PRODUCTION OF HEAVY-MEDIA-QUALITY MAGNETITE CONCENTRATE FROM KESİKKÖPRÜ IRON ORE TAILINGS

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PRODUCTION OF HEAVY-MEDIA-QUALITY MAGNETITE CONCENTRATE FROM KESİKKÖPRÜ IRON ORE TAILINGS

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ABSTRACT

PRODUCTION OF HEAVY-MEDIA-QUALITY MAGNETITE CONCENTRATE FROM KESİKKÖPRÜ IRON ORE TAILINGS

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The aim of this research was to investigate the possibility of the production of a magnetite concentrate which is suitable for preparation of heavy media from iron ore tailings of Güncem Mining Company magnetic separation facility.

During the study, three different tailings named as low grade, medium grade and high grade with 5.91 % Fe_3O_4, 19.06 % Fe_3O_4 and 37.06 % Fe_3O_4, respectively, were used. Mineralogical analyses of test samples showed that magnetite and hematite were the major ore minerals while pyrite and chalcopyrite were found in trace amounts. Actimolite, tremolite, epidote, chlorite, quartz, calcite, and dolomite were the gangue minerals. The effects of feed particle size and applied magnetic field intensity on the Fe_3O_4 grade and recovery of concentrate were examined throughout magnetic concentration tests. The highest grade magnetite concentrate with 79.98% Fe_3O_4 content was obtained with 65.42% recovery from 100% -75 μm size feed at 1000 Gauss magnetic field intensity from high grade tailing.

Key words : Magnetite, Magnetic separation, Heavy media

ÖZ

KESİKKÖPRÜ DEMİR CEVHERİ ARTIKLARINDAN AĞIR ORTAM KALİTESİNDE MANYETİT KONSANTRESİ ÜRETİMİ

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Tez Yöneticisi: Prof. Dr. M. Ümit Atalay

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Bu araştırmada Güncem Madencilik Şirketine ait manyetik ayırma tesis artıklarından ağır ortam hazırlamaya uygun manyetit konsantresi üretimi amaçlanmıştır.

Çalışma sırasında düşük tenörlü, orta tenörlü ve yüksek tenörlü olarak adlandırılan ve sırasıyla % 5.91 Fe_3O_4, %19.06 Fe_3O_4 ve %37.06 Fe_3O_4 içeren artık numuneleri kullanılmıştır.

Deney örneklerinin minerolojik analizi, manyetit ve hematit'in esas cevher mineralleri olduğunu, pirit ve kalkopirit'in az miktarda bulunduğunu, aktimolit, tremolit, epidot, klorit, kuvars, kalsit ve dolomitin değersiz mineralleri oluşturduğunu göstermiştir. Manyetik zenginleştirme testleri sırasında, besleme tane boyu ve manyetik alan şiddetinin konsantrenin Fe_3O_4 tenörü ve verimi üzerindeki etkileri araştırılmıştır. En yüksek tenörlü konsantre %79.98 Fe_3O_4 içeriği ve %65.42 verimle, yüksek tenörlü artığın %100'ünün 75 μm altına öğütülüp 1000 Gauss'luk bir manyetik alandan geçirilmesiyle elde edilmiştir.

Anahtar Kelimeler : Manyetit, Manyetik ayırma, Ağır ortam

To My Family

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Abbreviations	**Description**
HMS	Heavy Medium Separation
DMS	Dense Medium Separation

Units	**Description**
cm	Centimeter
mm	Millimeter
µm	Micrometer
g	Gram
kg	Kilogram
g/cm^3	Gram/Cubic centimeter

Symbols	**Description**
Σ	Cumulative

CHAPTER 1

INTRODUCTION

1.1. General Remarks

Dense medium separation (DMS) process, also referred to as heavy medium separation (HMS), is one of the most widely applied and efficient gravity concentration method for demineralization (removal of ash forming minerals) of coal and preconcentration of large variety of minerals. According to a survey (Kempnich, 2003), nearly 55% of the cleaned coal in preparation plants worldwide is treated in DMS units. Dense medium circuits presently account for approximately 65% of the installed capacity in the United States (Luttrel *et al.*, 2003) and is responsible for the production of nearly 250 million tons of clean coal from the 413 million tons processed coal annually (Honaker and Patwardhan, 2006). The partial list of commercial applications of the HMS concept for processing industrial minerals over the last 25 years is listed in Table 1.1 (Bhappu and Highttower, 2003).

Table 1.1 Partial list of HMS processing plants (Bhappu and Highttower, 2003).

Operator/Plant Location	Mineral Processed	Size Range	Plant Feed tph	HMS Units	Sink/Float Ratio	Separa. Density
Aluminum Co. of Canada, Ltd. St. Lawrence, Newfoundland	Fluorspar Barites	–3/4"+20M	80	2–15"	40/60	2.72
Barton Mines North Creek, NY	Garnet	–1/4"+45M	60	1–12" & 1–9"	60/40	3.2
Basic Inc. Gabbs, NV	Magnesite	–3/8"+20M	30	1–9"	75/25	2.9
Bethlehem Steel Corp. Icomi Mine, Amapa, Brazil	Manganese	–1/4"+20M	130	2–15"	80/20	2.9
Cia. Minera de Autlan S.A. Autlan Mine	Manganese	–20mm +1mm	90	1–18"	70/30	2.95
Universe Tankships Inc. Para, Brazil (Jari, Project)	Bauxite	–3/8"	18	1–9"	95/5	2.3
Companhia Mineira do Lobito Jamba Mine, Angola, Africa	Iron	–1/4"+20M	400	6–15"	80/20	2.7
Dresser Minerals Ryder Point Plant	Fluorspar Barites	–25mm +1mm	80	2–15"	50/50	2.75
Fundy Gypsum Co. Ltd. Windsor, Nova Scotia	Gypsum Rock	–3/4"+20M	80	2–15"	30/70	2.5
International Mining Co. Enramada Mine, Bolivia	Tin/ Tungsten	–1"+20M	30	1–12"	25/75	2.95
Lithium Corp. of America Bessemer City, NC	Lithium	–1/4"+65M	65	1–15"	30/70	2.8
NL Industries Inc. Guatemala	Scheelite	–1/2"+14M	10	1–9"	60/40	2.7
Renison Ltd. Zeehan, Tasmania	Tin	–1/2"+28M	80	2–15"	80/20	3.0
Southern Peru Copper Corp. Ilo, Peru	Coquina Shells	–1/4"+30M	50	1–15"	50/50	2.7
Turk Maadin Sirketi Beyoglu, Turkey	Chrome	–1/4"+20M	10	1–9"	60/40	2.9

The HMS process is one of the cheapest methods of mineral preconcentration, due to its simplicity of operation and equipment. Preconcentration is carried out at a fairly coarse size without grinding which is the most expensive step in the concentration operation. In the heavy medium separation process, the separation of coal from ash forming minerals or the separation of dense valuable minerals from light gangue minerals is achieved by preparing a medium having a density between the solid densities of the two products being separated. The medium is formed by suspending fine dense particles in a medium of water. The most widely used materials to prepare suspension in commercial application for metaliferrous ore is now ferrosilicon, while magnetite is used in cleaning of coal.

Turkey has lignite reserve over 10.4 billion tons with low calorific value and high ash content. Important portion of coal to be used for industrial and heating purposes need cleaning process to minimize environmental problems of combustion of low quality coals. The number of coal cleaning plants with heavy medium circuits has increased significantly in recent years. Important coal cleaning plants of Turkey with heavy medium circuits are tabulated in Table 1.2. The growing demand for magnetite coupled with a decrease in the availability of high grade magnetite ores makes it necessary to develop the technology needed for recovering magnetite from tailings. As a result, magnetite presently used for heavy medium is a product of existing iron ore mine. By utilizing low intensity magnetic separation in combination with selective flocculation, a concentrate with 67.6% Fe and 87.1% Fe_3O_4 was obtained from fine tailings of Divriği Concentrator with 70.7% recovery (Başaran, 1988). Concentration possibilities of C-Placer and B-Body ores fines from Divriği iron mines was studied by Akdoğan in 1987. By using the combination of jigging and shaking table concentration methods, concentrates containing 64.4% Fe and 62.4% Fe were obtained with 81.3% and 77% recovery from C-Placer and B-Body ore fines, respectively.

