The present work was submitted to the Faculty of Engineering

Beneficiation and Flowsheet Development of a Tumurtei iron ore: A Case Study

Bachelor Thesis

by
Enkhtuul Gantumur

Supervisor 1 / Examiner 1	Prof. Dr. Thomas Hollenberg
Supervisor 2 / Examiner 2	MSc. Munkhjargal Chimeddorj

Ulaanbaatar, 5/16/2022

Statutory Declaration

Gantumur Enkhtuul Last Name, First Name	15349175224418 Student ID Number

I hereby affirm in lieu of an oath that I provided the submitted bachelor thesis

BENEFICIATION AND FLOWSHEET DEVELOPMENT OF A TUMURTEI IRON ORE: A CASE STUDY

I did not utilize any sources other than those stated. In case that the work is additionally submitted on a data medium, I declare that the written and the electronic form are completely identical. The work was not submitted in the same or similar form to any examination authority.

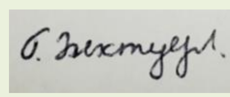
Ulaanbatar/Nalaikh, 12th of May, 2020 Place, Date	 Signature

Table of Contents

Abstract

This case study is performed to investigate the optimum process route to produce iron ore fine with the content of more than 62% Fe and dry concentrate with the content of more than 58% Fe from the iron ore from the Tumurtei mine, using “Wet low-intensity magnetic separation” and Dry Low-Intensity Magnetic separation, respectively.

The aim of this case study is to develop the flowsheet of the Tumurtei iron ore processing plant’s wet processing and wash system by applying the wet and dry magnetic separation. The Fe content of the iron concentrate from the wash system is around 56%. However, the quality requirement for commercial iron ore concentrate is 62% in order to supply an upward treatment plant. Therefore, it is required to increase the Fe grade and reduce the impurities of the iron ore in order to make more value-added products at a higher price.

For this purpose, three samples coded “Feed”, “Screen-1 OS” and “Screen-2 OS” were taken from 3 different processing stages of the wet processing and wash system at the Tumurtei iron ore mine.

The experiment consists of several parts: sample characterization including chemical and size distribution analysis, sample preparation, grinding time determination, and wet and dry magnetic separation process.

The chemical content of the samples was determined at the “Quality control department” of Tumurtei mine’s laboratory of material. According to the chemical analysis result, the initial Fe content of the material was from 42% to 46%. As a result of the wet magnetic beneficiation, the iron content of the concentrate reaches 66%, which means the purpose of the experiment was accomplished on the target, and the impurities in the sample were reduced to a sufficient amount.

Moreover, the Fe content of the dry concentrates of “Screen-1 OS” and “Screen-2 OS” reached 54% and 58% respectively. It can be said that the dry magnetic separation experiment on “Screen-2 OS” was successfully completed. However, the Fe content of sample “Screen-1 OS” couldn’t achieve the target because of its course size. Consequently, it is recommended to crush the ore until the top size becomes less than 3mm for the magnetic separation process.

Acknowledgements

The completion of this thesis would not have been possible without the support of my supervisors, Prof. Dr. Thomas Hollenberg and MSc.Munkhjargal Chimeddorj.

Mrs. Munkhjargal's support was not limited to giving me feedback on my thesis writing and guiding me through the experiments. She also helped me to double-check the result by sending my samples to the “Quality control department” of Tumurtei mine's laboratory of material to measure the chemical composition of those samples for more precise and accurate results.

I express my sincere gratitude to Mr.Baasandorj, laboratory assistant of the raw material processing laboratory at GMIT. He instructed me how to use the laboratory equipment properly in compliance with the safety rules. And he guided me to perform the experiments more professionally and accurately.

Furthermore, I would like to thank my colleague, Ms. Ankhchimeg, Ms. Anujin and Mr.Dugar always supported me in writing this Bachelor's thesis and constantly exchanged their valuable ideas with me.

List of figures

List of Tables

1. Introduction

1.1 Background

Iron ore is a rock mineral mainly containing a metallic iron element, which can be economically efficiently extracted. The iron ores containing more than 60% of magnetite and hematite are called direct shipping ores, directly used as a feed material for iron-making blast furnaces. [1]

1.1.1 Significance of iron ore

Many research institutes point to the rapid growth of the world's population, growing urbanization, and the need for industrialization to increase the demand for steel. It is used in almost every sector of industrialization. For instance, the total steel consumption in 2019 was 1,768Mt: 51% used for buildings and infrastructure, 15% for mechanical equipment, 12% for automobiles, 11% for metal products, and the rest of the percent were used for domestic appliances, electrical equipment and so on).

Iron ore is a primary source of iron for the steel production. Nearly 98 percent of iron ore is used for the steel industry. [2] Therefore, consumption of the iron ore concentrate is described by the demand from steel manufacturing plants.

However, the iron ore concentrates are not directly used in steel manufacturing. In order to make steel from iron ore, it passes several processes. A general process flow diagram of steel manufacturing is shown below Figure 1-1.

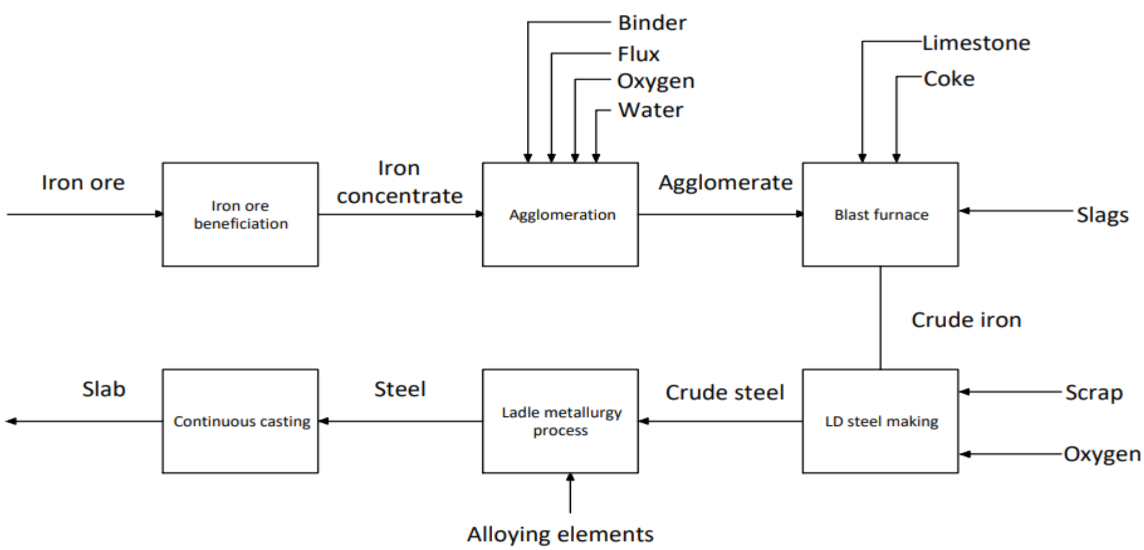


Figure 1. 1 A General process flow diagram of steel manufacturing.

According to Figure 1-1, the iron ore is beneficiated and produces iron concentrate. Then the product is used as a raw material for the agglomeration process. In other words, the iron ore concentrate is directly used for making agglomerates in the pelletizing and sintering plants.

1.1.2 Introduction to Darkhan Metallurgical plant

"Darkhan Metallurgical Plant" JSC was established in Darkhan-Uul aimag in 1990, based on the cooperation agreement between the Governments of Mongolia and Japan. Since the plant was established in 1994, the company has expanded its operations to include mining, processing, metallurgy, and international trade. [3]

Darkhan Metallurgical plant timeline:

- 2017/01 - Establishment of Steel ball factory.
- 2014/12 - Establishment of Wet magnetic concentration plant of iron ore.
- 2014/09 - Opening an open-pit mine on the east side of Tumurtei deposit.
- 2017/07 - Establishment of Iron ore Dry magnetic concentration plant
- 2010/08 - Installed dry magnetic separation line on the Tumurtolgoi mine and produced their first iron ore concentrate.
- 2010 - Implementation of the project called "Mining and Metallurgical complex".
- 2009/09 - Establishment of open-pit mine based on Tumurtolgoi deposit.
- 2002-2006 - Operated under the management contract with Mongolrostsvetmet SOE.
- 1994 - Plant operation completely started.
- 1993/10 - The first ever smelting of steel performed.
- 1990/07 - The foundation of a Metallurgical plant. [3]

1.1.3 Introduction to Tumurtei iron ore mine

"Tumurtei iron ore deposit" is located in Khuder soum of Selenge province, 130 km northeast of Darkhan city and 20 km southwest of Khuder soum. It is connected with the "Bold Tumur Yuruu Gol " LLC's railway by 3.6 km branched railway. The location of the Tumurtei iron ore mine is illustrated in Figure 1-2. [3]

Figure 1. 2 The location of the Tumurte iron ore mine. [4], [5]

Darkhan Metallurgical Plant JSC opened the western part of the east Tumurtei deposit on October 1, 2011 with its own funds and started mining operations. They started mining the eastern part of the east Tumurtei deposit on September 28, 2014.

The deposit consists of three parts:

- Eastern part of east deposit
- Eastern part of west deposit
- Western part of the deposit

The Tumurtei deposit is registered in the State Reserve Fund as having 229 273 thousand tonn reserves. [3]

Tumurtei mine has its own dry concentration plant (equipment supplied by TRIO&Eriez) established in 2014 and additionally installed a fine crushing and separation unit in order to increase Fe content in 2020. The plant has a capacity of 750 tph and produces a dry iron lump and fine ore concentrate with an iron content of more than 56%. [3]

1.1.4 CDE Combe A400 all-in-one wet processing and wash line system at Tumurtei iron ore mine

Darkhan Metallurgical plant has been installed at Tumurtei Iron ore mine wet processing and wash line system called CDE Combo A400 all-in-one in between 2019 to 2020. This system combines five processes on one chassis: Washing, Grading, Dewatering, Water recycling, and Stockpiling. [6] The system produces a higher-value product with 56% iron content from the slaggy and sandy iron ore feed.

The system consists of a feed hopper, belt conveyor, screen, hydro cyclone classifier, dewatering system, control system, and so on as shown in the Figure 1-3 below.

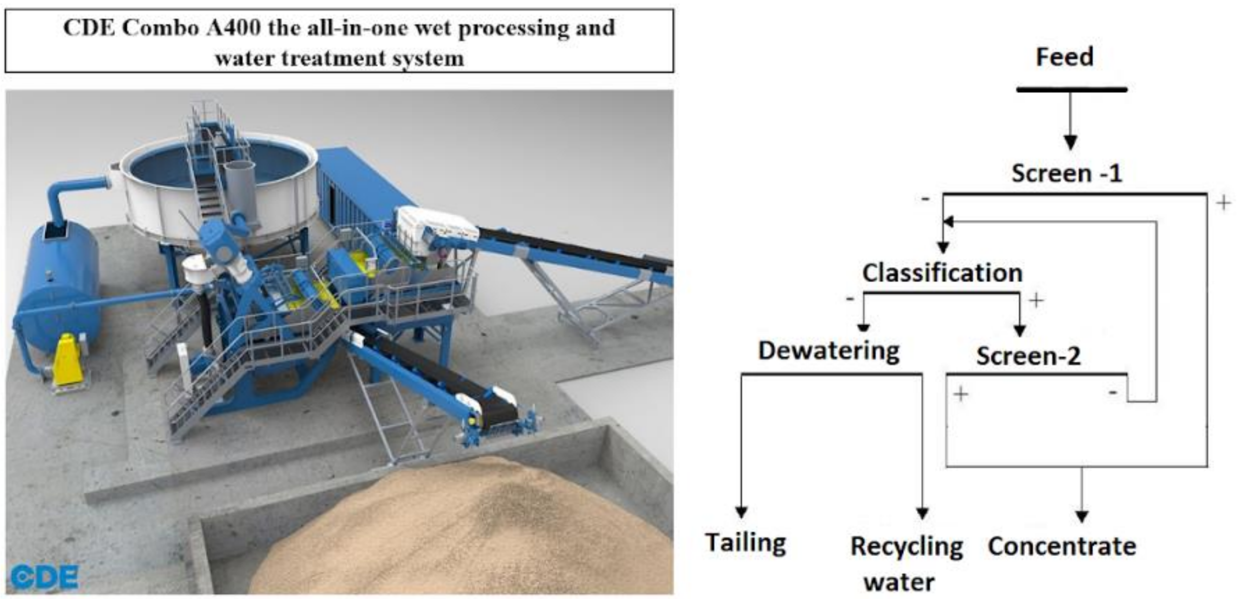


Figure 1. 3 CDE Comdo A400 all-in-one wet processing and water treatment system.

The basic flow sheet of the CDE Combo A400 washline system is illustrated in Figures 1-1. As can be seen from Figure 1-1, the iron ore is fed into the feed bunker which has a screen on top of it. Then the feed in the bunker is delivered by the belt conveyor to the screen with the size of 3mm. Then the undersized material from the screen is conveyed to the hydro cyclone which classifies the material based on its specific gravity. With the help of a hydro cyclone, the lighter material goes to the dewatering system as a tailing while the heavier materials go to the next screen to be classified by its size. The undersized material is recycled back to the Screen-1 while the oversize of the material becomes the product.

The samples investigated during the experiment were taken from three separate processing steps of the water treatment wash line system. The first sample is a feed material of the wash line system, the second sample is taken from the oversize of Screen-1 and the third sample is the oversize material of Screen-2 as shown in the Figure 1-1 above.

