.69 | 3.41 | 52.00 |
| Fine Table Middling | 6.63 | 9.16 | 42.00 |
| Fine Table Tail | 7.41 | 40.62 | 12.23 |
| Water 4 (TBS Feed) | - | 95.00 | - |
| Water 5 (coarse table) | - | 47.29 | - |
| Water 5 (fine table) | - | - | - |

It can be revealed from Table 13. that approximately 50% of the feed reports to shaking table circuit. According to grade/recovery calculations, 86% of the total iron can be pre concentrated by spiral circuit. The calculated product specifications of gravity concentration circuit are tabulated in Table 14.

From the gravity concentration flowsheet, it is possible to obtain a concentrate containing 65.43% Fe, 2.38% $SiO_2$, 2.74% MgO, 0.70% CaO and 0.34% $Al_2O_3$. Total iron recovery of gravity concentration circuit is 51.96%. Impurity rejection values for the gangue contents in this flowsheet were higher than 80%. According to calculations approximately 17% of the total feed can be obtained as middling. Total iron recovery of middling is 17.13%. As for the middling, re - grind or middling beneficiation options can be considered because of the particularly high grade and high weight percent of this product. It is well known from the Davis tube test that liberation degree was quite high below 75 µm. In this condition a high grade iron concentrate can be obtained by using magnetic separation. According to results, a middling beneficiation circuits including a regrind mill and three stages of magnetic separation was developed (Figure 8).

Middling concentration circuit includes a regrind ball mill closed circuit with a hydrocyclone. Cyclone underflow fed to regrind mill and cyclone overflow fed to three stages low intensity magnetic separation. Performance of three stage magnetic separation circuit as calculated by using experimental and mass balance results (Table 15).

Table 14- Product specifications of gravity concentration circuit.

| | | GRADE (%) | | | | |
|---|---|---|---|---|---|---|
| Product | Weight (%) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
| R.O.M Ore | 100.00 | 21.91 | 26.25 | 20.48 | 5.85 | 1.86 |
| Gravity Concentrate | 17.40 | 65.43 | 2.38 | 2.74 | 0.70 | 0.34 |
| Gravity Middling | 15.28 | 24.58 | 23.12 | 18.64 | 6.26 | 2.16 |
| Gravity Tail | 67.32 | 10.06 | 33.13 | 25.48 | 7.09 | 2.18 |
| | | RECOVERY (%) | | | | |
| Product | Weight (%) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
| R.O.M Ore | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| Gravity Concentrate | 17.40 | 51.96 | 1.58 | 2.32 | 2.08 | 3.18 |
| Gravity Middling | 15.28 | 17.13 | 13.45 | 13.90 | 16.34 | 17.78 |
| Gravity Tail | 67.33 | 30.90 | 84.97 | 83.77 | 81.59 | 79.05 |

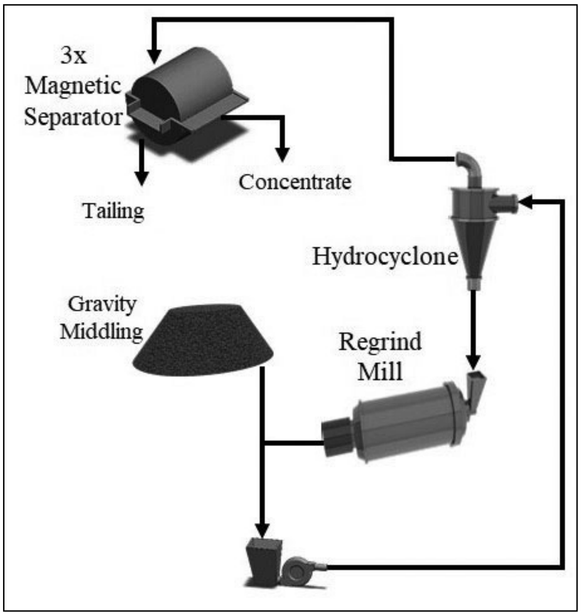


Figure 8- Middling regrind and concentration circuit.

After regrinding and three stages of magnetic separation, middling of tables can be concentrated up to 65.33% Fe, 3.20% $SiO_2$, 3.05% MgO, 0.69% CaO and 0.24% $Al_2O_3$. Total iron recovery of magnetic separation circuit is 70.00%. Impurity rejection values for the gangue contents in this flowsheet were higher than 95%. As a conclusion the overall performance of circuit and product specifications was calculated. The overall product specifications of circuit are listed in Table 16.