Table 1.2 Examples of coal cleaning plants with HMS process (Arslan, 2010)

Plant Name	Capacity (tph)	Coarse Circuits	Fine Circuits
Çiftay Mining Co.(Soma)	800	Drum separator	Dense medium cyclone
TKİ (Tuçbilek)	700	Drum separator	Dense medium cyclone
TKİ (Tuçbilek-Ömerler)	600	Drum separator	Dense medium cyclone
İmbat Mining Co. (Soma)	500	Drewboy	Dense medium cyclone
Soma Coal Mining Co. (Soma)	350	Drewboy+Drum	Dense medium cyclone
Park Teknik Co. (Çayırhan)	300	Drewboy	Dense medium cyclone
Park Teknik Co. (Seyitömer)	300	Drewboy	Dense medium cyclone
Park Mining Co. (Kozlu-Zonguldak)	300	Drewboy	Dense medium cyclone
Park Mining Co. (Üzülmez-Zonguldak)	300	Drewboy	Dense medium cyclone
TKİ (Yeniköy-Muğla)	220	Drum separator	Dense medium cyclone
Amasra	210	Drum separator	Dense medium cyclone
De-Ka Mining Co. (Zonguldak)	200	Drewboy	Dense medium cyclone
Çelikler Mining Co. (Çorum)	175	Drewboy	Dense medium cyclone
Eski Çeltek Mining Co. (Suluova)	175	Drewboy	Dense medium cyclone
Uysal Mining Co. (Tekirdağ)	175	Drewboy	Dense medium cyclone
Zirve Mining Co. (Zonguldak)	175	Drewboy	Dense medium cyclone
Ortur Mining Co. (Balıkesir)	150	Drum separator	Dense medium cyclone
Hema Coal Mining Co. (Kandilli)	150	Drewboy	Dense medium cyclone
Milten Mining Co. (İstanbul)	150	Drewboy	Dense medium cyclone
Polat Mining Co. (Balıkesir)	125	Drum separator	Dense medium cyclone
Özerdemler Mining Co. (Kütahya)	120	Drum separator	Dense medium cyclone
Kartalkaya Mining Co. (Azdavay)	120	Drewboy	Dense medium cyclone
Eli Deniş Washery	100	Drewboy	Dense medium cyclone
Özçevreci Mining Co. (Balıkesir)	100	Drum separator	Dense medium cyclone
Enerji Mining Co. (Kepsut)	100	Drum separator	Dense medium cyclone
De-Ka Mining Co. (Azdavay)	100	Drewboy	Dense medium cyclone
İbrice Mining Co. (Tekirdağ)	100	Drum separator	Dense medium cyclone
TKİ (Merdivenli-Muğla)	100	Drum separator	Dense medium cyclone
Çelikler Mining Co. (Dodurga)	75	Drewboy	Dense medium cyclone
Forbes Mining Co.	75	Drewboy	Dense medium cyclone
Volkar Energy Co. (Tekirdağ)	75	Drewboy	Dense medium cyclone
Arılar Mining Co. (Zonguldak)	60	Drewboy	Dense medium cyclone
Bahadır Mining Co. (Zonguldak)	60	Drewboy	Dense medium cyclone
Yılmazlar Coal Mining Co. (Zonguldak)	60	Drewboy	Dense medium cyclone
Tuncerler Mining Co.	50	Drum separator	Dense medium cyclone
Yeni Çeltek Coal Co. (Merzifon)	50	Drum separator	Dense medium cyclone

1.2. Objective of the Thesis

The objective of the thesis is to investigate the possibility of magnetite recovery from the iron ore tailings with the final intention of using it in heavy media separation. Three iron ore tailing samples having different Fe_3O_4 content were selected and concentration tests were performed with Davis tube magnetic separator. The effect of particle size and induced magnetic field intensity were investigated with regard to Fe_3O_4 grade and recovery of the magnetite concentrate.

CHAPTER 2

LITERATURE REVIEW

2.1 Dense Medium Separation

Dense medium separation (DMS) or heavy medium separation (HMS) is the most widely applied gravity concentration process for coal preparation. In the process, the separation of coal from the ash forming mineral matter is achieved by preparing a medium having a density between the densities of the two materials being separated. As a result, the coal particles float while the heavier mineral matter sinks through the medium. The most relevant advantages of dense medium separation process are as follows (Bhappu and Higttower, 2003, Wills, 1997, Palowitch and Deurbrouck, 1968).

- DMS has the ability to make sharp separations at any required density.
- It has high efficiency in the presence of high amount of near gravity material
- The density of separation can be closely controlled
- The separating density can be changed very quickly to meet the varying conditions
- Ability to handle a wide range of sizes
- Relatively low capital and operating costs when considered in terms of high capacity and small space requirement

2.1.1 History of Dense Medium Separation

Historical information was summarized in the following sentences (Pryor, 1974., Palowitch and Deurbrouck, 1968, Erten, 1964). Henry Bessemer was the first person to patent the use of solutions of the chlorides of iron, manganese, barium and calcium. In 1911 Du Pont developed the use of chlorinated hydrocarbons to obtain high densities. The first important success was achieved by the Chance process patented in 1917, using a mixture of sand and water. The first plant was erected in 1921 for cleaning anthracite. In 1925 the process was used for cleaning bituminous coal. In 1928 Lessing re-developed the use of calcium-chloride solution as a dense medium bath of 1.35 g/cm^3 density. In 1931 clay, gypsum and pyrite were used for preparation of heavy medium. In 1932 G.J. de Vooys established a coal-cleaning process based on use of a barite-clay medium. In 1935, the use of suspension of finely ground galena in water was investigated. This method was successfully applied at the lead mine in Wales, England. The tromp process, developed in 1938, was the first to employ magnetite medium commercially. The “heavy media separation” process, originally developed for the concentration of ore, was introduced by the American Cynamid Company for cleaning of coal in about 1940. The process used magnetite as the medium. Through the use of instrumentation and process controls, today highly automated dense medium plants are capable of high throughput and result in a separation of raw coal into clean coal.

2.1.2 Types of Dense Medium

Organic liquids, solutions of salts in water and suspensions of solids are the three main types of dense media. Autogeneous media, provided by the coal itself is also rarely used as heavy media in some heavy medium separators.

Heavy organic liquids are restricted for small scale laboratory use and even in laboratory they are becoming less utilized because of toxic and carcinogenic nature of the organics. Table 2.1 summarizes the properties of the heavy liquids used (Gupta and Yan, 2006). Densities up to 12.0 can be achieved for separation of non-magnetic minerals by use of magnetohydrostatics. This density is produced in paramagnetic salt solution by the application of magnetic field gradient (Walker, 1985). This type of high density medium is applicable to separation of non-magnetic particles down to about 50 microns (Gupta and Yan, 2006).

Table 2.1 Heavy liquids used in laboratories

Heavy Liquid	**Formula**	**S.G.**	**Dilution**	**Health**
Tri-Chloro-ethylene	CCl_2CHCl	1.46	-	Group 2A* carcinogen
Carbon-tetrachloride	CCl_4	1.50	Most organic liquids	Group 2B** carcinogen
Bromoform, Tribromomethane	$CHBr_3$	2.87	Alcohol, CCl_4	Liver damage, Group 3***
Tetrabromoethane (TBE)	$C_2H_2Br_4$	2.95	Alcohol, CCl_4 Chloroform	Suspected carcinogen
Di-iodo methane (Methylene iodide)	CH_2I_2	3.31	CCl_4, Benzene	Moderate toxicity-central nervous system
Clerici solution(thallium malonate/thallium formate)	$(TCOOH)_2C/$ TICOOH	4.20-5.00	Water	Highly toxic, cumulative poison
Lithium heteropolytungstate (LST)	$Li_mX_n(W_{12}O_{40})$	2.95	Water	Low to moderate toxicity
Sodium polytungstate (SPT)	$Na_6(H_2W_{12}O_{40})$	3.1	Water	Low to moderate toxicity
Lithium metatungstate (LMT)	$Li_6(H_2W_{12}O_{40})$	3.0	Water	Low to moderate toxicity

* Group 2A is a probable carcinogen

** Group 2B is a probable carcinogen

*** Group 3 is unclassifiable carcinogen

The medium used for separation of low density mineral may be made up of dissolved salts like calcium chloride ($CaCl_2$) and zinc chloride ($ZnCl_2$) in water where densities up to 1.35 g/cm^3 and 1.90 g/cm^3 may be produced, respectively. Due to high cost and corrosive property of $ZnCl_2$ dissolved salt solution is restricted to only laboratory use (Rhodes *et al*., 1993, Wills, 1985)

When high medium densities are required, the suspensions of finely divided high density particles in water (pseudo liquids) are used. In the 1930's the Barvoys process was developed in Holland, which used a mixture of clay (specific gravity 2.3) and finely ground barites (specific gravity 4.2) in a ratio of 2:1 which gave a density up to 1.8 g/cm^3. Froth flotation was used to regenerate the fouled dense-media by removing the fine coal. The process was abandoned owing to the high regeneration cost with flotation. Galena (specific gravity 7.5) was also used initially as medium. The high cost of cleaning of contaminated medium with flotation, oxidizing and sliming tendency of galena which impairs the flotation efficiency prevented the use of finely ground galena suspended in water. Studies have been performed to evaluate the potential of alternative materials that can be used to generate a dense medium for coal cleaning application. Waste steel slags, fine sands, blast furnace flue dust and autogeneous reject material were tested. Compared to other medium types, steel slag and blast furnace flue dust provided the most stable suspensions (Honaker and Bimpong, 2009., Sripriya *et al*, 2003).