1.2 Problem Statement

International research organizations predict that the demand for steel or iron ore will increase due to global population growth, urbanization, related infrastructure, and road construction. Particularly, economic growth in China (the world's largest consumer) is a major factor influencing spot iron ore prices. China's 14th five-year plan, which calls for 5.5 percent economic growth in 2021-2025, is to support domestic transportation, infrastructure, urbanization, and housing by stepping up steel production. [7]

In February 2022, Chinese iron ore import was 83.69 million tons and 86.14 million tons in January. And Chinese import of iron ore is predicted to increase through the years constantly. [8]

Mongolian largest consumer of iron ore and concentrate is China which means an increase in demand for iron concentrate will be a huge opportunity for us. Therefore, producing value-added iron concentrate from iron ore would become a benefit for both Mongolian economic growth and the profit of the Darkhan Metallurgical Plant.

The price of iron ore fines at Chinese Qingdao Port depending on their grade on the 13th of May 2022 is tabulated below.

Table 1. 1 The Price of Iron fines at Chinese Qingdao Port on 13th of May 2022. [8]

Product	Price	Change
58% Fe fines (CFR Equiv.)	110 (USD/dmt)	-1.28
58% Fe fines (IOPI62)	796 (RMB/mt)	-2
62% Fe fines (CFR Equiv.)	133.72 (USD/dmt)	+0.33
62% Fe fines (IOPI62)	968.7 (RMB/mt)	+10.7
65% Fe fines (CFR Equiv.)	156.66 (USD/dmt)	+0.17
65% Fe fines (IOPI62)	1,133 (RMB/mt)	+11

According to Table 1.1, the price of 58% Fe fines in China is around 20-30 USD lower than the price of 62% fines in China. And the price of 65% iron fines is also higher than 62% iron fines by around 20-30 USD.

The comparison between the price change of iron ore concentrates depending on their grade is shown in Figure 1. 4 below.

Figure 1. 4 The price change of iron ore fines in China from March 2018 to March 2022. [9]

As shown in Figure 1. 4, the price of the iron ore fines sharply increased in 2021 and decreased by the end of 2021. However, the price of iron ore fines started to increase from the beginning of 2022 and is expected to grow in the future. And the price of 62% Fe fines is always higher than the 62% Fe fines by $20-30.

Furthermore, the Fe content of the iron concentrate produced by the CDE Combo A400 all-in-one wet processing and water treatment system at the Tumurtei iron ore mine is around 56% while the commercially compatible grade of iron ore fine is 62% in order to meet the quality requirements of blast furnaces in agglomeration plants such as pelletizing and sintering. Therefore, it is essential to develop a process flow to increase the grade of the iron concentrate produced by the wash line system at the Tumurtei iron ore mine in order to make value-added higher price products.

1.3 Objectives of the Research

1.3.1 General objective of the Research

The main objective of this study is to investigate the process route to extract a higher-grade iron ore concentrate in order to make the product of the Tumurtei iron ore mine commercially more compatible.

Therefore, this study's general purpose is to develop a scheme for the wet and dry magnetic separation experiment and achieve the highest possible Fe grade and reduce the content of impurities to the standard quality level in the iron ore concentration.

To develop a successful magnetic separation flowsheet, several important factors should be considered. Based on past papers and studies, the determination of liberation size, and an optimum number of cleaning stages are investigated.

1.3.2 Specific objectives of the research

- To investigate the optimum process route to produce the iron concentrate with a content of more than 62% from the delivered iron ore sample, taken from the feed of the Tumurtei mine, using low-intensity wet magnetic separator by changing the grinding size of the material.
- To Investigate an optimum processing solution to produce iron ore concentrate with the Fe content of more than 58% from the samples “Screen-2 OS” and “Screen-1 OS”, using a low-intensity dry magnetic separator.

2. Literature review

2.1 Introduction to iron

2.1.1 Chemistry of iron

Iron is a chemical element with the symbol Fe, atomic number 26, and atomic mass of 55.847 gr. It belongs to the first transition series and VIII group of periodic tables. [10] An electron configuration of this element is $1s^2 2s^2 2p^6 3s^2 3p^6 3d^6 4s^2$. Degrees of oxidation are +2, +3, +1, +4 and +6. Among those oxidation states, +2 and +3 are naturally more stable. The atomic radius of iron elements with +2 and +3 oxidation numbers are $0.80 \cdot 10^{-10} m$ and $0.67 \cdot 10^{-10} m$ respectively. The element has 4 naturally occurring isotopes: ^{54}Fe (5.84%), ^{56}Fe (91.68%), ^{57}Fe (2.17%), ^{58}Fe (0.31%). Also, there are several artificial radionuclide isotopes are created such as ^{52}Fe ^{53}Fe ^{55}Fe ^{59}Fe and ^{60}Fe . [11]

Iron forms various oxide, sulfide, silicate, phosphate, hydroxide carbonates and more than 300 compounds in nature: the most common are iron (II, III) oxide (Fe_3O_4) known as magnetite and iron(III) oxide (Fe_2O_3) also called hematite. [10]

For the chemical activity, iron forms rust ($FeO \cdot nH_2O$) in the presence of moisture. It is soluble in weak acids but not soluble in base. It is covered by the thin oxide coating by the action of strong acids such as H_2SO_4 and HNO_3. When Fe_3O_4 is heated up to 845C, FeO is heated more than 845C, they react with water and release oxygen. If iron is heated from 473C to 845C, it is covered by a thin acid coating. Under the condition with high temperature, it reacts with Cl, S, P, N and Ti in the water then it forms halides, sulfide, phosphide, and nitrite [11]

2.1.2 Physics of iron

Pure iron is a bright silvery-white metal. It is malleable, ductile and strongly magnetic. Iron is one of the three naturally occurring magnetic elements. Other 2 elements are nickel and cobalt. The specific gravity of iron is 7.84, melting point is 1536C. It has an average heat conductivity of 74.04Bt compared to other metals. Electronegativity of iron is $9{,}7 \cdot 10^{-8} \Omega/m$ which means it conducts electricity but not as good as other highly conductive materials. [12]

At atmospheric pressure, iron has three different allotropic forms depending on its temperature: alpha iron (α-Fe) that has a body centered crystal structure below 912C, known as ferrite, gamma iron (Ɣ-Fe) which has a face centered crystal structure above 912C, known as Austenite, and delta iron (δ-Fe) that has a body centered crystal structure above 1394C. [13] Furthermore, there is one more allotropic form which only occurs in high pressure called epsilon iron (ε-Fe). The physical properties also change with these allotropic forms of iron. For instance, alpha iron has the highest volume and is the least dense, while gamma iron has the lowest volume and is the densest type of three allotropes. Alpha iron is the most stable one found in the ambient temperature, so that most iron which is found naturally would be in an alpha iron form. [14]

2.1.3 Iron ore in the nature

Iron is found not only in Earth's crust but also in the sun, stars, and meteorites. The iron originated through nuclear fusion in stars and in dying stars that are large enough to explode as supernovae. [15]

Iron is the fourth most abundant element in the Earth's crust by weight behind aluminum, oxygen, and silicon. However, pure iron is rarely found in nature because of its high reactivity, rather it occurs in iron ore form with other minerals such as oxygen, sulfur, zinc, magnesium, and so on. The ores are mostly rich in oxides and vary in color from dark gray, deep purple, and rusty red to bright yellow depending on their constituents. [16]

The most common iron ores are hematite (Fe_2O_3), magnetite (Fe_3O_4), and siderite ($FeCO_3$). And there are more oxide minerals such as lepidocrocite and goethite, each has a chemical formula: $FeO(OH) * nH_2O$ and $FeO(OH)$. Moreover, iron is found with zinc and manganese in the form of an oxide mineral called Franklinite. [16]

Iron ores containing Fe content of greater than 60% (magnetite, hematite) are known as “natural ore” or “direct shipping ore”. Such kinds of ores are directly fed into iron-making blast furnaces. However, direct shipping ores contain significantly higher amounts of penalty elements such as phosphorus, water content, and aluminum. [17]

2.1.4 World iron ore reserves

Iron ore has been used in everyday life since the dawn of time, and iron ore is one of the strategically important minerals. Iron ore is the main raw material for the production of cast iron and steel, and 98% of the total mined iron ore is used for steel production.

As mentioned above, iron ores such as magnetite (Fe_3O_4), hematite (Fe_2O_3), goethite (FeO (OH)), limonite (FeO (OH) · n (H2O)), and siderite ($FeCO_3$) are the most widespread iron ores and considered as the most economically important iron ore types.

As of 2020, the world's total crude iron ore reserves are projected at 175.5 billion tons. [18]

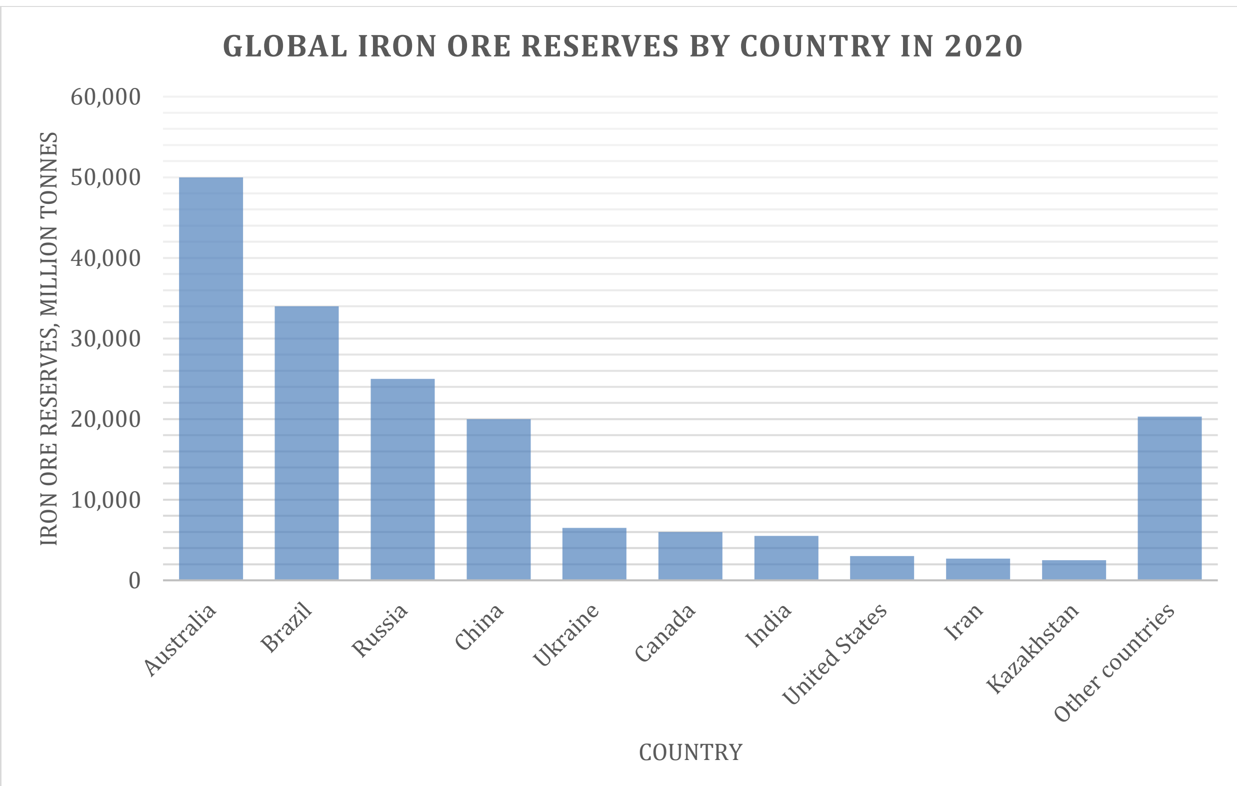


Figure 2. 1 Global iron ore reserves by country in 2020

As of 2020, Australia has the largest reserves at 28.5%, 50 billion tons, followed by Brazil, Russia, China, Canada and India with 45% of the total reserves and other countries with only

11.6% of the total reserves. While the average reserves in Ukraine, Canada, India, USA, Iran, and Kazakhstan are also high between 2.5 billion tons to 6.5 billion tons. [18]

2.1.5 World Iron ore production and consumption

In 2020, the global iron ore production is estimated to have 2.4 billion tons in 2020, slightly lower than the 2.5 million tons produced in 2019. The global leading producer of iron ore is Australia, accounting for 38% of the total production. Followed by Australia, top three iron-ore-producing countries are Brazil, China and India, accounting for 40.5% of global production. [18]

World mine production of iron ore in 2020 is illustrated in the figure below.