It can be observed from Table 16 that specifications of final concentrate are suitable for the pellet/sinter making (Roy et al., 2007; Shobhana et al., 2012; Harman, 2012; Mark and Henry, 2016). Silica content of R.O.M. ore could be reduced down to 2.54% $SiO_2$. Impurity rejection values for the gangue contents were higher than 95% in the overall. In industry the general acceptance limit of $SiO_2$ for sinter/pellet feed is given as in the range of 1%–5% in the references (Roy et al., 2007; Shobhana et al., 2012; Harman, 2012; Mark and Henry, 2016). It is also reported that $SiO_2$ content

Table 15- Product specifications of magnetic separation circuit.

| | | GRADE (%) | | | | |
|---|---|---|---|---|---|---|
| Product | Weight (%) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
| Gravity Middling | 100.00 | 24.58 | 23.12 | 18.64 | 6.26 | 2.16 |
| Magnetic Concentrate | 26.33 | 65.33 | 3.20 | 3.05 | 0.69 | 0.24 |
| Magnetic Tail | 73.67 | 10.01 | 30.24 | 24.21 | 8.25 | 2.85 |
| | | RECOVERY (%) | | | | |
| Product | Weight (%) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
| Gravity Middling | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| Magnetic Concentrate | 26.33 | 70.00 | 3.64 | 4.31 | 2.90 | 2.92 |
| Magnetic Tail | 73.67 | 30.00 | 96.36 | 95.69 | 97.10 | 97.08 |

Table 16- Product specifications of final products.

| | | GRADE (%) | | | | |
|---|---|---|---|---|---|---|
| Product | Weight (%) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
| R.O.M Ore | 100.00 | 21.91 | 26.25 | 20.48 | 5.85 | 1.86 |
| Final Concentrate | 21.42 | 65.41 | 2.54 | 2.79 | 0.70 | 0.32 |
| Final Tail | 78.58 | 10.05 | 32.72 | 25.30 | 7.26 | 2.28 |
| | | RECOVERY (%) | | | | |
| Product | Weight (%) | Fe | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
| R.O.M Ore | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| Final Concentrate | 21.42 | 63.96 | 2.07 | 2.92 | 2.55 | 3.70 |
| Final Tail | 78.58 | 36.04 | 97.93 | 97.08 | 97.45 | 96.30 |

can be as high as 9.5% in some cases (Harman, 2012). Based on the analysis of $SiO_2$ and $Al_2O_3$ contents, the alumina to silica ratio of final concentrate can be calculated as 0.12 which is below acceptable limits. According to results it may be concluded that the final concentrate can be used for iron production.

## 6. Conclusion

In this study, possibilities for beneficiation and flowsheet development of a low grade iron ore were evaluated. Detailed material characterization studies were performed to developing the optimum flowsheet for the iron ore sample.

Different physical beneficiation methods were performed to ore to obtain a high grade iron concentrate including jigging, low intensity magnetic separation, and shaking table. Desliming and hydraulic classification also performed to ore to prepare an optimum feed to shaking table test.

A high grade iron concentrate could not be obtained above 1 mm by using DLIMS or jigging methods. This may be related to the low liberation degree of iron ore sample Gravity concentration method can produce a high grade concentrate below 1 mm while an acceptable magnetic concentrate can be obtainable only below 100 μm. The main advantage of the gravity concentration method can be seen as producing a pre concentrate by using spiral concentration. A coarse size pre - concentration below 1 mm has various advantages. An important amount of gangue material can be discarded early in the process. It decreases the amount of material that needs to be treated in downstream process. This significantly reduces the energy and water consumption and operating cost per ton of concentrate. Spiral concentration can be used a pre - concentration method below 1 mm. Spiral concentration can be beneficial to decreasing the numbers of shaking tables and increasing the feed grade of shaking table circuit.

According to results, a high grade iron concentrate can be obtained from shaking table. However, approximately 75% of the feed material by weight reports to middling in coarse table. It shows that liberation degree of -1 mm size fraction is better than +1 mm but also poor. The grade/recovery curve method indicates that the performance of fine table was better than the coarse table. It can be concluded that the higher liberation degree of fine table feed can resulted a better separation efficiency on the test.

The lower recovery values of gravity separation can be increases by using a wet low intensity magnetic separation (WLIMS). Feed size of the WLIMS should be below 100 μm according to Davis Tube tests. A small diameter of regrind mill can be suitable for grinding of table middling stream.

As a conclusion the overall performance of the proposed circuit and product specifications was calculated. According to calculations a final concentrate containing 65.41% Fe, 2.54% $SiO_2$, 2.79% MgO, 0.70% CaO and 0.32% $Al_2O_3$ can be obtained. Overall iron recovery of circuit is 63.96% shows that complex mineralogical composition and liberation characteristics of iron ore sample can limit the recovery and prevents to obtain higher recovery values. Overall gangue rejection recovery of circuit was over 95%. These specifications show that specifications of final concentrate are suitable for the pellet/sinter making.

A grinding size below 100 μm followed by magnetic separation with cleaner and scavenger stages can be discussed as an alternative beneficiation circuit. A decrease of grinding size increases the both grinding costs and total recovery. However, operational costs must be accurately calculated for this situation.

An efficient, low cost and environmentally friendly concentration processes by gravity and magnetic separation were developed for beneficiation of low grade iron ore sample. Through the process, 67.33% of the feed is directly discarded, greatly reducing the ore processing capacity of the magnetic separation circuit. The main benefit of preconcentration is the selective discard of waste from the feed stream, thus improving project economics while reducing the power and amount of material which reports to downstream process.

It should be noted that if the proposed flow sheets are considered for operation, they should be re - evaluated in terms of the number of required equipment, amount of water, and some other operational parameters considering market prices.

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