The most widely used medium for metalliferrous ores is now ferrosilicon, whilst the magnetite is used for coal preparation.

Both magnetite and ferrosilicon have the following characteristics:

- They don't have tendency to slime easily.
- They have chemical stability. They are not corrosive and they do not react with minerals or coal.
- They show slow settling at reasonable viscosity. They form a fairly stable suspension without having to be ground very fine.
- They have high enough specific gravity to give the required bath density at low % solids.
- They are easily removed from the mineral surfaces or coal surfaces by washing.

- They are easily regenerated from the contaminated medium by magnetic separation.

Ferrosilicon which meets the above specifications (specific gravity 6.7 – 6.9) is an alloy of iron and silicon. It's iron content should be greater than 82% while silicon is in the range of 15 – 16%. If ferrosilicon contains more than 16% Si in it, its magnetic susceptibility will decrease and its regeneration with magnetic separation will become difficult, less than 15% silicon will cause corrosion of ferrosilicon alloys. At 15% silicon, the density of ferrosilicon is 6.8 gr/cm^3 and a medium of 3.2 gr/cm^3 can be prepared. Magnetite which is the most widely used medium for coal cleaning will be examined in more details in the following section.

2.1.3 Standards for Magnetite Heavy Media

Separation efficiency of heavy medium process depends upon the rheology and stability of magnetite media. This is more important for the dense medium cyclone which gives a sharper separation than the other types of coal washing equipment. The flow behavior in dense medium cyclone is quite complex. There is an extensive literature on particle separation for dense medium cyclones.

A detailed in-plant evaluation of the dense medium process employed in an operating dense medium cyclone was conducted to determine the relationship between apparent separation density and the medium density and to quantify the process efficiency. The separation density was found to be about 0.08 to 0.03 RD (relative density) greater than the medium density range of 1.35 to 1.50 RD. 300% decrease in separation efficiency was observed as a result of increasing medium density over the same range. The Ep values increased from about 0.02 to 0.06. The decline in efficiency was a result of increase in the recovery of particles having density slightly greater than the separation density to the clean coal product (Honaker and Patwardhan, 2006).

A mathematical approach was proposed to describe the flow in an industrial dense medium cyclone. It is found that as the medium density increases, the pressure drop increases, resulting in a high pressure gradient force on coal particles and reduced separating efficiencies. The segregation of magnetite particles becomes serious as magnetite particle size increases (Wang *et al*., 2009).

A complete mass balance of magnetite and coal in various parts of a dense medium cyclone (DMC) circuit was determined and fractional size distribution of magnetite and coal were analyzed for the circuit. The DMC overflow product contained 71.34% of feed coal, whereas 88.35% of the feed magnetite was reported to DMC underflow (Çelik, 2009).

An attempt has been made to study the magnetite medium stability behavior inside the heavy medium cyclone (HMC) and Vorsyl separator (VS). It is found that, at any operating condition, the difference between the underflow and overflow slurry density is always less in VS than HMC. This signifies that magnetite medium is more stable in VS than in HMC (Majumder *et al*., 2006)

The effect of size distribution of the magnetite in HMC has been fully studied. The ultra-fine magnetite sizes (2 – 7 microns) are distributed uniformly throughout the cyclone. As the size of magnetite increases, more segregations of magnetite occur close to the wall. By using X-Ray tomography highest-slurry density was detected in apex region (Narasimha *et al*, 2007).

An extensive separation test was carried out on a 6-inch dense medium cyclone by changing the magnetic particle size and medium density. It was found that, while the separation efficiency and cut point shift for coarse particles (>2.0 mm) were mainly determined by the medium stability, the separation performance of fine particles (<0.5 mm) was more sensitive to the change in medium rheology (He and Laskowski, 1994).

Physical properties used to specify the quality and suitability of a particular source of magnetite must be assessable by standard techniques. Several countries have been actively involved in establishing magnetite specifications for heavy medium applications (Mikhail and Osborne, 1990., Osborne, 1988).

The general specifications for magnetite based on the British coal mining industry:

a) Particle size distribution : Maximum 5% by weight larger than 45 µm and 30% by weight smaller than 10 µm
b) Relative density : 4.9 – 5.2 g/cm^3
c) Magnetite content : not less than 95% by weight

Table 2.2 gives working specifications of magnetite for worldwide usage (Osborne, 1988)

Table 2.2 Coal-cleaning dense-medium magnetite specifications (Osborne, 1988)

Country	**Moisture content (%)**	**Size (microns)**	**Magnetics content (%)**	**Relative density g/cm^3**
Canada	<10	<5%, +45	>95	>4.8
United States	<10	<5%, +45	>95	>4.8
South Africa	<10	<5%, +45 <30%, -10	>95	4.9 – 5.2
Australia	<10	<5%, +45 <30%, -10	>95	>4.8

On the other hand General Directorate of Turkish Coal Works accepted the following specifications for magnetite concentrate :

a) Particle size distribution	: 95% (min) -45 µm, and 5%(max) + 45 µm
b) Iron content	: 60 – 67 % Fe
c) Magnetite content	: 90% Fe_3O_4
d) Density	: 4.1 – 4.9 g/cm^3
e) Moisture Content	: 7 – 12 %

Industrial experience and practices by several coal producing countries have been used to develop standard procedures to test magnetite for coal preparation purposes. The international standard ISO 8813 specifies the following properties for testing :

a) Moisture content
b) Particle size distribution
c) Magnetic content
d) Relative density

Physical properties used to specify the quality and suitability of a particular source of magnetite must be assessable by standard techniques. Several recognized procedures and equipment are used in the determination of physical properties of magnetite. These are summarized in Table 2.3.

Table 2.3 Methods used in the determination of the physical properties of magnetite (Osborne, 1988)

Property	Method or equipment	Limitations
Particle size	Dry screening Wet screening Cyclosizer Coulter method Sedigraph or other sedimentation analyser Bahco or Haultain: pneumatic classification Microtrac or other microscopic methods Optical sizing	Valid only above 53 µm Many variables introduced Time consuming; only limited points obtained Sensitive to auto-coagulating properties High density of particles causes rapid settling Time consuming; potential high loss of very fine material Irregular shapes may introduce bias Sophisticated equipment needed
Magnetic content	Davis tube ISO apparatus Magnetic chute Hand magnet	Many variables Simple method with good reproducibility Variable magnetic field Accuracy depends on operator; only approximate
Density	Beckman pycnometer Density bottle	Slightly operator dependent Often difficult with fine powders

2.1.4 Heavy Medium Separators (Dense Medium Separators)

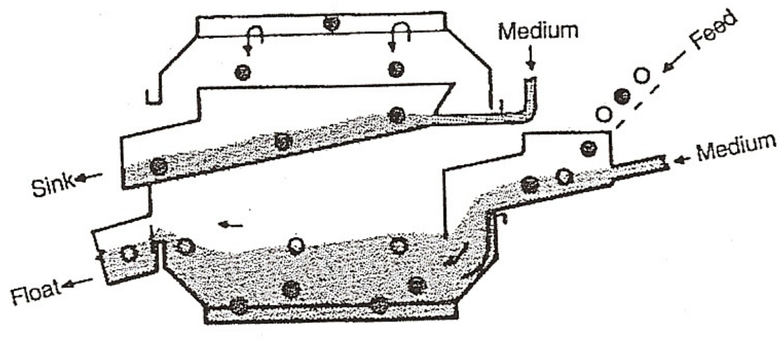
Heavy medium separators generally produce two products. A float product of lower density and a sink product of higher density than the medium. In some separators a third, middling product is also produced. Heavy medium separators are classified into gravitational type heavy medium (bath or through) separators and centrifugal type heavy medium separators.

2.1.4.1 Gravitational Type Heavy Medium Separators

The crushed ore or coal and dense medium are fed into the tank of trough of the medium. The floating material overflows or is removed from the bath by scrapers or paddles while the sink material which falls to the bottom of tank is removed by some means. Since the coal separation has a very high float content in the feed, the separator will need a high float capacity whereas separators for the mineral industry may require a high sink capacity. Drum separator, Cone separator, Drewboy and Norwalt separator are the examples of gravitational type heavy medium separators.

2.1.4.1.1 Drum Separators

Consisting of a cylindrical rotating drum, they are used for mineral and coal separation (Figure 2.1). The size of the drums ranges up to about 4.6 m diameter and by 7.0 m length, with capacities up to 800 t/h. The drums may consist of a single compartment, producing two products from a single dense medium suspension or consist of two compartments with two baths of different density to produce three of four products. Drum feed size ranges from 6 mm to 30 cm (Wills, 1985).