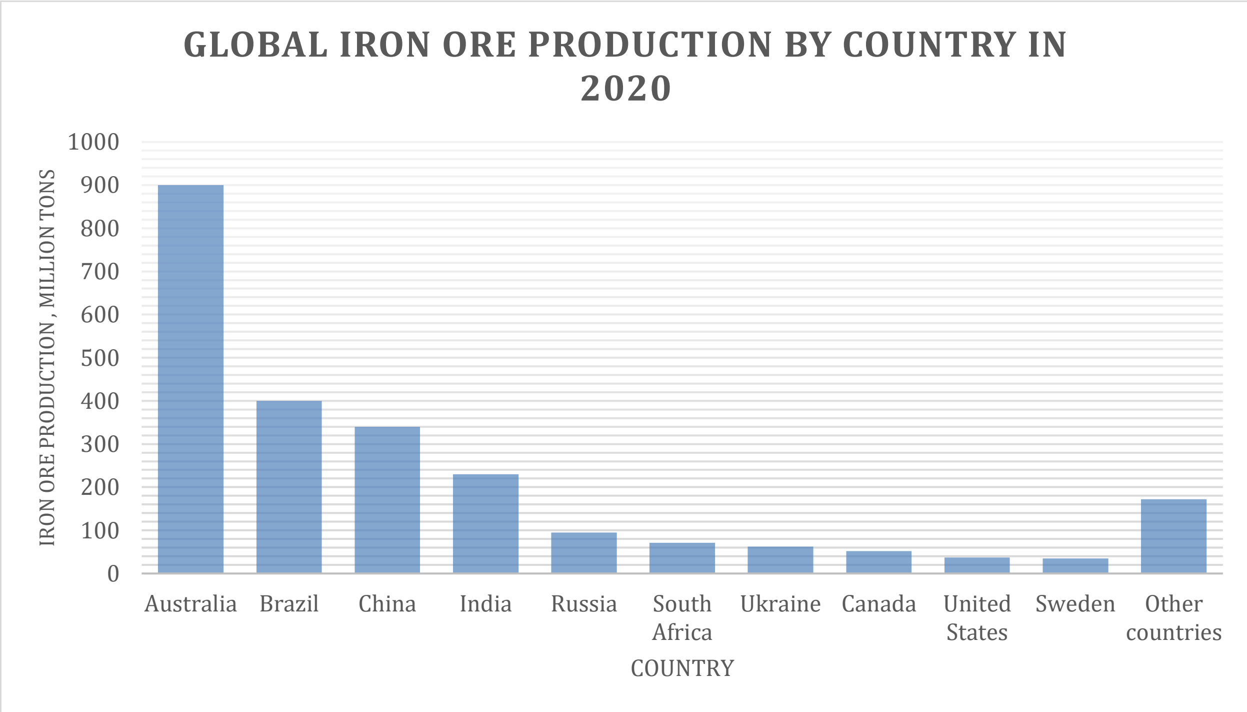


Figure 2. 2 Global iron ore production by country in 2020

According to Figure 2.2, iron ore production in Russia, South Africa, Ukraine, Canada, United States, Sweden are also high, ranging from 35 million tons to 95 million tons. [18]

Steel is the most important material, and steel production is directly related to human growth. The world's population is expected to grow by 2 billion over the next 30 years, from 7.7 billion in the current year to 9.7 billion in 2050, according to a new UN report released in 2019. [19]

As a result, urbanization is accelerating and the need for construction and infrastructure will continue to grow worldwide in the coming years. [19]

Today, the world produces an average of 1.7 billion tons of steel a year, using more than 2 billion tons of iron ore, about 1 billion tons of steel coal and about 600 million tons of scrap metal. [19]

2.1.6 Iron ore types

There are four main types of iron ore deposit, commonly mined: hematite, magnetite, goethite and lepidocrocite. They vary in iron content, color from dark gray to rusty red and many other characteristics. [11]

Hematite

Hematite is the most common iron ore oxide with a chemical formula of Fe_2O_3, formed as a result of oxidation. A pure hematite consists of 70% iron and 30% oxygen by weight. Hematite has a crystal structure of rhombohedral lattice system, designed an alpha polymorph of Fe_2O_3. This type of iron ore occurs in black, silver-gray, brown, reddish-brown or red colors. The deposit is commonly found in banded iron ore formations. Hematite occurs in places still, standing water or hot springs and even in the absence of water, as a result of volcanic activity. [11]

The biggest sedimentary deposit of hematite is located in the Lake Superior district in North America. The production is nearly 75 million tons of hematite annually. Other important deposits are Minas Gerais of Brazil, which occurs in metamorphosed sediments, Cerro Bolivar of Venezuela and Labrador and Quedec of Canada. [11]

Magnetite

Magnetite is an iron (II, III) oxide with an empirical formula of Fe_3O_4, included in a hexoctahedral crystal class. When it reacts with oxygen, it produces hematite. The color of the magnetite is black or brownish-black with metallic luster. It consists of highly magnetic iron-containing minerals, described as being ferrimagnetic. Also, it can be magnetized to become a permanent magnet itself. [11]

It is found in igneous, metamorphic and sedimentary rocks including banded iron formations and in lake and marine. Magnetite deposit is sometimes found in large quantities in beach sand, also called black sand, found as part of placer deposit of magnetite. Such deposits occur in Lung Kwu Tan of Hong Kong, California, United States and west coast of the North Island of New Zealand. Another form of magnetite deposit is banded iron formation where the sedimentary magnetite is carried to the beach by rivers and concentrated by wave action and currents. Huge deposits of magnetite are also found in the Atacama region of Chile, the Valentines region of Uruguay, Kiruna, Sweden, the Tallawang Region of New South Wales and in the Adirondack region of New York in the United States. Other deposits are also found in Norway, Romania and the Ukraine. Kediet ej Jill Mountain of Mauritania is made entirely of this mineral. [11]

Goethite

Goethite is an iron (III) oxide-hydroxide: the alpha-polymorph containing ferric iron. The empirical formula of goethite is $\alpha - FeO(OH)$. It is commonly found in soil and environments with low temperature. The crystal class of goethite is dipyramid and the crystal system is orthorhombic. The color of the ore varies from yellowish to reddish to dark brown or black. Goethite usually forms through the weathering of other iron-rich minerals. Therefore, it is commonly found in the form of concretions, stalactite formations, oolites, reniform or botryoidal accumulations. Huge goethite deposits are found in England, Cuba, and Minnesota, Missouri, Colorado, Alabama, Georgia, Virginia and Tennessee, in the United States. [11]

Lepidocrocite

Lepidocrocite is a mineral included in a group of hydroxides containing 89.86% Fe_2O_3, 10.14% H_2O, MnO, Al_2O_3, SiO_2, CaO, MgO, and other minerals. In some cases, it contains excessive amount of H_2O. The crystal structure of lepidocrocite is orthorhombic and the crystal class of the ore is dipyramidal. The color of the lepidocrocite varies from ruby-red to reddish brown, light reddish to red-orange in transmitted light gray-white in reflected light. Such ore is usually found in the weathering of primary iron minerals and in iron ore deposits. [11]

In this test work, magnetite ore is investigated. Therefore, the magnetic separation is the most efficient method to beneficiate the ore because of its high magnetic susceptibility and strong response to a magnetic field.

2.2 Beneficiation of Iron ore

2.2.1 Magnetic separation of iron ore

Magnetic separation is a mechanical processing method, widely used in separating iron ore from gangue materials. The main principle of the separation method is based on the difference between the magnetic properties of the materials.

The science of magnetic separation has exceptionally developed during the last three decades. Consequently, a variety of applications and design concepts of magnetic separation have been derived. Magnetic separation can be used as either a primary or secondary processing operation to beneficiate minerals. The application of magnetic separation is not only limited by the mineral processing of raw materials but also involves removing trump materials such as shovel teeth or chains in a crusher, or micrometer-sized iron of abrasion from a high-purity industrial minerals process stream. It is also applicable for removing gangue materials to purify non-magnetic elements, such as for the production of ceramics and refractories. Additionally, applications of magnetic separation in the recycling and secondary recovery are thriving with increasing interest in using explicit methods for removing residual values from various process streams and hazardous constituents from waste streams.

2.2.2 Magnetic characteristics of minerals

The main principle of magnetic separation is based on the ability to magnetize a specific mineral and then physically attract it. The magnetic susceptibility of the mineral is an intrinsic property, directly proportional to the response of a magnetic separation and is the single most important parameter when addressing the characteristics of magnetic separation. In case a particular matter is subjected to a magnetic field, all particles respond in a particular manner and can be classified as one of three groups: ferromagnetic, paramagnetic or diamagnetic.

Among all these magnetic groups, ferromagnetic is the most strongly induced by a magnetic field. The most common examples of ferromagnetic minerals are magnetite, titaniferous magnetite, monoclinic pyrrhotite, and so on. Minerals having a low magnetic susceptibility and a weak response to a magnetic field are called paramagnetic. For instance, biotite, chalcopyrite, chromite, columbite, garnet, goethite, hematite, hexagonal pyrrhotite, ilmenite et cetera. On the other hand, Minerals that have a negative susceptibility are named as diamagnetic and non-magnetic. Ferromagnetic and paramagnetic materials can be magnetized when they are placed in a magnetic field and show a certain pattern depending on the magnetic field and susceptibility. The amount of magnetization depends on the mass and magnetic susceptibility of the particle and the intensity of the applied magnetic field. [22] This parameter is expressed as:

$$M = m\chi H$$

Where M - induced magnetization of the particle

m - mass of the particle

χ - specific magnetic susceptibility

H - magnetic field intensity

2.2.3 The characteristics of magnetic separator

In the design of a magnetic separator, two variables affect a separation response: the magnetic field intensity and magnetic field gradient. High intensity magnetic separators operate in regions more than 8G (0.5 T). On the other hand, low-intensity magnetic separators generate magnetic field strength of less than 2,000G (0.2 T). The magnetic field gradient refers to the rate of change or the convergence of magnetic field strength, as shown in Figure.2.3

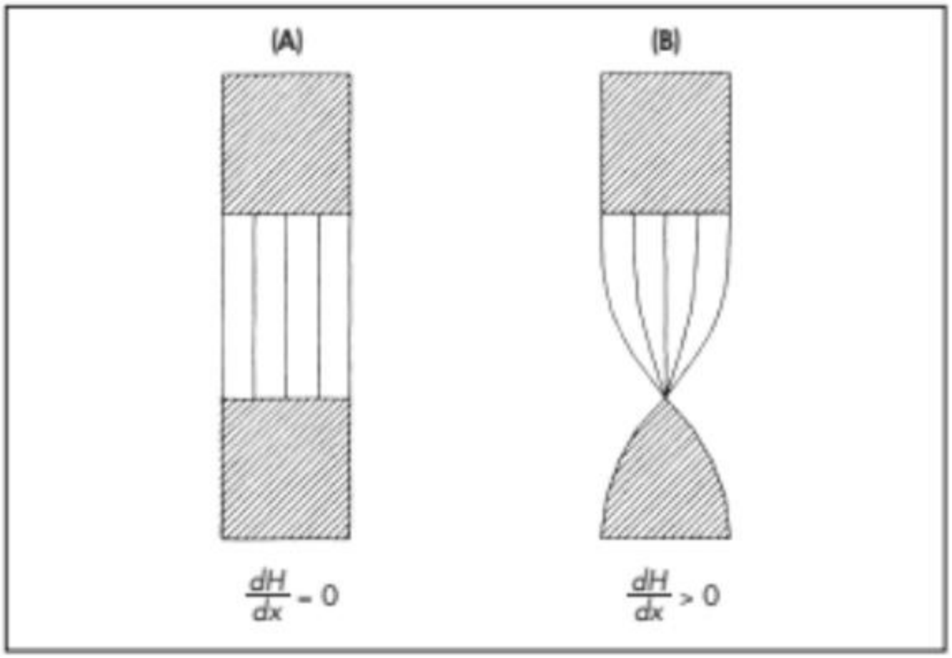


Figure 2. 3 Magnetic field configurations [22]

According to Figure.2.1, case A shows the uniform pattern of flux lines. Consequently, when a magnetic particle enters the field, they are attracted along the lines of flux and remain stationary without migrating to either pole. On the other hand, case B shows the converging pattern of the magnetic field which indicates higher gradient. When particles enter this magnetic field, they are attracted to both lines of flux and migrate to the region of the highest flux density. Simply, magnetic field gradient causes the particle to move and magnetic field intensity holds the particle, entering the magnetic field. The magnetic attractive force acting on the particle is as follows:

$$Fm = m\chi H \frac{dH}{dx} \text{ or } M \frac{dH}{dX}$$

Where:

Fm - magnetic attractive force

dH/dx - the magnetic field gradient.

Magnetic field generation

There are two different methods to generate magnetic fields: permanent magnets and electromagnets. Both magnets generate the magnetic field on any given magnetic separator.

- In the case of electromagnets, the magnetic properties are displayed when current is passed through it. And the strength is adjusted depending upon the amount of flow current. To maintain the magnetic field, a continuous electricity supply is required. The poles of electromagnet are changed with the flow of current.
- Meanwhile, magnetic properties of permanent magnets exist when the material is magnetized. The strength depends upon the nature of the material, utilized to make these magnets. When the magnetic property is lost, then it becomes useless. It doesn't require a continuous electricity supply. Furthermore, the poles of this kind of magnet cannot be changed. [23]

2.2.4 Introduction to Dry Low-Intensity drum type magnetic separator

Low-Intensity Drum Type magnetic separators are widely used in separating ferromagnetic materials such as magnetite. These types of separators use a permanent magnetic field with the self-cleaning feature. Magnetic drum-type separators are commonly used in two different modes of operation. The separator is equally effective for both concentrating a magnetic material and rejecting magnetic materials to produce a clean nonmagnetic mineral product.

It consists of a rotating non-magnetic drum with high speed, containing stationary magnets which produce alternating polarity, as shown in the Figure 2.4, Initially, electromagnets were used in drum type magnetic separators. However, modern devices are employing permanent magnets.