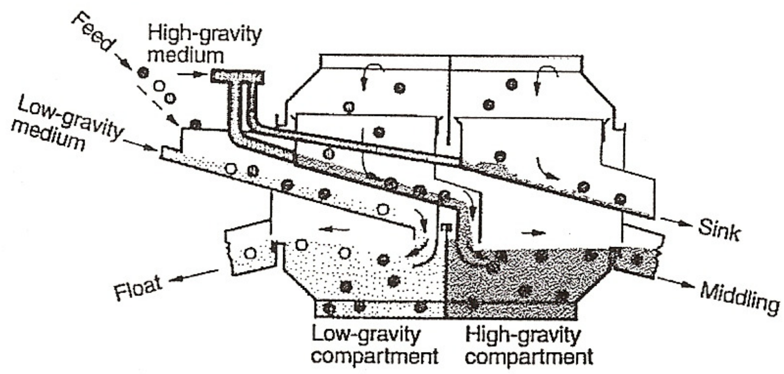


Figure 2.1 (a) Single compartment drum separator
(b) Two compartment drum separator (Wills,1985)

2.1.4.1.2 Drewboy Separators

Drewboy separator is used widely for cleaning of coal (Figure 2.2). It has high float capacity and handles a feed size from 12 mm to 600 mm at up to 820 t/h capacity for 4 m diameter bath. The coal is fed into the separator at one end, and floats are discharged from the opposite end while the sinks are lifted out from the bottom of the bath by the vanes of a slowly revolving inclined wheel. (Wills, 1985)

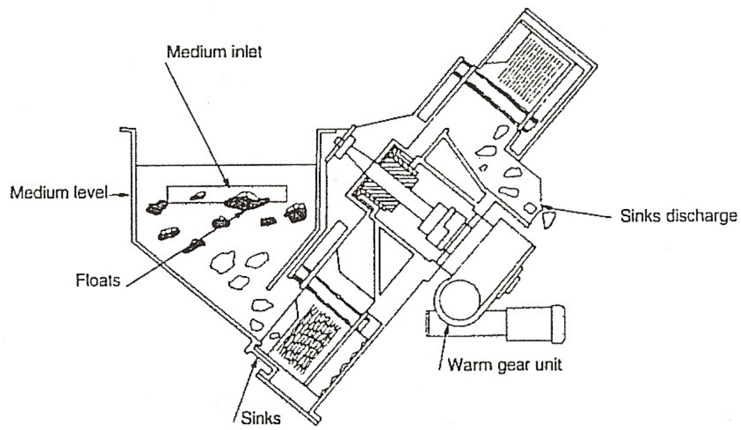


Figure 2.2 Drewboy separator (Wills, 1985)

2.1.4.1.3 Cone Separators

Cone separators are widely used for ore concentration, and they have high sink capacities (Figure 2.3). Cone separator with 6 m diameter has a capacity of up to 500 t/h for feed up to 10 cm size. The feed is introduced on to the surface of the medium; the float fraction overflows the weir, whilst the sinks are removed by pump or external or internal air lift. (Osborne, 1988.,Wills, 1985)

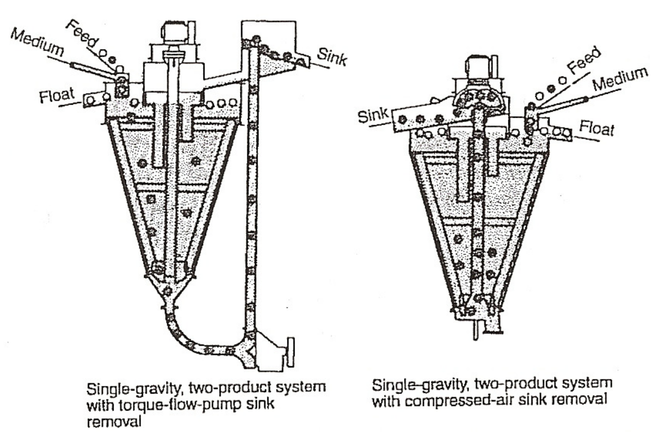


Figure 2.3 Cone separator

2.1.4.1.4 Norwalt Separators

Norwalt separator was developed in South Africa (Figure 2.4). Raw coal is introduced centrally. The floats are carried round by the stirrers and are discharged over the weir while the sinks are dragged along by scrapers attached to the bottom of the stirring arms. (Wills, 1985)

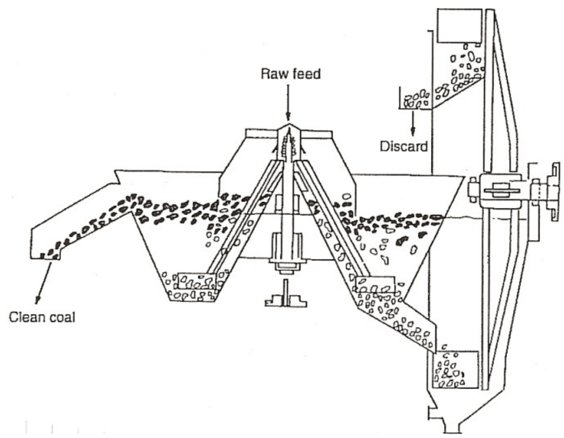


Figure 2.4 Norwalt separator (Wills, 1985)

2.1.4.2 Centrifugal Type Heavy Medium Separators

Centrifugal type heavy medium separators are widely used in the treatment of ores and coal. They provide a high centrifugal force and a low viscosity in the medium, enabling a finer separation than in gravitational separators. DSM (Dutch State Mine) cyclones, Vorsyl separator, Larcodems separator, Dyna Whirlpool separator, Tri-flo separators and water-only cyclones are the widely used centrifugal type heavy medium separators.

2.1.4.2.1 DSM Cyclones

DSM cyclones are used to treat ores and coals in the size range of 40 – 0.5 mm (Figure 2.5). The feed is suspended in a very fine medium of magnetite of ferrosilicon and is introduced tangentially to the cyclone under pressure. The sink product leaves via apex nozzle while float product is discharged through vortex finder. (Osborne, 1988., Wills, 1985)

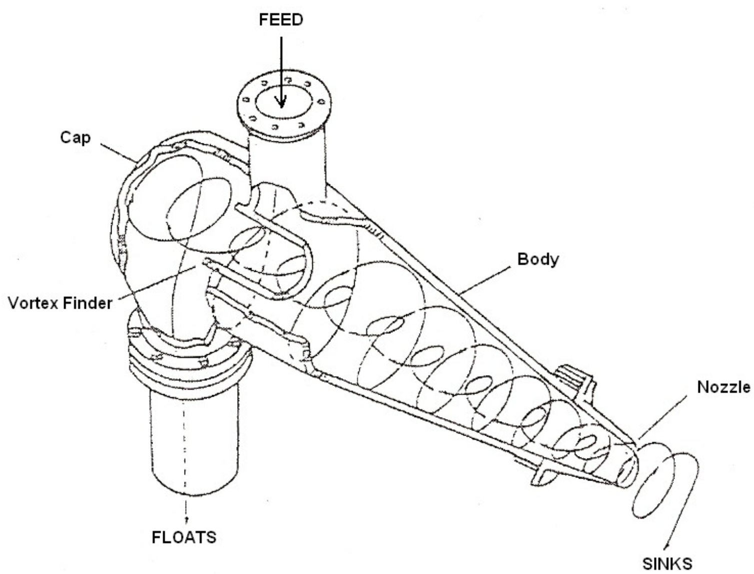


Figure 2.5 DSM Cyclone (Wills, 1985)

2.1.4.2.2 Vorsyl Separators

Vorsyl separator is used for the cleaning of fine coal sizes up to 50 mm (Figure 2.6). The feed together with the medium is introduced tangentially at the cylindrical separating chamber under pressure. Clean coal particles are discharged from the vortex finder, while reject product moves to the wall of vessel and is discharged from a second shallow chamber known as vortex tractor (Wills, 1985).

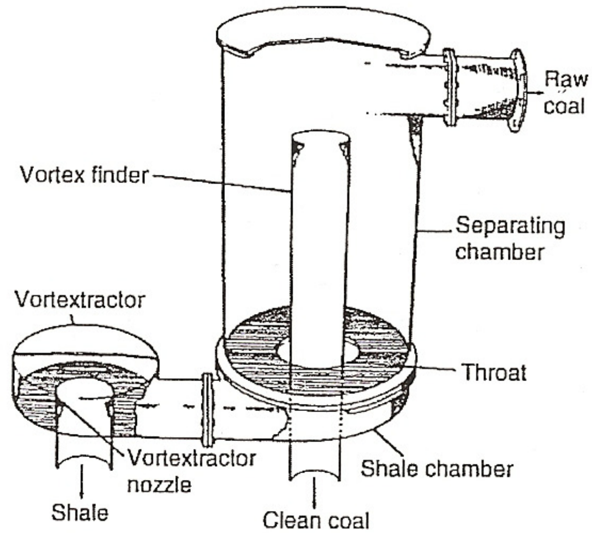


Figure 2.6 Vorsyl separator (Wills, 1985)

2.1.4.2.3 Larcodems Separators

Larcodems separator is used for treatment of coal up to 100 mm (Figure 2.7). It consists of a cylindrical vessel at inclined position. Medium is introduced under pressure at the lower end. Coal is fed into the separator at the top end. After separation clean coal is discharged through the bottom outlet while reject materials are removed through the outlet of the vortex tractor. The capacity of the separator can be as high as 250 t/h (Osborne, 1988., Wills, 1985).

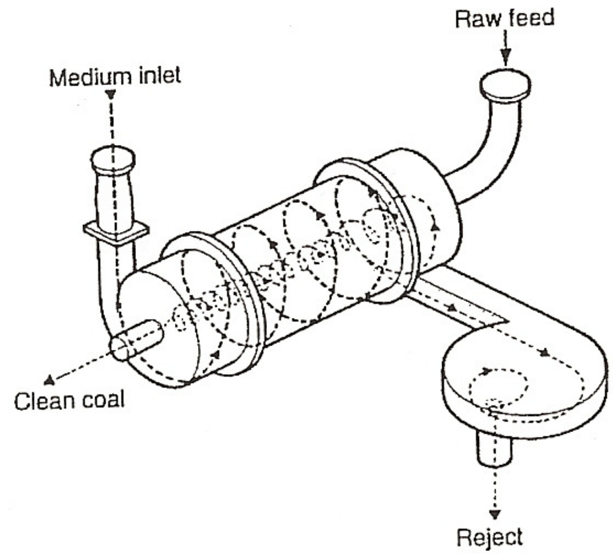


Figure 2.7 Larcodems separator (Wills, 1985)

2.1.4.2.4 Dyna Whirlpool Separator

Dyna Whirlpool separator consists of a cylindrical vessel at inclined position (Figure 2.8). Medium is pumped under pressure from the lower inlet. Raw feed enters the separation chamber from the upper vortex tube. The floats are discharged from the lower vortex outlet tube while sinks are discharged through the upper outlet. It is used for treatment of coal as well as minerals in the size range 0.5 – 30 mm with capacities up to 100 t/h (Wills, 1985).

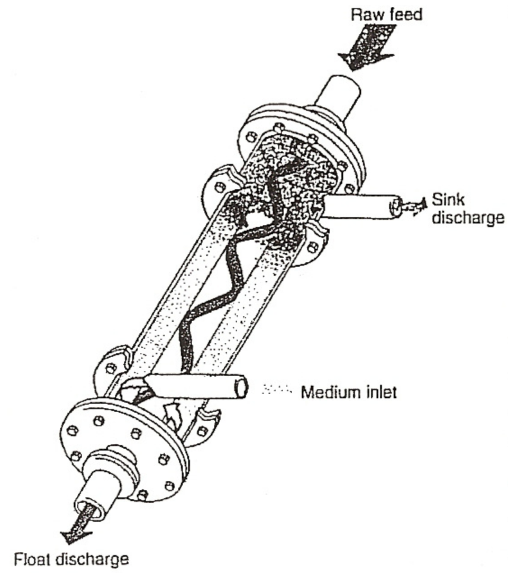


Figure 2.8 Dyna Whirlpool separator (Wills, 1985)

2.1.4.2.5 Tri-flo Separator

Tri-flo separator can be regarded as two Dyna Whirlpool separators connected in series (Figure 2.9).The separator operates with two media of different densities. When the separator is used for coal, the lower part cleans the float and the upper part eliminates the true reject product (Wills, 1985).

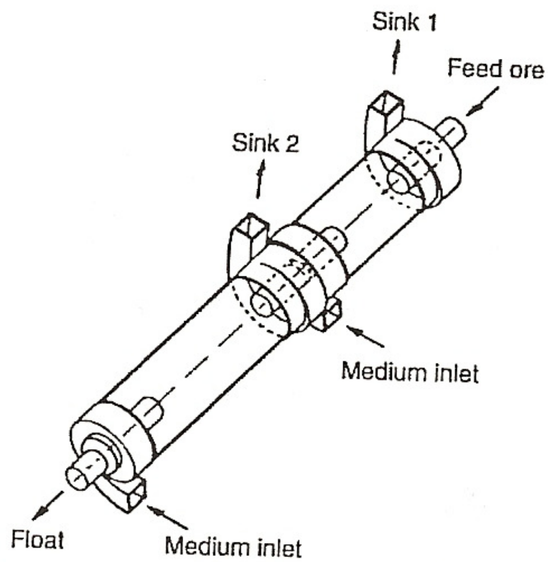


Figure 2.9 Tri-flo separator (Wills, 1985)

2.1.4.2.6 Water-only Cyclone

The water-only cyclone is used in coal cleaning of the -0.6mm coal (Figure 2.10). It does not need dense medium. Medium is developed from the coal feed. These cyclones have a larger cone angle up to 120^{o} and longer vortex finder.

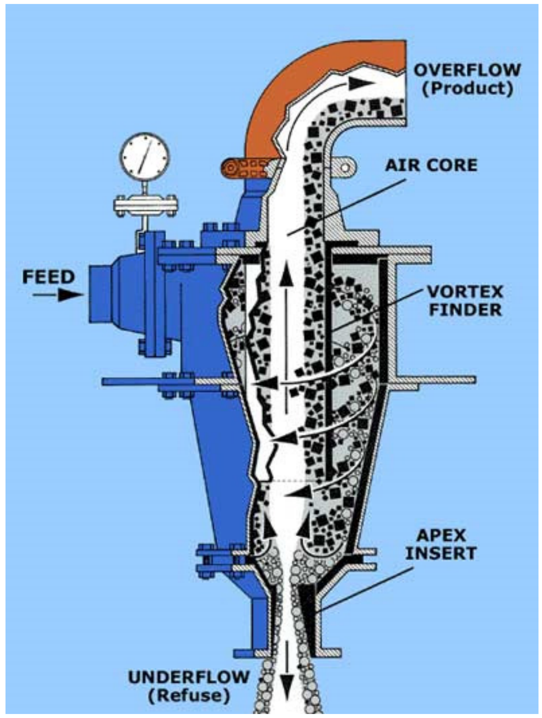


Figure 2.10 Water-only cyclone (www.flsmidthminerals.com)

2.1.5 Heavy Medium Regeneration Circuit

The biggest portion of the operating cost of heavy medium separation process comes from recovery and cleaning of the medium which leaves the separator with sink and float products. A typical circuit for regeneration of medium is given in Figure 2.11. More than 90% of the medium in the separator products is recovered with drainage screens and is pumped directly to the medium sump of the separator. The products then pass on to washing screens, where under washing spray, complete medium and adhered fines removal is accomplished. The undersize product of washing screens is treated in low intensity magnetic separator to recover magnetic medium from non-magnetic fines. Cleaned medium is then thickened to the required density by the densifier. The densified medium passes through demagnetizing coil to prevent flocculation of magnetic particles and to maintain suspension in the separator.

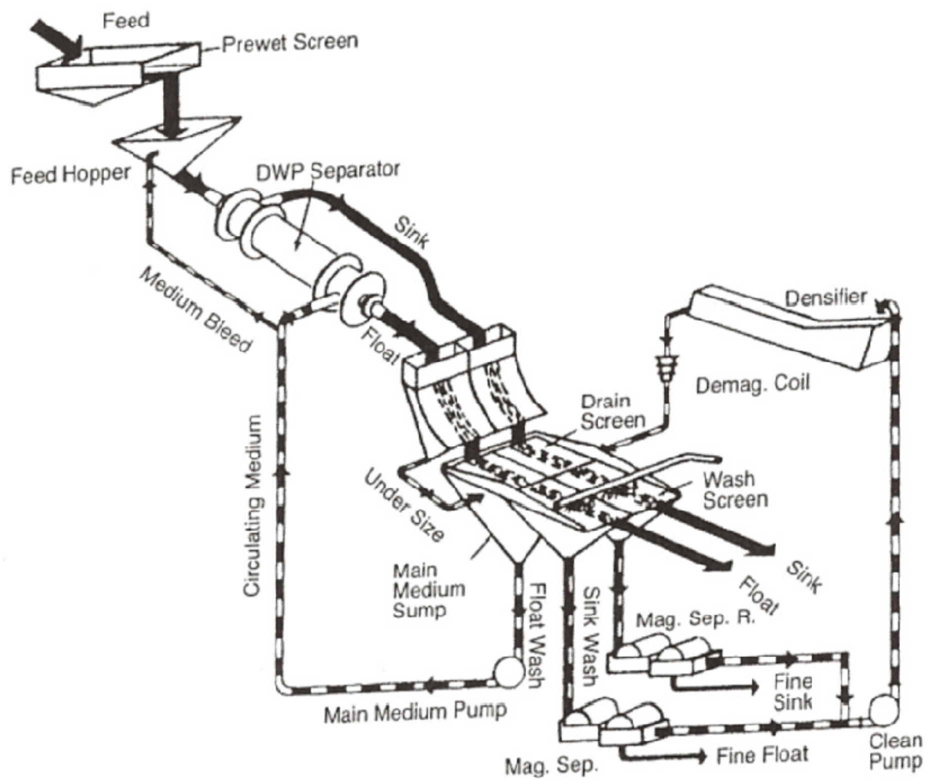


Figure 2.11 HMS circuit with regeneration unit (Wills, 1985)