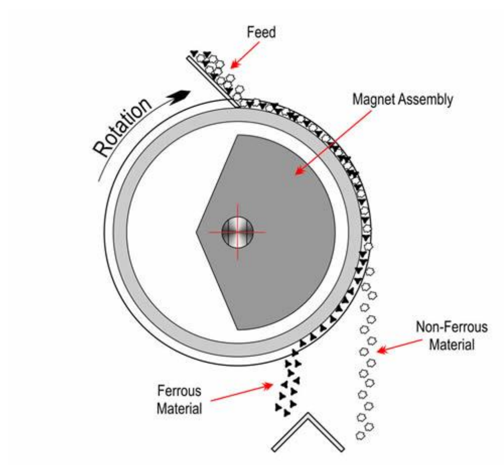


Figure 2. 4 Dry Low-Intensity drum type magnetic separator [22]

The main function of drum type magnetic separators is based on the "pick-up" principle which means that when the material is fed to the header box of the separator, magnetic particles are attracted to the drum, where the permanent magnet is attached, and are conveyed out of the field. The rest of the material, not attached to the drum, is considered as a gangue material which is removed through the tailing compartment.

In the application of dry magnetic separators, coarse particles ranging in size from –25 mm to +6 mm respond well to a magnetic circuit employing large magnetic poles. Coarse iron ore can be treated at a relatively high unit capacity. During the preliminary magnetic separation, the separator removes a nonmagnetic product, which are free of iron, and produces rougher concentrate of magnetite with an intermediate grade, containing locked particles. Therefore, the product of these types of magnetic separators requires a further liberation for purified concentrate.

On the other hand, fine particles in the size range of –100 mesh respond well to a magnetic circuit with narrow magnetic poles. Applications in these size ranges include iron ore fines and intermediate grade concentrates, slags, fly ash, and iron carbide. [22]

2.2.5 Introduction to Wet Low-Intensity drum magnetic separator

The wet drum magnetic separator is used for collecting magnetite or black sands from tailings and gold-bearing materials. When the size range of the particle is less than 0.5 cm, the dry magnetic separator tends to be replaced by the wet magnetic separator in order to reduce dust loss and to produce cleaner products. The peak magnetic field intensity on the wet drum is approximately 2,000 G (0.2 T) and is extensively used for removing ferromagnetic minerals.

The operating principle: The magnetic drum is placed in a tank. Slurry is fed to the tank and flows through the magnetic field generated by the drum. The magnetic minerals are pinned to the drum shell by the magnetic circuit and are rotated out of the slurry stream. [22] The magnetic minerals discharge from the drum shell when rotated out of the magnetic field as shown in Figure 2.5.

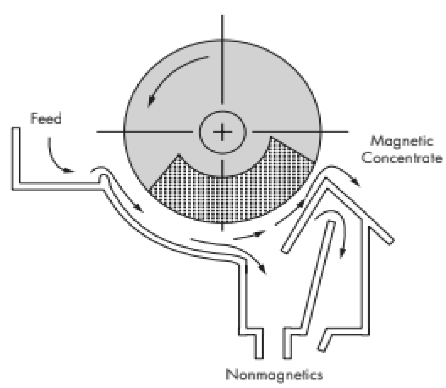


Figure 2. 5 Wet drum separators with concurrent tank [24]

Following parameters affect the collection of the ferromagnetic materials in wet drum magnetic separators:

- **Magnetic field strength**.
  The magnetic field strength has to be sufficient to effectively collect ferromagnetic minerals.
- **Hydraulic capacity.**
  The recovery is directly related to the flow rate through the separator. When the flow rate increases, the slurry velocity and the fluid drag force increase, which tends to detach more magnetite from the opposing magnetic field.
- **Percent solids.**
  The percent solids of the feed are directly related to the selectivity of the separation. As the percent solids increases, the slurry becomes more viscous which results in minimizing the effects of the fluid drag.
- **Ferromagnetic content.**
  The magnetic loading of a wet drum magnetic separator to remove a ferromagnetic material based on the diameter of the drum, rotating speed, and the magnetic field strength. Exceeding the limits of this magnetic loading causes increased magnetite losses. [22]

2.3 Impurities in Iron ore

As previously mentioned, the iron ore concentrate is used for the blast furnaces to make agglomerates. Therefore, there is a certain standard quality requirement for the iron ore concentrates from the customers to keep efficiency of the blast furnaces as high as possible.

Along with increasing the Fe grade, removing the content of impurities plays a significant role in producing a qualified product and obtaining a higher efficiency of blast furnaces.

The iron ore from the Tumurtei mine contains several impurities such as alumina (Al_2O_3), silica (SiO_2), sulfur (S), phosphorus (P), titanium oxide TiO_2, magnesium oxide (MgO), calcium oxide (CaO), potassium oxide (K_2O), sodium oxide (Na_2O) and manganous oxide (MnO) along with the iron (Fe). Among all these impurities, alumina, silica as an unwanted material, sulfur and phosphorus, as a toxic element, are mostly considered in the quality requirements of iron ore.

The ratio of alumina and silica more than one causes serious problems in the operation of sintering and smelting blast furnaces. Specially, high alumina content causes a production of viscous slag in smelting blast furnaces. The production of excessed slags results in an increase in coke requirements, and some problems during tapping of the viscous slag. Therefore, the content of the silica has to be less than 6% and the alumina has to be less than 4%. [20]

Phosphorus and sulfur are considered to be trace elements in iron ores. Phosphorus lowers the solidification temperature, indirectly increases fluidity due to the production of low melting constituents in steel making. Furthermore, it cannot be completely removed from iron ores by fluxing and smelting for the blast furnace. [21]

Another trace element that has a significant deleterious effect in the properties of the product is sulfur. A sulfur in the iron ore occurs in the form of either iron sulfide (FeS) and manganese sulfide (MnS). Iron sulfide tends to promote cementite which produces harder iron. Manganese sulfide also hardens the iron. Generally, sulfur can be removed by the roasting and washing process in order to be used in the blast furnace. [21]

The standard requirements for phosphorus and sulfur in commercial iron ore has to be less than 0.07% and 0.1%, respectively. [21]

3. Experimental Methodology

This section explains the raw materials, apparatus and process flow of the experiment. Furthermore, the procedure of sample characterization, size distribution analysis, grinding time determination and magnetic separations were carried out.

The experiment was conducted on three different samples, taken from the three different processing stages of the Tumurtei iron ore wet processing and wash system, as illustrated in Figure. 3.1

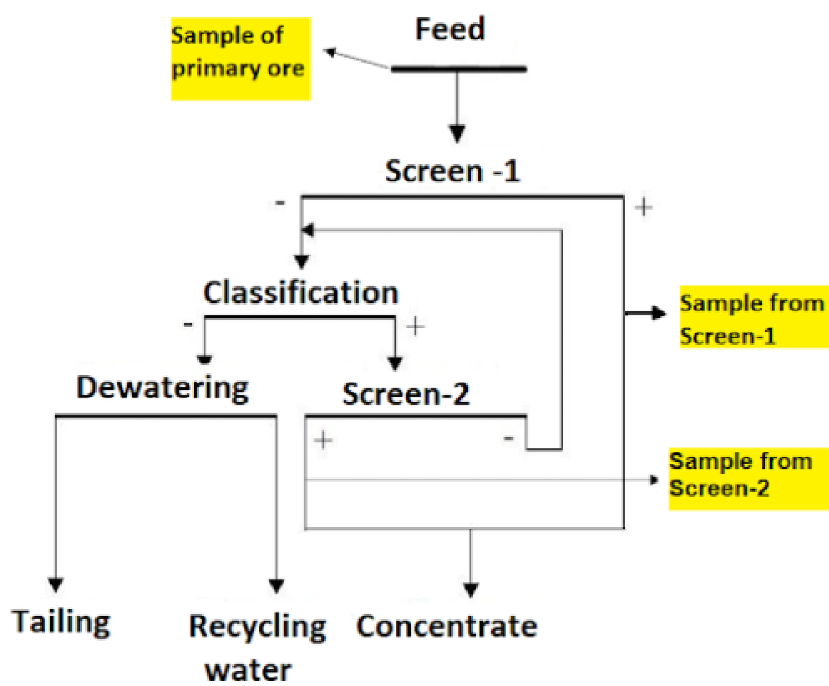


Figure 3. 1 Flowsheet of CDE Combo A400 water Treatment

First sample is collected from the primary ore feed coded “Feed” of CDE Combo A400 all-in-one wet processing and wash system. The next sample is coded “Screen-1 OS” which is the sample from oversize of Screen-1 as shown in Figure 3.1. The second sample is coded “Screen-2 OS” which is the sample from oversize material of the Screen-2 as shown in Figure 3.1.

Figure 3. 2 “Feed” sample as received.

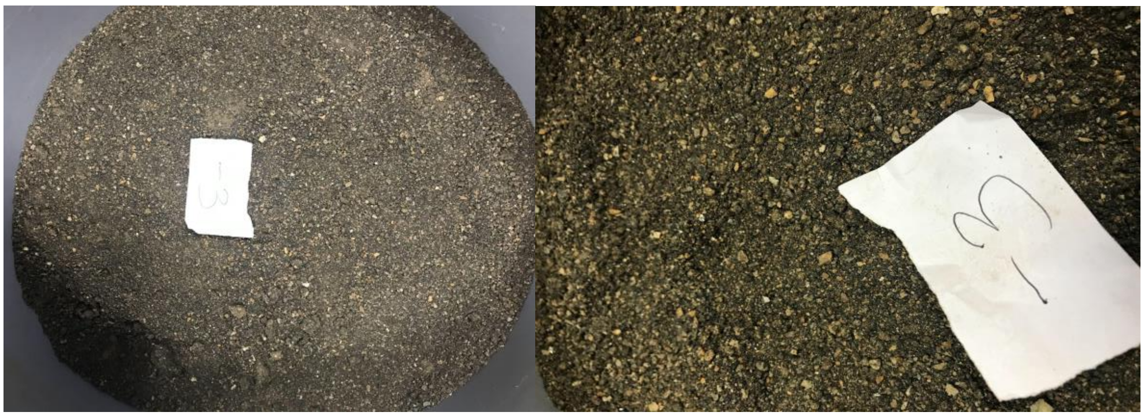


Figure 3. 3 “Screen-2 OS” sample as received.

Figure 3. 4 “Screen-2 OS” sample as received.

3.1 Sample characterization and test work

The sample characterization and test work is considered as a fundamental part of this test work. In this section, size reduction process, sample preparation, chemical analysis, size distribution analysis and grinding time determination processes were carried out.

3.1.1 Size reduction

The size reduction process was performed only on the “Feed” sample. About 42.5kg iron ore sample was taken from the Tumurtei iron ore mine. The sample was initially passed through the comminution process to liberate the valuable mineral from the gangue material. The process diagram of size reduction process is as follows:

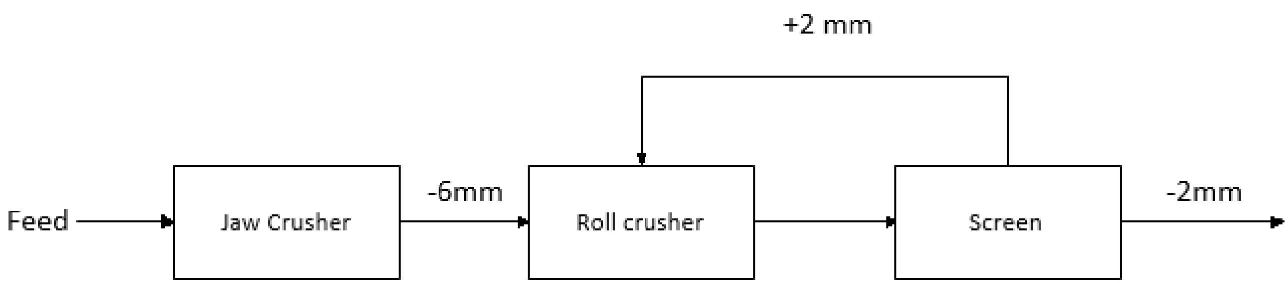


Figure 3. 5 The process diagram of size reduction process

The whole “as received” sample was fed into the jaw crusher (model 5E-JCA150*125). The output size of the jaw crusher was adjusted at 6mm. Then, the sample passed through the secondary crusher, roll crusher (model LRMC). The product size of the secondary crusher was -2mm. Then, the whole sample was classified by the 2 mm sieve and the oversized particles were recycled to the roll crusher until all particles became smaller than 2 mm.

3.1.2 Sample preparation

The basic step of the experiment is sample preparation. The aim of this process is to take an acceptable subsample which can represent the whole sample for the successful outcome. As a result of this process, the size and chemical content distribution of the sample is expected to become as uniform as possible to perform the further procedures accurately.

The sample preparation was performed on the sample “Feed”, and “Screen-2 OS”. The particle size of the “Feed” sample was less than 2mm while the particle size of the “Screen-2 OS” sample was less than 3mm.

Jones Riffle method

In order to take the representative subsample from the whole sample, the method of Jones riffle was applied. This method helps to mix and divide the material evenly.

Firstly, the sample was divided into 4 equal parts by automatic splitter (model ZS-A). Then, one quarter of the whole sample, weighted around 10kg (Feed) and 15kg (Screen-2 OS) were divided by small scale hand splitter and packed by 1kg as shown in Figure 3.8.

Figure 3. 6 1kg evenly divided samples

3.1.3 Chemical analysis

Sample characterization of the sample describes the chemical composition of three samples. The type of the iron ore, utilized during the experiment was magnetite. Therefore, the main chemical content of the sample was Fe_2O_3.

In order to determine the chemical content of the sample, a sufficient amount of sub-sample, around 200gr sample, was taken from the whole sample by standard sample preparation method. Then, the subsample was pulverized by the “Ring and Puck Pulverizer machine” to liberate all the valuable minerals from the gangue rock.

After pulverizing the sample for 4 minutes, the sample was grinded enough to measure the chemical content of it. Then the chemical content of the sample was measured by the “Thermo Scientific Niton XRF analyzer”.