2.1.6 Magnetite Consumption

The magnetite losses commonly encountered in modern plants will normally range from 0.5 to 3.0 kg/ton, quoted in tones of feed to the dense medium section of the plant (Osborne.1988, Mikhail and Osborne, 1990). The consumption of magnetite is governed by several factors, of which the most important are;

a) The fineness of the magnetite
b) The fineness of the coal being treated
c) The efficiency of magnetic separator
d) The design of the magnetite regeneration circuit
e) Poor operation and maintenance

2.2 Mineralogical Properties and Uses of Magnetite

Magnetite (Fe_3O_4) is one of the most common oxide minerals and also one of the most common iron minerals with 72.4% theoretical iron content. The formula of magnetite may also be written as $FeO.Fe_2O_3$, which is one part wüstite (FeO) and one part hematite (Fe_2O_3). It is black, opaque, submetallic to metallic mineral with hardness between 5.5 and 6.5 (http://geology.com, Hurlbut, 1959).

It is the most widely found magnetic mineral in nature. Lodestone is a form of magnetite that acts a natural magnet. Normally magnetite is attracted by a magnet but lodestone acts as a magnet, attracting iron particles. Weathering of magnetite to hematite with cubic crystalline shape results in a new mineral named martite. Most of the magnetite mineral mined is used as an ore of iron. Iron extracted from the ore is usually used to make steel. Powdered magnetite is often mixed with water for use as heavy media. Some synthetic emery is produced by mixing magnetite with aluminum oxides. Magnetite powder efficiently removes As (III) and As (V) from water. Other uses of magnetite include: as a toner in electrophotocopy, as a micronutrient in fertilizers, as a pigment in paints, as ballast in elevators and washing machines and as an aggregate in high-density concrete. The magnetite ore tailing can be used as materials for the preparation of cementations material. The obtained cement has the mechanical properties comparable with Portland cement (Chao *et al.*, 2010).

2.2.1 Iron Ore Deposits of Turkey

Although the iron ore deposits of Turkey are distributed through the Anatolia, region of Sivas, Malatya and Erzincan provinces have bigger ore reserves (Figure 2.12).

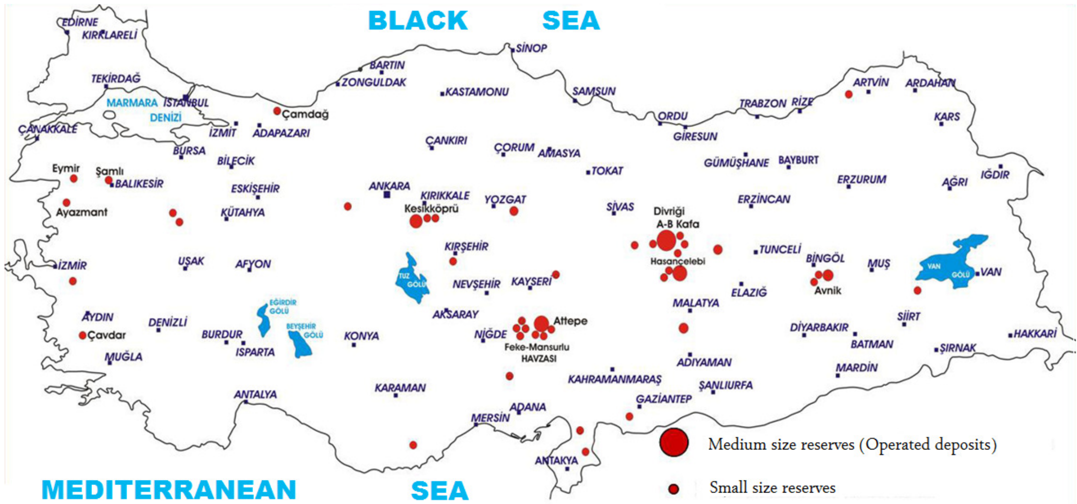


Figure 2.12 Iron ore deposits of Turkey (Yıldız, 2009)

Table 2.4 show the minable iron ore deposits with possible and proven ore reserves as cited by Yıldız, 2009.

Table 2.4 The minable iron ore deposits of Turkey (Yıldız, 2009).

No	Reserve Name	Province	Grade Fe%	Reserve (*1000 ton)		
				Possible	Proven	Problem
1	A ve B Kafa+Ekinbaşı	Sivas/Divriği	52-55	0	47.000	
2	Koruyeri	Adana/Feke	44-55	0	4.500	Overburden
3	Ulukent (Mn)	Denizli/Tavas	31	0	2.216	Overburden
4	Purunsur	Sivas/Divriği	55	1.800	100	Overburden
5	Deveci	Malatya/Hekimhan	38-52	2.000	38.000	Grade
6	Attepe	Adana/Feke	57	600	1.000	
7	Karakuz	Malatya/Hekimhan	41-54	1.900	3.809	SiO_2, Al_2O_3
8	Otlukilise	Sivas/Gürün	53	8.000	990	
9	Çetinkaya	Sivas/Çetinkaya	54	5.000	870	
10	Taşlıktepe	Sivas/Divriği	62	150	90	
11	Şamlı	Balıkesir/Balya	58	150	48	Overburden
12	Karamadazı	Kayseri/Yahyalı	51	100	1.800	Grade Overburden
13	Menteş+Elmadağ+Karaağaç	Kayseri/Yahyalı	54	3.050	8.000	
14	Büyükeymir	Balıkesir/Havran	52	3.500	2.500	As
15	Madentepe	Kırıkkale/Bala/Kesikköprü	54	1.800	1.520	
16	Suluocak	Kırıkkale/Bala/Kesikköprü	56	500	860	
17	Kapaklı (Fe+Mn)	Burdur	16-33	0	200	
18	Dedefengi	Malatya/Doğanşehir	60	120	70	Cu
19	Yakuplu	Erzincan/Ilıç	59	25	115	
20	Çaltı	Erzincan/Kemaliye	59	40	50	
21	Aşılık	Adana/Saimbeyli	52	800	200	Al_2O_3
22	Darılı	Malatya/Hekimhan	55	30	80	
23	Değirmendere	Elazığ/Ömermurat	12-26	0	30	
24	Dağyurdu	Kayseri/Tomarza	51	25	60	
25	Dokuztekne	Adana/Ceyhan	20	76	30	
26	Çataldere	Ankara/Bala	49	0	750	
27	Yenigireği	Adana/Karsantı	57	80	50	Overburden
28	Korucu (Fe+Mn)	Elazığ/Ömermurat	16-29	0	200	
Total				29.746	115.138	

The test sample of this study belongs to the iron ore deposits of Kesikköprü, Ankara. Regarding the origin of iron ore deposits of Kesikköprü area, there are two different ideas (Wondemagegnehu, 1990): some workers argue that these deposits originated from the nearby basic rocks which are subjected to a strong leaching by hydrothermal fluids that originated from the magma while the others say iron can be remobilized from any rock that has been traversed by the hydrothermal fluids as it is a contact metasomatic ore. Table 2.5 show the list of Kesikköprü region iron ore deposits with their proven, possible and probable ore reserves.

Table 2.5 Kesikköprü region iron ore deposits*

Deposit	Proven reserve (ton)	Possible reserve (ton)	Probable reserve (ton)	Total reserve (ton)	Average Fe grade (%)
Madentepe + Büyükocak	1.294.060	213.400	272.476	1.779.936	48 - 57
Maden geçidi	814.310	167.900	-	982.210	50 – 55
Yeni maden	1.065.511	153.253	-	1.218.764	45 – 55
Sulu ocak	160.264	53.652	-	213.916	48 – 55
Çataldere	134.568	11.546	-	146.132	30 – 50
Boyal in	-	384.840	-	384.840	45 – 55
Other locations	-	150.000		150.000	40 – 50
Total	3.468.713	1.134.591	272.476	4.875.798	

* Source : Güncem Mining Company

The run of mined iron ore of Güncem Mining Company is first crushed and then concentrated by low intensity magnetic separator and concentrate is sent to Karabük Iron and Steel Works, where tailings of magnetic separator are stored in different dumps regarding the grade of tailings.

2.3 Concentration of Magnetite with Low Intensity Magnetic Separator

Low intensity magnetic separators are used to treat ferromagnetic minerals like magnetite and some highly paramagnetic minerals like maghemite, pyrrhoite, martite, and franklinite. Table 2.6 shows the range of magnetic intensity required for the extraction of minerals while attractability of some minerals are tabulated in Table 2.7

Table 2.6 Magnetic intensities for recovery of minerals (Wills, 1977)

Mineral	Magnetic intensity (kG)	Mineral	Magnetic intensity (kG)
Alabandite	15–19	Maghemite	3–5
Ankerite	13–16	Magnetite	> 1
Apatite	14–18	Martite	2–6
Bastnasite	13–17	Monazite	14–20
Biotite	10–18	Muscovite	15–24
Braunite	14–18	Olivine	11–15
Chromite	10–16	Pyrochlore	12–16
Chrysocolla	20–24	Pyrolusite	15–19
Columbite	12–16	Pyrrhotite	1–4
Davidite	12–16	Renierite	14–18
Epidote	14–20	Rhodochrosite	15–20
Euxenite	16–20	Rhodonite	15–20
Ferberite	1–4	Samarskite	16–20
Franklinite	3–5	Siderite	10–18
Garnet	12–19	Staurolite	12–19
Goethite	15–18	Serpentine	3.5–18
Hematite	13–18	Tantalite	12–16
Hornblende	16–20	Titaniferous-magnetite	0.5–3
Ilmenite	8–16	Tourmaline	16–20
Ilmeno-rutile	15–18	Uraninite	18–24
Itabirite	8–14	Wolframite	12–16
Limonite	16–20	Xenotime	11–16

Table 2.7 Relative magnetic attractability of some minerals (Taggart, 1954)

Substances	Relative attractability
Iron (taken as standard)	100.00
Magnetite	**40.18**
Franklinite	35.38
Ilmenite	24.70
Pyrhotite	6.69
Siderite	1.82
Hematite	**1.32**
Zircon	1.01
Limonite	0.84
Corundum	0.83
Pyrolusite	0.71
Manganite	0.52
Garnet	0.40
Quartz	0.37
Rutile	0.37
Cerussite	0.30
Pyrite	0.23
Sphelarite	0.23
Molibden	0.23
Dolomite	0.22
Talc	0.15
Magnesite	0.15
Chalcopyrite	0.14
Gypsium	0.12
Fluorite	0.11
Galena	0.04
Calcite	0.00

Depending on the feed size, low intensity magnetic separator may be used in dry or wet conditions. Dry low intensity magnetic separation is confined mainly to the concentration of coarse sands that are strongly magnetic, the process being known as "***cobbing***". Drum type dry low intensity separators are the most common separators in current use (Figure 2.13).

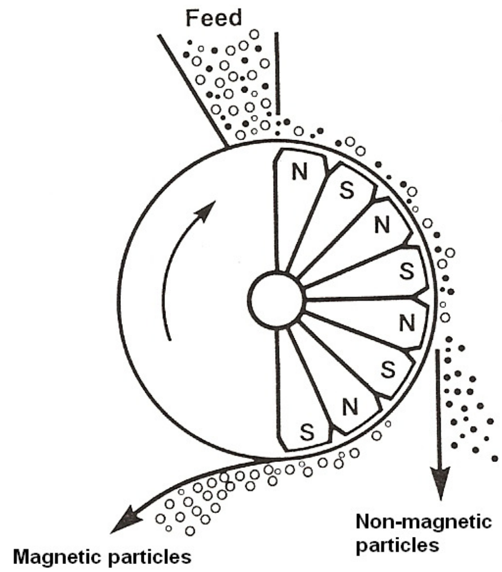


Figure 2.13 Low intensity dry drum type magnetic separator (Svoboda, 1987)

Drum type low intensity wet magnetic separators are the most common separators in current use for concentration of magnetite. Drum with non-magnetic shell consists of three to seven fixed poles which alternate in polarity and which are either electromagnets or permanent magnets. The design of the separator tank is very important. There are three types based on the pulp flow, as follows :

a) Concurrent
b) Counter-rotation
c) Counter-current

The concurrent tank design is shown in Figure 2.14. The feed flow is in the direction of drum rotation. Magnetic particles are picked up by the magnet and non-magnetic particles are discharged at the bottom through the tailing discharge opening. This design is most effective for producing an extremely clean magnetic concentrate from relatively coarse particle size and is widely used in dense medium regeneration systems.

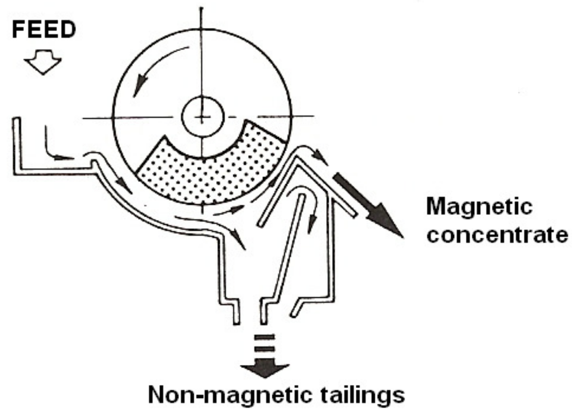


Figure 2.14 Concurrent magnetic separator (Svoboda, 1987)

In counter-rotation design of the tank (Figure 2.15) the feed is introduced through a special feed box to the drum which rotates in the opposite direction of pulp flow. Magnetic particles are picked up by the drum and discharged almost immediately. Very high recoveries can thus be achieved with this design.

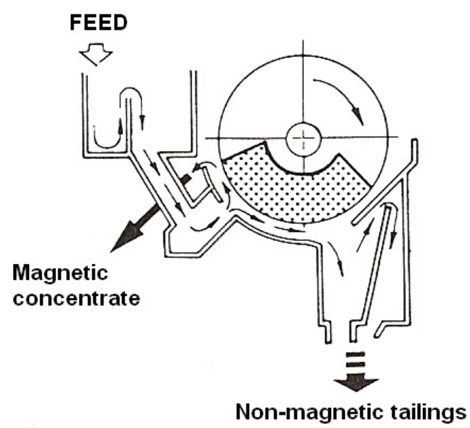


Figure 2.15 Counter-rotation magnetic separator (Svoboda, 1987)

The counter-current tank shown in Figure 2.16, is mostly used for finishing where very clean concentrate is required. The term “counter-current” derives from the fact that the tailings must flow counter to the rotation of the drum when leaving the separator. Magnetic particles are picked up by the drum and agitated as they are carried through wash water jets. Tailings flow from the opposite end of the tank.

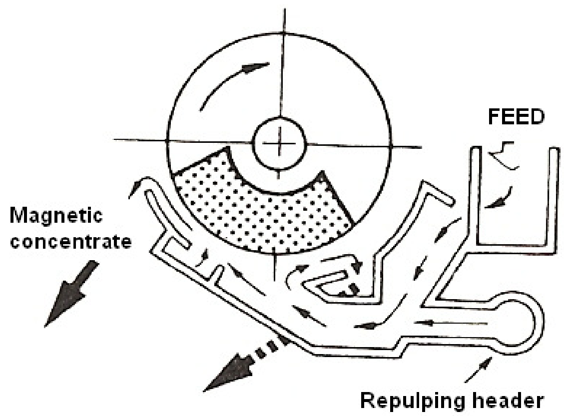


Figure 2.16 Counter-current magnetic separator (Svoboda, 1987)

CHAPTER 3

MATERIAL AND METHODS

3.1 Materials

During this study, tailings of magnetic separation facility of Güncem Mining Company were used. Three different types of samples with varying iron grade were taken from different sites of tailings dump. These samples were named as low grade, medium grade and high grade. Nearly 50 kg of sample from each quality were brought to mineral processing laboratory of METU Mining Engineering Department. Hand specimens were taken for microscopical examination. The remaining part was crushed to -5 mm by jaw crusher and then ground by roll crusher to –1 mm. Then, representative test samples were obtained from ground ores via ore sampling method of riffling.

3.1.1 Characterization of Samples

The mineralogical and chemical characterization of samples were accomplished using microscopical analysis, XRD (X-Ray Diffraction spectrometry) analysis and XRF (X-Ray Fluorescence Spectrometry) method, while magnetite (Fe_3O_4) content of samples were determined by Satmagan (saturation magnetic analyzer) (Figure 3.1).