The precision of “Thermo Scientific Niton XRF analyzer” is 60 percent and it decreases when the content of the measured composition in the material is more than 30 percent.

Fortunately, the chemical content of the samples, concentrates, and tailings were double checked by “Axios XRF spectrometer”, chemical content analyzer, at the “Quality control department” of the Tumurtei mine’s laboratory of material for more precise and accurate results.

3.1.4 Particle Size distribution analysis

This experiment was performed to determine the size distribution of the particles and indicate how the material fine or course is. In order to perform the experiment of size distribution analysis, different masses of representative subsamples were prepared from each three samples: 2 kg subsample of “Feed”, 2.5 kg subsample of “Screen-1 OS” and 1 kg of subsample of “Screen-2 OS”. Depending on the top size of three samples, different sized sieves were utilized during the experiment. For instance, to determine the size distribution of “Feed” and “Screen-2 OS”, 6 different sized sieves were used: 2mm, 1mm, 0.5mm, 0.25mm, 0.125mm, 0.075mm. On the other hand, the particle size of sample “Screen-1 OS” was determined by 8 different sized sieves: 12.5mm, 8mm, 6mm, 4mm, 2mm, 1mm, 0.5mm and 0.25mm sieves.

Figure 3. 7 Laboratory stainless steel sieves utilized in the experiment

Experimental procedure of size distribution analysis:

1. A representative subsample packed by 1 kg was taken from the whole sample.
2. 2mm, 1mm, 0.5mm, 0.25mm, 0.125mm, 0.075mm laboratory sieves were arranged as the largest sized sieve was placed at the top and the smallest sized sieve was placed at the bottom.
3. Then the sample was placed at the top of the sieve and was shaken by an automatic vibrating sieve machine for 10 minutes.
4. The weight of each sample in all sieves were measured separately.
5. In order to determine the chemical content distribution, with respect to their particle size, the chemical content of each different sized sample was measured by XRF analyzer.

3.1.5 Grinding time determination

The grinding time determination is performed to identify how much time is required to grind the sample where the sample reaches its liberation size. The liberation size means the optimum size where the valuable mineral is fully liberated from the ore body. In our case, the iron ore from the Tumurtei mine is completely liberated at the size of less than 74 micron. However, only 60% of the iron ore having less than 74-micron size is considered as sufficiently grinded in order to be economically profitable for the Tumurtei iron ore mine.

Note: 75-micron sieve was utilized to determine the grinding time, which was available in our laboratory.

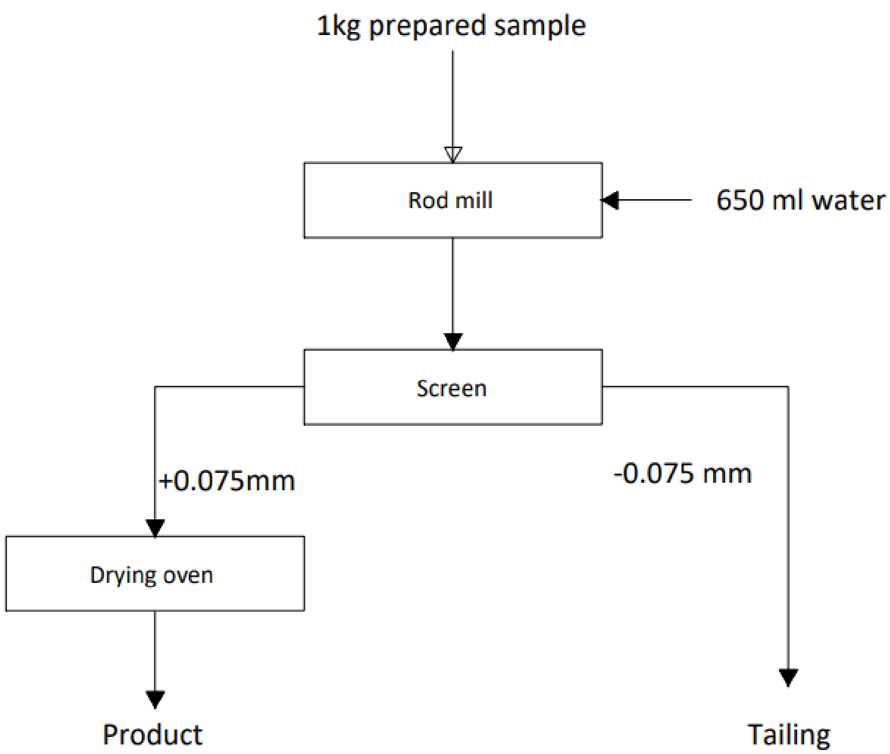


Figure 3. 8 Flowsheet of grinding time determining experiment

During the experiment, the rod mill (model XMQ 240x300), 0.075mm sieve, laboratory steel tray and water supply were utilized.

Procedure of Grinding time determining experiment

1. 1kg of packed sample was fed into the rod mill
2. Then 650ml water was added to the sample in order to obtain the 60% of solid percent.
3. Then the rotating minute was adjusted to different minutes where the 0.075mm passing percent of the sample reaches 60%, 70% and 80%.
4. The next step is to completely discharge the mill and clean it with plenty of water.
5. Then the discharged slurry (product of the rod mill) was screened by 0.075mm sieve by wet screening
6. The oversized product was dried in drying oven at the $105°C$.
7. The completely dried sample was weighed after the temperature of the sample was cooled down to ambient temperature.

Figure 3. 9 The sample “Feed”, The oversized material of 75-micron sieve at P60

In Figure 3-15, the liberated metallic iron particle from the rock can be seen by raw eyes, which means the material was sufficiently grinded. More the material grinded, the more valuable minerals are loosened from the rock.

3.2 Dry magnetic separation

Dry magnetic separation experiment was performed to investigate the sample coded “Screen-1 OS” and “Screen-2 OS” that have a particle size more than 3mm, and less than 3mm respectively. The samples were taken from the oversized products of screen-1 and screen-2 of CDE Combo A400 all-in-one wet processing and wash system. The maximum feed size of the magnetic separator in our laboratory, drum type dry magnetic separator, is 25mm. Therefore, it doesn’t require any grinding or additional crushing steps because the top size of both samples was less than 25mm. The magnetic intensity was adjusted at 1000 Gauss and the rotational speed was 40rpm, which was considered as the optimum rotational speed during the previous experimental studies on the sample from the Tumurtei iron ore mine. The weight of the sample was 9kg. Furthermore, size distribution and the chemical composition of the material were investigated before dry magnetic separation.

3.3 Experiment of Wet Low-Intensity Magnetic separation

As mentioned above, the experiment of wet low-intensity magnetic separator was performed to beneficiate the sample “Feed” from CDE Combo A400 all-in-one wet processing and water treatment system at the Tumurtei mine by the 1000 Gauss. The flowsheet of the experiment is shown in Figure 3. 17.

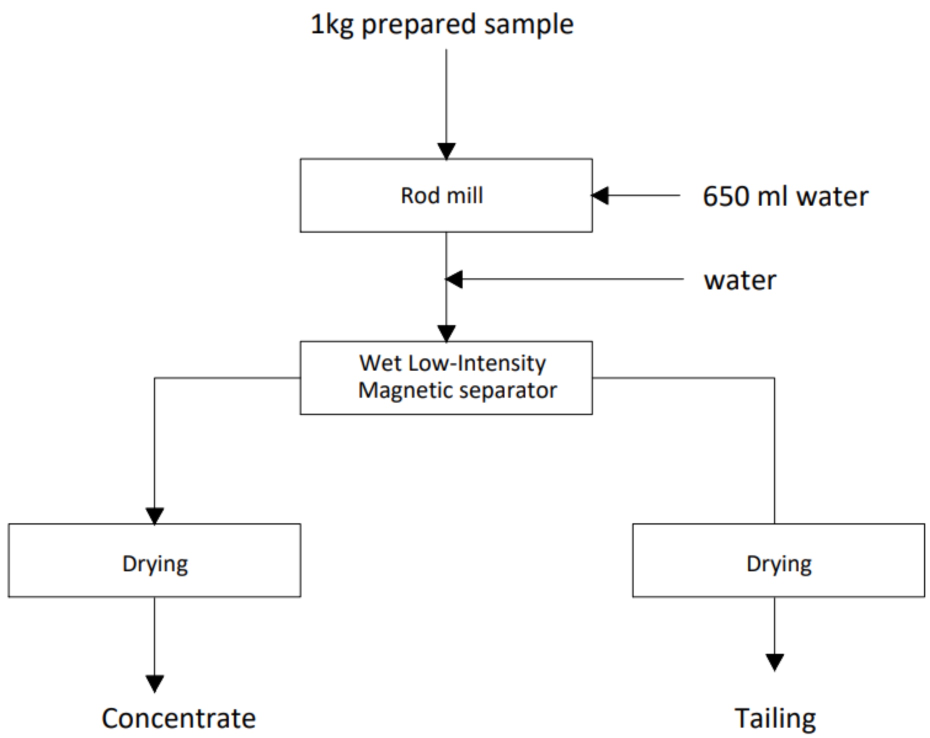


Figure 3. 10 Flowsheet of Wet Low-Intensity magnetic separation

Procedure of wet low-intensity drum magnetic separation

1. 1kg of packed sample was grinded by rod mill with the solid percent of 60%
2. The magnetic intensity of the wet low-intensity drum magnetic separator was adjusted at 100Gauss, the rotation of the drum was set as clockwise.
3. The grinded sample was eventually fed into the feed box of the magnetic separator.
4. Water was supplied with a low flow rate. When the water level is excessed, the unwanted overflow flows through the level adjusting section.
5. The concentrate is attached at the drum of the magnetic separator as shown in Figure 3.18.

Figure 3. 11 Wet Low-Intensity magnetic separation

After performing the magnetic separation, the tailing and concentrates were filtered in the Eriez filter press and the rest of the moisture content were dried in the drying oven at the temperature of 105C.

6. The completely dried products have been weighed separately for calculating the yield.
7. Then the chemical content of the products was measured. The chemical analysis results showed us the content of the magnetite, sulfur, aluminum oxide, silica, titanium oxide, phosphorus, magnesium oxide, calcium oxide, potassium oxide, sodium oxide and manganese oxide.

The chemical analysis was implemented by both the “Thermo Scientific Niton XRF analyzer” in the Raw material processing laboratory of GMIT, and the “Axios spectrometer XRF analyzer'' at the Material laboratory of the Tumurtei mine for double-checking the result. And this Bachelor thesis followed the result of the Material laboratory of the Tumurtei mine because of the higher precision and reliability offered by the laboratory.

The technical specifications of the related equipment to this experiment are attached in the Appendix.

4. Results and Discussion

4.1 Result of Sample characterization

During the sample characterization, the weight and chemical composition of all three samples were measured. The sample coded “Feed” was weighted as 42.5 kg, “Screen-2 OS” was weighted as 65.4 kg and the sample coded “Screen-1 OS” was measured as 43.2 kg. One quarter of each sample was utilized in the experiment procedure.

As a result of the chemical analysis, the Fe content of each three samples was more than 42% which is considered as an acceptable amount to be a commercial iron ore for further beneficiation.

Table 4. 1 The general result of sample characterization

№	Sample code	Weight	Fe content /%/
1	Feed	42508.8	42.93%
2	Screen-2 OS	65377.2	46.66%
3	Screen-1 OS	43256.1	42.345%

Table 4. 2 The specific results of sample characterization

Sample code	Size (mm)	Chemical content										
		Fe	S	Al2O3	SiO2	TiO2	P	MgO	CaO	K2O	Na2O	MnO
Feed	+2	39.77	0.46	4.424	18.46	0.27	0.012	4.13	5.36	0.64	<0.001	0.085
	+1	43.24	0.62	4.018	17.18	0.23	0.013	4.2	7.09	0.49	<0.001	0.1
	+0.5	44.86	0.36	4.026	17.23	0.24	0.014	4.27	6.995	0.43	<0.001	0.105
	+0.25	45.02	0.39	4.107	17.11	0.24	0.012	4.37	6.80	0.41	<0.001	0.11
	+0.125	36.69	0.47	4.341	19.36	0.2	0.015	4.33	8.65	0.47	<0.001	0.135
	+0.075	34.78	0.55	4.371	19.01	0.21	0.016	4.16	8.34	0.50	0.022	0.126
	-0.075	26.71	0.64	4.387	19.44	0.19	0.021	4.38	10.60	0.49	<0.001	0.13
Screen-1	+3	46.36	0.62	3.49	14.48	0.21	0.01	3.86	6.36	0.34	<0.01	61.24
Screen-2	-3	49.13	0.41	3.17	13.21	0.24	0.01	3.81	5.65	0.22	<0.01	0.12

The chemical contents of the sample "Feed" were separately measured on 1 kg packed sample divided by its particle size: +2mm, +1mm, +0.5mm, +0.25mm, +0.125mm, +0.075mm and -0.075mm. And the chemical content of the samples, coded "Screen-1 OS" and "Screen-2 OS" were measured on the small representative subsample.

As mentioned in the previous chapter called "Impurities in Iron ore", the content of alumina and silica included in a commercial iron ore has to be less than 4% and 6%, respectively. The alumina content in iron ore sample "Feed" was 4.1% and the silica content was 17.52% which are considered as more than the standard requirements. Therefore, those excessed gangue materials have to be removed during the magnetic beneficiation process to produce commercially acceptable iron ore concentrate.

Furthermore, the chemical content of the sulfur and phosphorus have to be less than 0.1% and 0.07%, respectively. Fortunately, the amount of phosphorus in the iron ore sample "Feed" is 0.013%, "Screen-1 OS" and "Screen-2 OS" are both 0.01% which can be accepted as sufficient values. On the other hand, the sulfur content of each three samples were more than the quality requirements 0.1% S. So, it requires a further beneficiation process to produce acceptable iron ore concentrate in order to be used for the blast furnace.

4.2 Result of Size distribution analysis

Determination of size distribution of a sample plays an important role in a size control and separation of any kind of mineral beneficiation. As a result of the size distribution analysis, the content of the course and fine particles included in the sample was determined which provides a possibility to approximate how much grinding is required to grind the sample until it reaches its degree of liberation. The optimum liberation size was known from the previous test work performed on the Tumurtei iron ore and therefore it is suggested as 0.075mm at the 60% passing by the project owner.

The result of the size distribution analysis of three samples are given below.

Table 4. 3 The result of size distribution analysis of sample "Feed"

Size (mm)	Retained weight, (gr)	Retained weight, %	Cumulative Passing, %
+2	20.2	1.01	100
-2+1	498.6	24.93	98.99
-1+0.5	713.5	35.675	74.06
-0.5+0.25	463.7	23.185	38.385

-0.25+0.125	206.2	10.31	15.2
-0.125+0.075	55.5	2.775	4.89
-0.075+0	42.3	2.115	2.115
Total	2000	100	

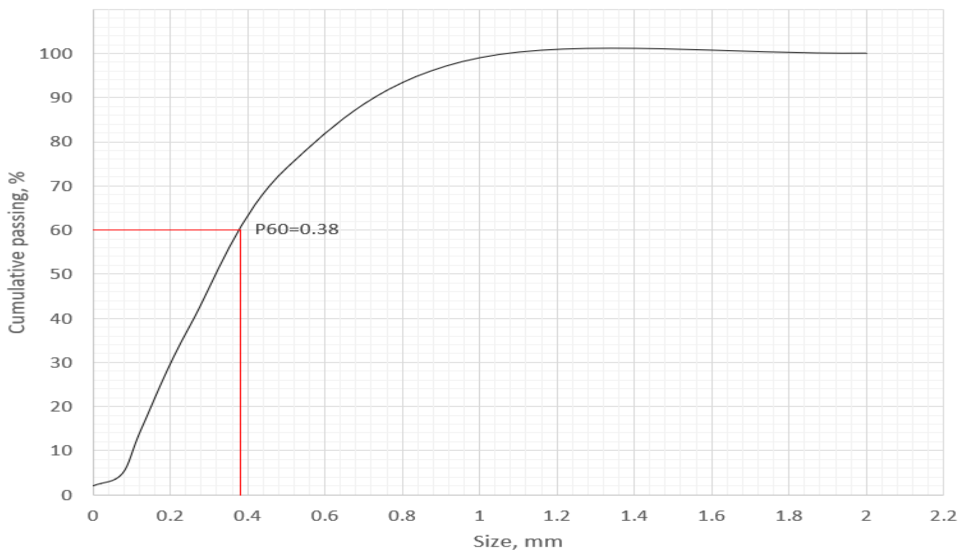


Figure 4. 1 Cumulative passing, %, diagram of sample "Feed"

The content of the fine particles included in the sample "Feed" is significant in this test work because the sample "Feed" is the only sample which is beneficiated by the wet magnetic separator. The maximum feed size of the wet magnetic separator in our laboratory is 2mm. And it is required to be finer than 2mm in order to obtain the optimum recovery. According to Figure 4.1, the P60 of the sample was equal to 0.38mm which is five times higher than our target 0.075mm. Therefore, it requires quite longer minutes to grind the sample to its liberation size. The overall shape of the graph is concave which means the content of finer particles in the sample is dominated.

Table 4. 4 The result of size distribution analysis of sample “Screen-1 OS”

size (mm)	Retained weight, gr	Retained weight, %	Cumulative passing, %
+12.5	74	2.97	100.00
-12.5+8	468.5	18.83	97.03
-8+6	524.3	21.07	78.20
-6+4	589.5	23.69	57.13
-4+2	623.7	25.06	33.44
-2+1	84	3.38	8.38
-1+0.5	46.1	1.85	5.00
-0.5+0.25	36.4	1.46	3.15
-0.25+0	42	1.69	1.69
Total	2488.5	100	

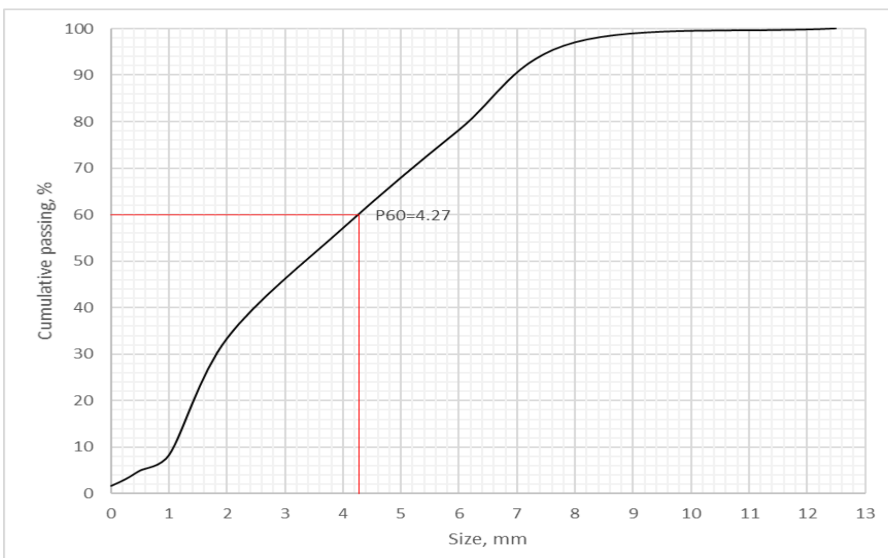


Figure 4. 2 Cumulative passing, %, diagram of sample “Screen-1 OS”

According to Figure 4.2, P60 of the sample was equal to 4.27mm. That means the sample is much coarser than the sample “Feed”. Therefore, it requires further crushing and grinding steps to approach the higher grade and recovery of concentrate. Fortunately, the sample “Screen-1 OS” is conducted to the dry magnetic separator which means that it doesn’t require a finer feed size to perform the experiment because the maximum feed size of the dry magnetic separator utilized during the experiment was 25mm. Therefore, the particle size of the sample “Screen-1 OS” is in an acceptable range.

Table 4. 5 The result of size distribution analysis of sample “Screen-2 OS”

Size, mm	Retained weight, gr	Retained weight, %	Cumulative Passing, %
+2	69.3	6.93	100
-2+1	226.7	22.67	93.07
-1+0.5	271.5	27.15	70.40
-0.5+0.25	213.1	21.31	43.25
-0.25+0.125	143.4	14.34	21.94
-0.125+0.075	47.1	4.71	7.60
-0.075+0	28.9	2.89	2.89
Total	1000	100	

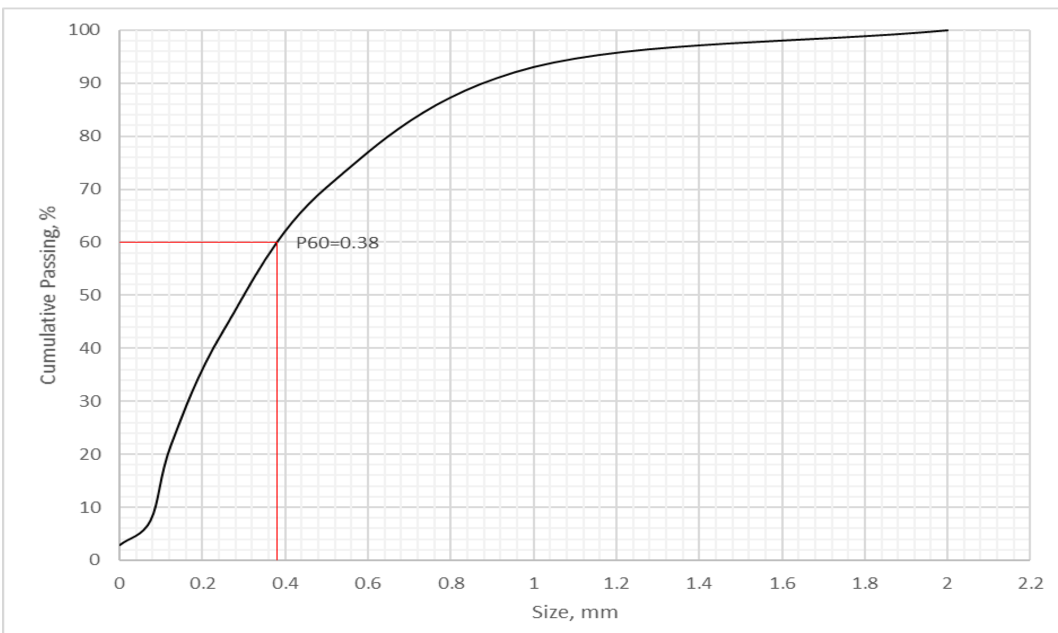


Figure 4. 3 Cumulative passing, %, diagram of sample “Screen-2 OS”

As shown in Figure 4. 3, the P60 of the sample “Screen-2 OS” was 0.38mm which is equal to the P60 of sample “Feed”. But in this case, the sample “Screen-2 OS” is beneficiated by the dry magnetic separation. Therefore, the sample can be fed to the magnetic separator directly.

4.3 Result of Grinding time determination

One of the most significant characteristics of the iron ore for the wet magnetic separation is the grindability of the material. The sample has to be grinded to its liberation size for the optimum recovery and purity.

The grinding time determining experiment was performed on the sample coded “Feed”, which was the only sample beneficiated by the wet magnetic separator. The objective of this experiment is to determine the grinding time when the sample is grinded to the certain level where 60%, 70% and 80% of the samples become finer than 0.075 mm.

The result of grinding the sample “Feed” for different minutes are tabulated below:

Table 4. 6 The result of 10 minutes 23 seconds grinding

Size, mm	Retained, gr	Retaining, %	Cumulative passing, %
+0.5	4.4	0.44	100
-0.5+0.25	102.8	10.28	99.56
-0.25+0.125	190	19	89.28
-0.125+0.075	103.5	10.35	70.28
-0.075+0	599.3	59.93	59.93
Total	1000		

Table 4. 7 The result of 15 minutes grinding

Size, mm	Retained weight,	Retaining %	Cumulative passing
+0.5	1.6	0.16	100
-0.5+0.25	44.6	4.46	99.84
-0.25+0.125	175.1	17.51	95.38

-0.125+0.075	128.8	12.88	77.87
-0.075+0	649.9	64.99	64.99
Total	1000		

Table 4. 8 The result of 18 minutes 38 seconds grinding

Size	Retained	Retaining %	Cumulative passing
+0.5	1.1	0.11	100
-0.5+0.25	30.5	3.05	99.89
-0.25+0.125	142.4	14.24	96.84
-0.125+0.075	135	13.5	82.6
-0.075+0	691	69.1	69.1
Total	1000		

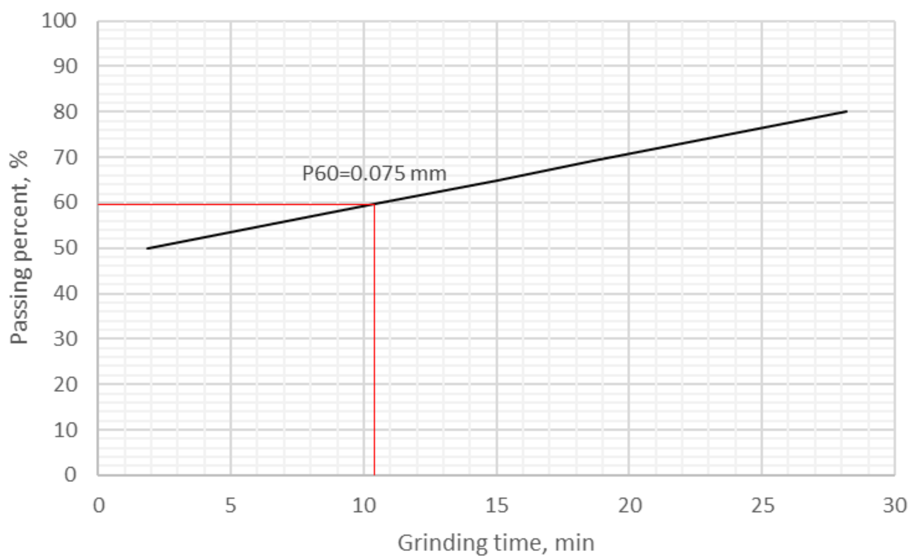


Figure 4. 4 Grinding time versus the percent of the sample finer than 0.075 mm.

The sample was ground for 3 different minutes: 10’ 23”, 15’ and 18’ 38”. The percent of the material, passing 0.075mm sieve, was varied depending on the durations of grinding. As a result of grinding the sample for 10’ 23”, 15’ and 18’ 38”, 60%, 65%, and 69 percent of the sample passed through the sieve with the size of 75 micron during the sludge removal.

Based on this result, 70% and 80% percent of the sample, having a particle size less than 75 micron, was estimated to be obtained when it is grinded for 19’ 25” and 28’ 11” respectively. The estimation was based on the Forecast function of the EXCEL program.

4.4 Result of Low-Intensity Dry Magnetic Separation

The second task of the case study was to beneficiate the samples coded “Screen-1 OS” and “Screen-2 OS” using a dry magnetic separator. The magnetic separator utilized during the experiment was a low-intensity drum type dry magnetic separator. The magnetic intensity was 1000 Gauss and the rotational speed of the drum was 40rpm.

The maximum feed size of the dry magnetic separator in the laboratory was 25mm.

The result of the dry magnetic separation experiment was tabulated below:

Table 4. 9 The result of Dry Magnetic Separation

№	Code of the sample	Weight of the feed /gr/	Grade of feed /%/	Weight of Conc. /gr/	Grade of Conc. /%/	Weight of tailing /gr/	Grade of tailing /%/	Yield /%/	Recovery /%/
1	Screen-1	9312.7	46.36	7377.4	54.4	1935.3	14.95	79.2	92.96
2	Screen-2	7985	49.13	6276.4	58.28	1708.6	13.88	78.6	93.24

According to Table 5-11, the grade of the iron ore sample “Screen-1 OS” increased from 46.36% to 54.4%. However, the target was to reach more than 58% Fe. The reason why the grade of concentrate couldn’t reach the desired value even though the yield of the concentrate was higher than the yield of “Screen-2 OS” is because of unlocked iron particles. The particle size of the “Screen-1 OS” was coarser than the “Screen-2 OS”, which means a valuable mineral couldn't be liberated from the ore sufficiently. Therefore, in order to reach the desired grade, it is recommended to apply the additional crushing process to the process flowsheet.

On the other hand, the grade of the sample "Screen-2 OS" successfully reached 58.28% without any cleaning steps. Therefore, it is assumed that it does not require any additional grinding or cleaning steps.

To sum up the results of dry magnetic separations on these samples, the efficiency of the magnetic separation was more than the expectation because the task of the case study was successfully completed by having more than 90% recovery. The flowsheet based on the result is given below.

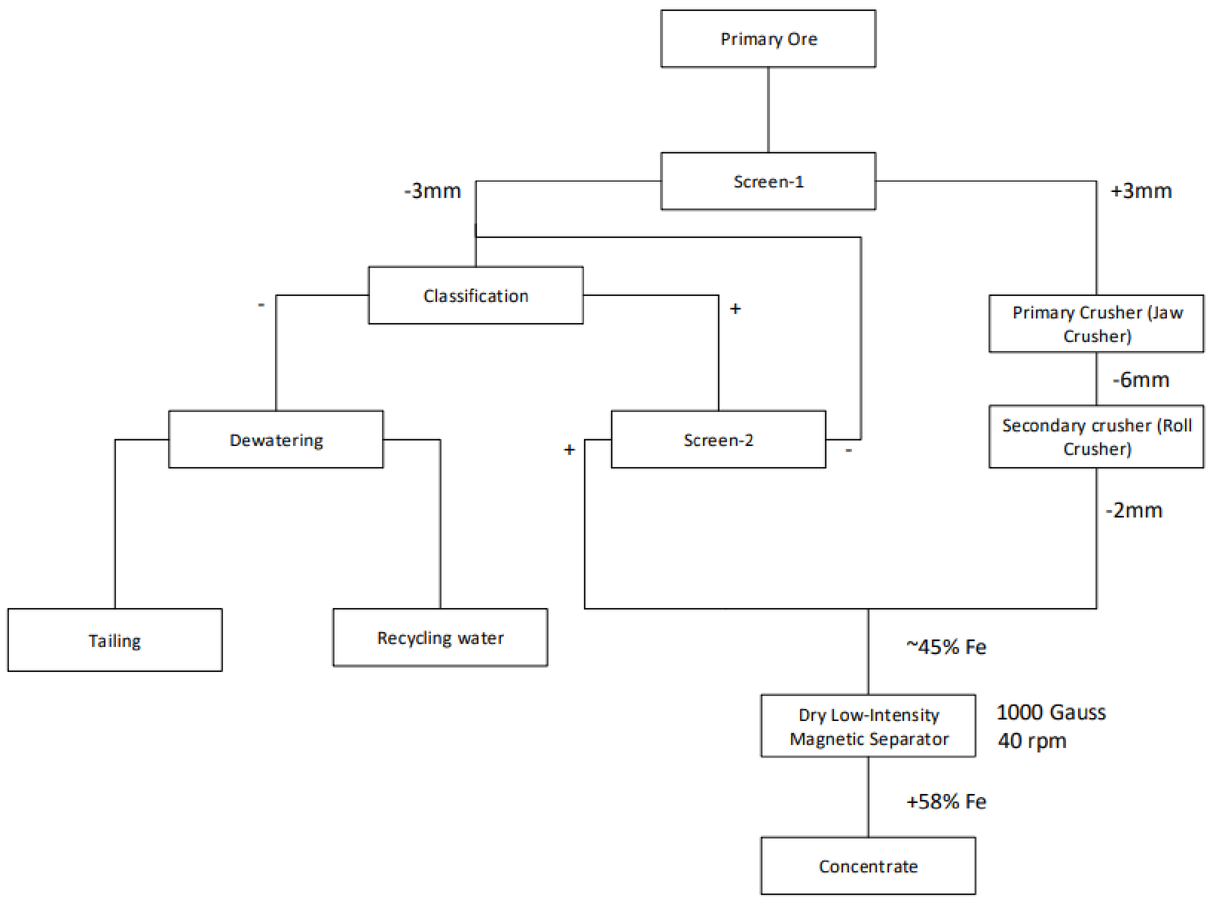


Figure 4. 5 A development of the process flowsheet by Dry Magnetic separation

4.5 Result of Low-Intensity Wet Magnetic Separation

The second objective of this thesis experiment was the beneficiation of the iron ore sample by wet magnetic separator. The target of the experiment was to remove the gangue materials from the feed and increase the iron content of the sample to more than 62%, which is one of the most significant requirements for the commercial iron ore concentrates to be sold by clients as a feed of blast furnaces. The significance of the magnetic beneficiation is described not only by increasing the grade of the iron ore but also by removing the deleterious elements such as sulfur and phosphorus.

The sample coded Feed was beneficiated by the Low-Intensity Wet magnetic Separator with the magnetic intensity of 1000 Gauss. Before the magnetic separation experiment, the 1 kg of 3 distinct samples, grinded by the rod mill for three different minutes, were prepared. Then, these three samples passed through the Low-Intensity Wet Magnetic separator under exactly the same conditions including the amount of magnetic intensity, solid percent, rotational speed of the drum and so on.

The result of the wet magnetic separation of sample "Feed" was given below:

Table 4. 10 The result of Wet Magnetic Separation

№	Grinding time	Content of -75 micron, %	Weight of concentrate /gr/	Grade of concentrate /%/	Weight of tailing, gr	Grade of tailing, %	Yield, %	Recovery, %
1	10'23"	60%	554.40	65.68	256.70	17.71	55.44	84.82
2	19'25"	70%	565.80	67.40	260.40	17.84	56.58	88.83
3	28'11"	80%	577.60	66.69	346.90	18.58	57.76	89.29

As previously mentioned, the initial grade of the feed was 42.93%. As a result of the experiment, the grade of the feed increased to 65.68% at 75-micron P60, 67.4% at P70 and 66.69% at P80 which are high enough to be considered as a high-grade iron ore concentrate.

Theoretically, as the grinding of material increases, more valuable material is loosened from the ore that results in a higher-grade concentrate being collected at the drum of the magnetic separator. Simply, when the material becomes finer, the grade of the extracted concentrate should increase.

However, the grade of the concentrate at P70 was more than P80 due to the random error. But, in overall, the recovery of the sample at P80, which was the one grinded the most, was the highest of all three samples. That means, the efficiency of the magnetic separation is the highest at P80.

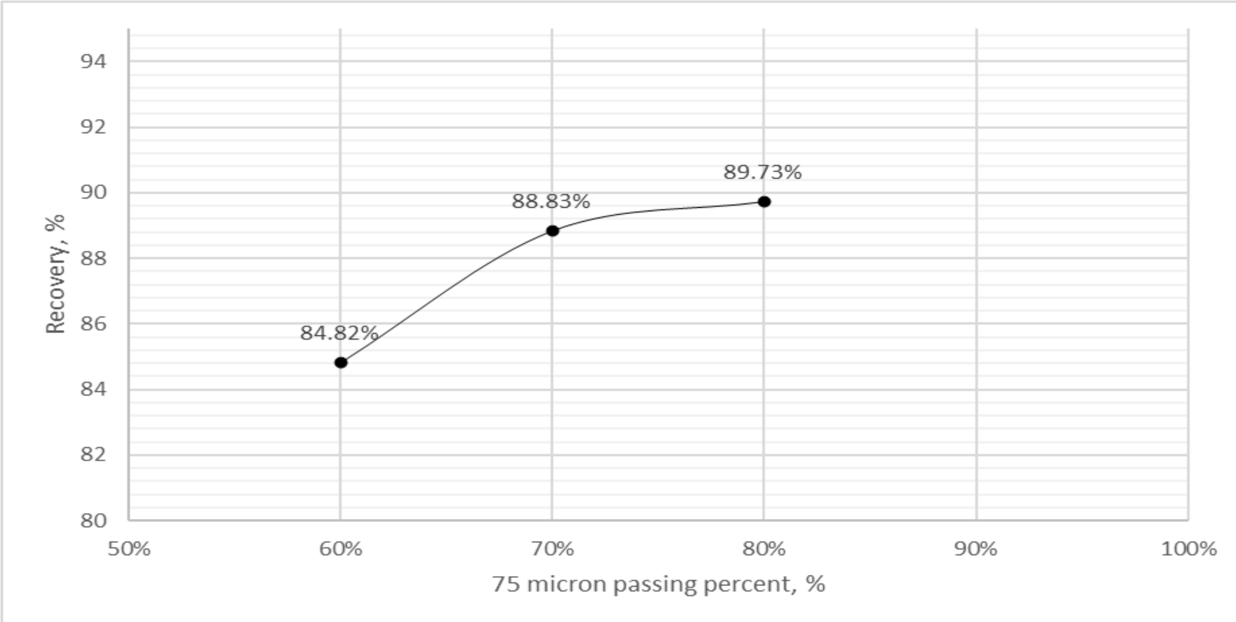


Figure 4. 6 The result of wet magnetic separation: 75 micron passing percent versus Recovery

According to the Graph 5-5, the recovery is directly related to the 75 micron passing percent. It can be concluded that the efficiency of wet magnetic beneficiation process increases and higher-grade material can be extracted as the particle size of the feed becomes finer.

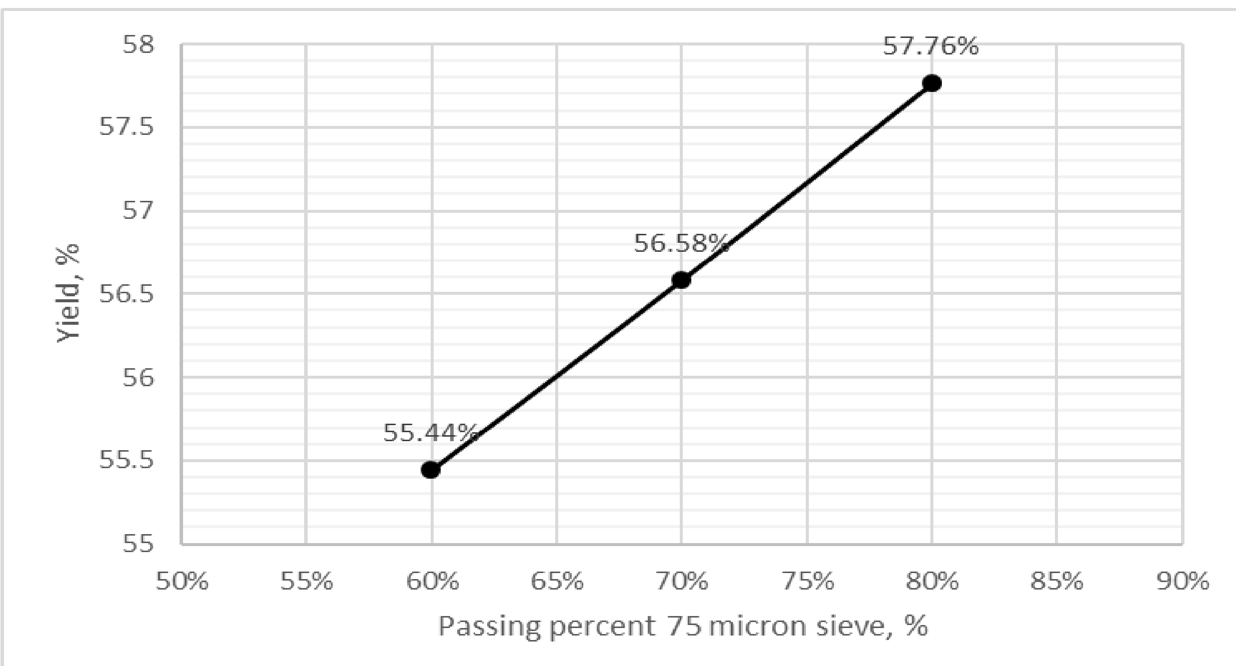


Figure 4. 7 The result of wet magnetic separation: 75 micron passing percent versus Yield

The efficiency of the magnetic separation is not only described by the recovery and grade of the concentrate but also yield is one of the most important parameters. As a result of the experiment, yields also increase with increasing grinding time. Therefore, it can be concluded that 75-micron P80 is the most efficient particle size for the wet magnetic separation from the aspect of processing engineering.

After beneficiation of the sample by wet magnetic separator, the chemical content of the sample was measured at the "Quality control department" of Tumurtei mine's laboratory.

Table 4. 11 Chemical content of concentrations and tailings of each wet magnetic separation experiments

№	Product name	Fe	S	Al2O3	SiO2	TiO2	P	MgO	CaO	K2O	Na2O	MnO
1	10'23" ConC	65.6	0.075	0.967	2.131	0.377	<0.001	0.439	0.238	<0.001	<0.001	0.028
3	10'23" Tailing	17.7	0.41	5.015	23.3	0.203	0.018	4.522	9.547	0.655	<0.001	0.188
4	19'25" ConC	67.4	0.029	0.981	2.546	0.373	<0.001	0.473	0.416	<0.001	<0.001	0.034
6	19'25" Tailing	17.8	0.558	4.648	21.87	0.192	0.02	4.345	9.859	0.634	<0.001	0.185
7	28'11" ConC	66.7	0.029	1.145	3.586	0.374	<0.001	0.575	0.949	<0.001	<0.001	0.039
9	28'11" Tailing	18.6	0.536	4.572	21.35	0.188	0.018	4.349	10.006	0.648	<0.001	0.172

As previously mentioned, the content of the alumina and silica, has to be less than 4% and 6% in iron ore products. As can be seen from Table 4-10, the alumina and silica content in the concentrates of each experiment meets the standard quality requirements for iron ore concentrates. Furthermore, the deleterious elements included in the iron ore concentrates are also low enough. Therefore, it can be summarized that all the deleterious elements gangue material contents could be lowered as a result of wet low intensity magnetic separation.

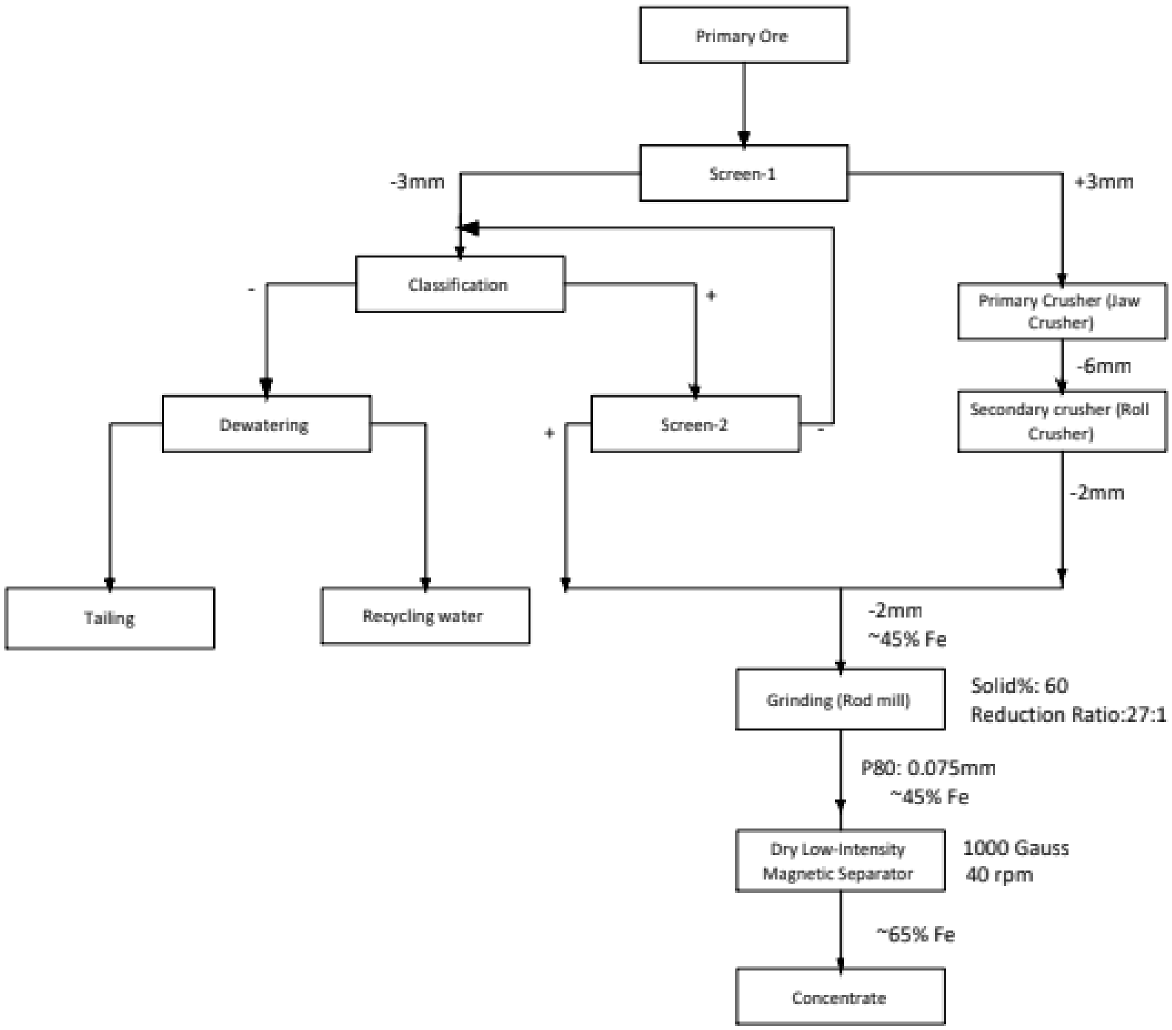


Figure 4. 8 A developed process flow sheet by Wet Magnetic Separator

5. Conclusion

5.1 Conclusion

Iron is one of the most significant elements in the world. Steel manufacturing plays an important role in the development of urbanization and industrialization. Therefore, the demand in iron ore has constantly increased throughout history. Furthermore, it will increase more rapidly in the future regarding world population growth.

The aim of this Bachelor thesis is to investigate the optimum processing solution to increase the iron ore grade of the Tumurtei iron ore mine to produce value-added commercial products.

The experiment consisted of 3 main parts:

1. Sample characterization: In this section, the weight of the sample, chemical content, size distributions and grinding time determinations of each three samples were measured.
2. Wet low-intensity magnetic separation: This is the main part of the experiment. The subsamples of "Feed", grinded at different levels, P60, P70 and P60, were beneficiated by the wet low -intensity magnetic separator under the magnetic intensity of 1000 Gauss for determining the optimum grinding size to beneficiate the ore.
3. Dry low-intensity magnetic separator: This is also one of the most significant parts of the whole experiment. During the experiment around 9kg and 7kg of subsamples taken from "Screen-1 OS" and "Screen-2 OS" were utilized. The samples didn't grinded because the top size of the materials was lower than the maximum feed size of the magnetic separator utilized in the experiment. Each sample was beneficiated by the magnetic intensity of 1000 Gauss and the rotation speed of 40 rpm.

As a result of the experiments, the sample "Feed" and "Screen-2 OS" could be beneficial to the desired level. On the other hand, sample "Screen-1 Os" couldn't reach the desired grade due to its coarse particle size.

Based on the result of the experiment, the optimum process flowsheets were designed separately on both wet magnetic separation and dry magnetic separation.

5. References

[1] Eri.mn. 2022. [online] Available at: <http://www.eri.mn/download/TKHUDER.pdf> [Accessed 15 May 2022].

[2] Nrcan.gc.ca. 2022. *Iron ore facts*. [online] Available at: <https://www.nrcan.gc.ca/our-natural-resources/minerals-mining/minerals-metals-facts/iron-ore-facts/20517> [Accessed 15 May 2022].

[3] Dmp.mn. 2022. [online] Available at: <https://www.dmp.mn/g69> [Accessed 15 May 2022].

[4] Worldometers.info. 2022. *Mongolia Map (Political) - Worldometer*. [online] Available at: <https://www.worldometers.info/maps/mongolia-political-map/> [Accessed 15 May 2022]. Worldometers.info. 2022. *Mongolia Map (Political) - Worldometer*. [online] Available at: <https://www.worldometers.info/maps/mongolia-political-map/> [Accessed 15 May 2022].

[5] Earth.google.com. 2022. *Google Earth*. [online] Available at: <https://earth.google.com/web/search/ > [Accessed 15 May 2022].

[6] 2015. *Control & HMI Manual*. [online] p.63. Available at: <http://www.cdeglobal.com> [Accessed 15 May 2022].

[7] Li, F., Wang, Z. and Huang, L., 2021. Economic growth target and environmental regulation intensity: evidence from 284 cities in China. *Environmental Science and Pollution Research*, [online] 29(7), pp.10235-10249. Available at: <https://www.reuters.com/markets/europe/iron-ore-outlook-is-more-bullish-than-lower-china-growth-target-suggests-russell-2022-03-07/#:~:text=China's%20iron%20ore%20imports%20have,the%2089.29%20million%20from%20November.>.

[8] Price.metal.com. 2022. *Iron-Ore Price Chart,China Iron-Ore Price Today-Shanghai Metals Market*. [online] Available at: <https://price.metal.com/Iron-Ore> [Accessed 15 May 2022].

[9] Angerer, T., Thorne, W., Hagemann, S., Tribus, M., Evans, N. and Savard, D., 2022. Iron oxide chemistry supports a multistage hydrothermal genesis of BIF-hosted hematite ore in the Mt. Tom Price and Mt. Whaleback deposits. *Ore Geology Reviews*, 144, p.104840.

[10] En.wikipedia.org. 2022. *Iron - Wikipedia*. [online] Available at: <https://en.wikipedia.org/wiki/Iron#Chemistry_and_compounds> [Accessed 16 May 2022].

[11] Ba Bus T. Engineering Guide 7. 1st ed. Ulaanbaatar; 2020.

[12] Iron [Internet]. Hyperphysics.phy-astr.gsu.edu. 2022 [cited 16 May 2022]. Available from: http://hyperphysics.phy-astr.gsu.edu/hbase/pertab/fe.html

[13] iron | Element, Occurrence, Uses, Properties, & Compounds [Internet]. Encyclopedia Britannica. 2022 [cited 16 May 2022]. Available from:

[14] [Internet]. 2022 [cited 16 May 2022]. Available from: https://study.com/academy/lesson/allotropes-of-iron-types-density-uses-facts.html

[15] Sözmen E, Kavakli K, Cetinkaya B, Akçay Y, Yilmaz D, Aydinok Y. Effects of Iron(II) Salts and Iron(III) Complexes on Trace Element Status in Children with Iron-Deficiency Anemia. Biological Trace Element Research. 2003;94(1):79-86.

[16] Iron ore - Wikipedia [Internet]. En.wikipedia.org. 2022 [cited 16 May 2022]. Available from: https://en.wikipedia.org/wiki/Iron_ore#Sources

[17] Iron [Internet]. Hyperphysics.phy-astr.gsu.edu. 2022 [cited 16 May 2022]. Available from: http://hyperphysics.phy-astr.gsu.edu/hbase/pertab/fe.html

[18] Iron Ore Statistics and Information | U.S. Geological Survey [Internet]. Usgs.gov. 2022 [cited 16 May 2022]. Available from: https://www.usgs.gov/centers/national-minerals-information-center/iron-ore-statistics-and-information

[19] 10. Iron ore facts [Internet]. Nrcan.gc.ca. 2022 [cited 16 May 2022]. Available from: https://www.nrcan.gc.ca/our-natural-resources/minerals-mining/minerals-metals-facts/iron-ore-facts/20517

[20] [Internet]. Spglobal.com. 2022 [cited 16 May 2022]. Available from: https://www.spglobal.com/commodityinsights/plattscontent/_assets/_files/en/our-methodology/methodology-specifications/ironore.pdf

[21] 15. Jansen T, Jüstel T. The optical properties of Sr 3 SiAl 10 O 20 and Sr 3 SiAl 10 O 20 :Mn 4+. Journal of Physics and Chemistry of Solids. 2017;110:180-186.

[22] YoungC K. SME mineral processing & extractive metallurgy handbook. 1st ed. Society for Mining, Metallurgy and Explorations.; 2019.

[23] 13. ITO Y, ODA Y, OKUNO K, NARITA T, KATO H. Electromagnetic Levitation System for Thin Steel Plate Combined Electromagnet and Permanent Magnet. The Proceedings of Yamanashi District Conference. 2018;2018(0):YC2018-071.

6. Appendix

6.1 Technical specifications of laboratory equipment

Table 6. 1 Technical specifications of jaw crusher

	Model	5E-JCA150*125
	Feed opening size [mm]	100
	Output size [mm]	6 to 38
	Capacity [kg/h]	100
	Motor power [kW]	380

Table 6. 2: Technical specifications of roll crusher

	Model	LRMC
	Feed opening size [mm]	-30
	Output size [mm]	-2
	Capacity [kg/h]	100
	Motor power [kW]	380

Table 6. 3 Technical specifications of laboratory automatic splitter

	Model	ZS-A
	Object	Coal, Ore, Limestone, Coke, Zeolite etc.
	Feed opening size [mm]	<13, 6, 3
	Handling capacity	About 1000kg/H
	Specification	ISO 9001:2000

Table 6. 4 Technical specifications of a rod mill

	Model	XMQ 240x300
	Capacity (gram)	1000-5000
	Feed opening size [mm]	<2mm
	Discharging size (mm)	<0.074mm
	Power (kW)	0.55
	Dimensions (mm)	1050x615x1160
	Weight (kg)	160

Table 6. 5 Technical specifications of Dry Magnetic separator

	Model	DFA-10
	Capacity (mtph/m)	45-120
	Feed size range [mm]	-25 +6
	Magnetics in Feed	~50%
	Drum speed (mpm)	0.55