Figure 3.1 Satmagan (saturation magnetic analyzer)

For the mineralogical analysis of the samples, a number of polished sections were prepared from selected hand specimens and they were examined through optical microscope by Dr. Ahmet Çağatay.

Mineralogical examination of samples under microscope indicated the presence of magnetite, hematite, chalcopyrite and pyrite as ore minerals while quartz, calcite, dolomite, epidote, chlorite, actinolite and tremolite were the gangue minerals.

Figure 3.2 - Figure 3.9. show the polished-section photographs of samples taken with 10X-magnified ocular and 32X-magnified oil objectives.

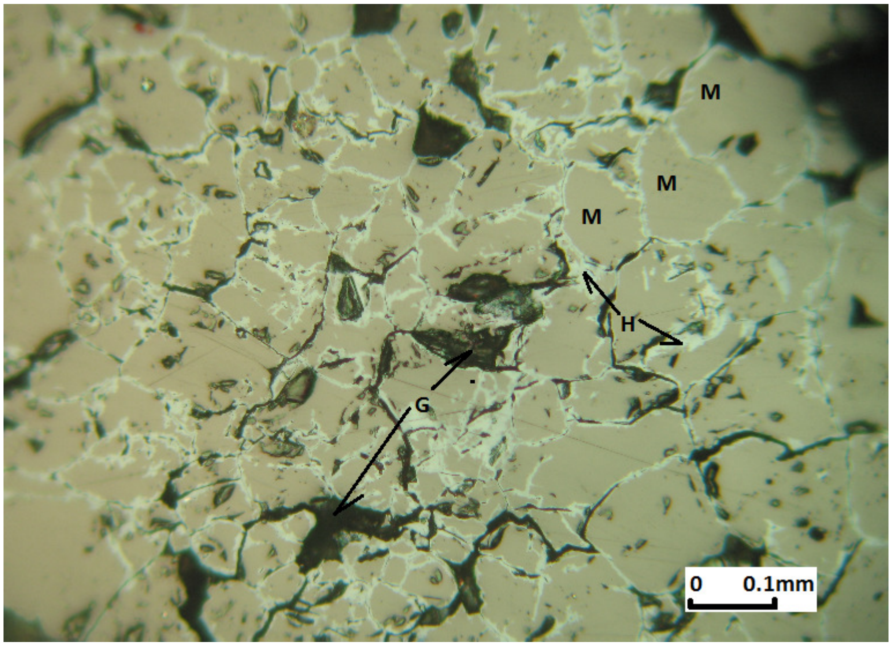


Figure 3.2 Interlocked magnetite (**M**) crystals turned to the hematite (**H**) along their margins. Gangue (**G**) minerals are actinolite-tremolite

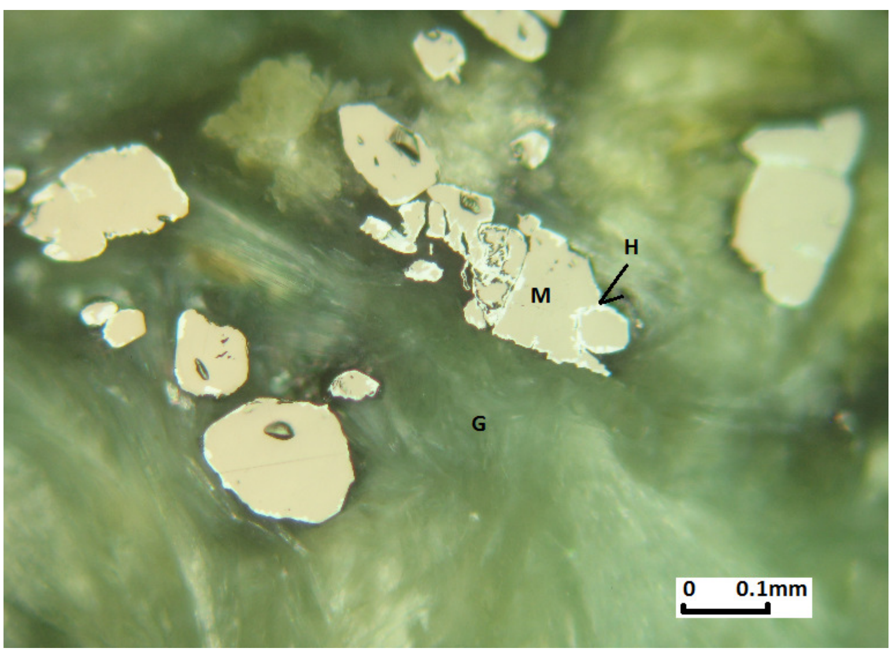


Figure 3.3 Magnetite (**M**) crystals are observed as disseminations in the gangue (**G**) minerals of actionolite-tremolite and epidotes

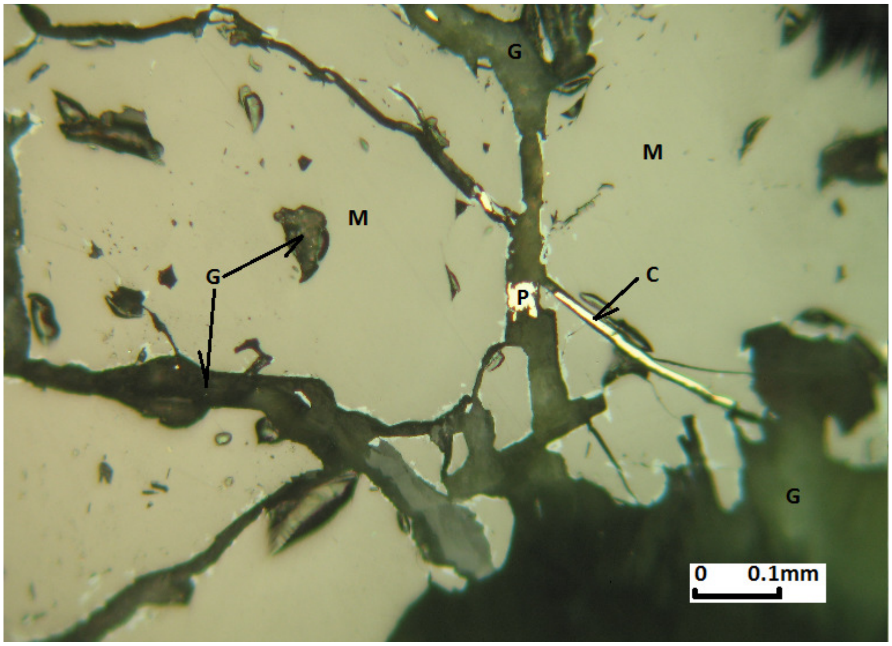


Figure 3.4 Pyrite (**P**) and chalcopyrite (**C**) are infilling the fractures of magnetite (**M**). Gangue (**G**) minerals are composed of actinolite-tremolite, epidote and chlorite

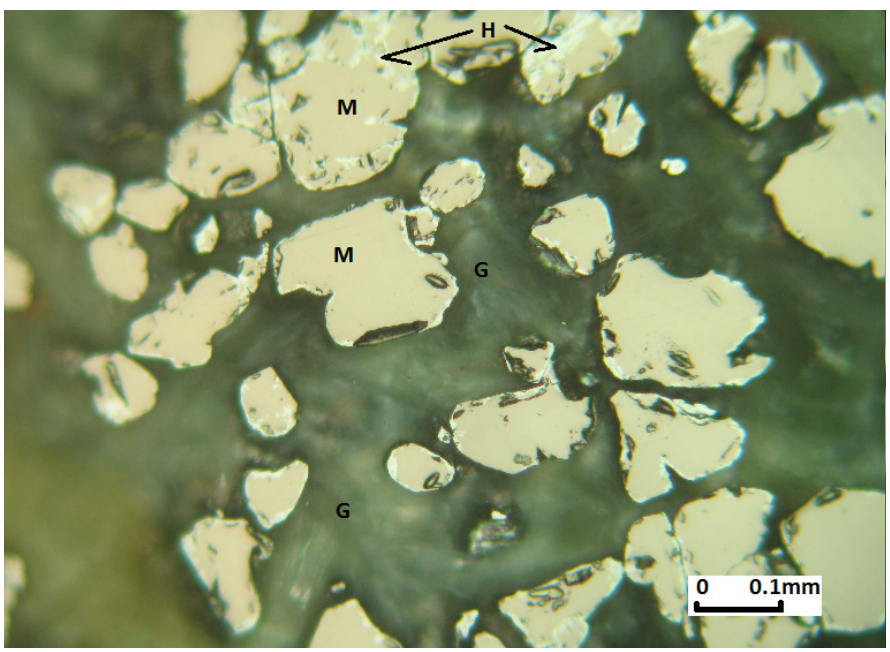


Figure 3.5 Fine grained magnetite (**M**) is disseminated in the gangue (**G**) minerals and seen locally as martite; in other words, turned to hematite (**H**)

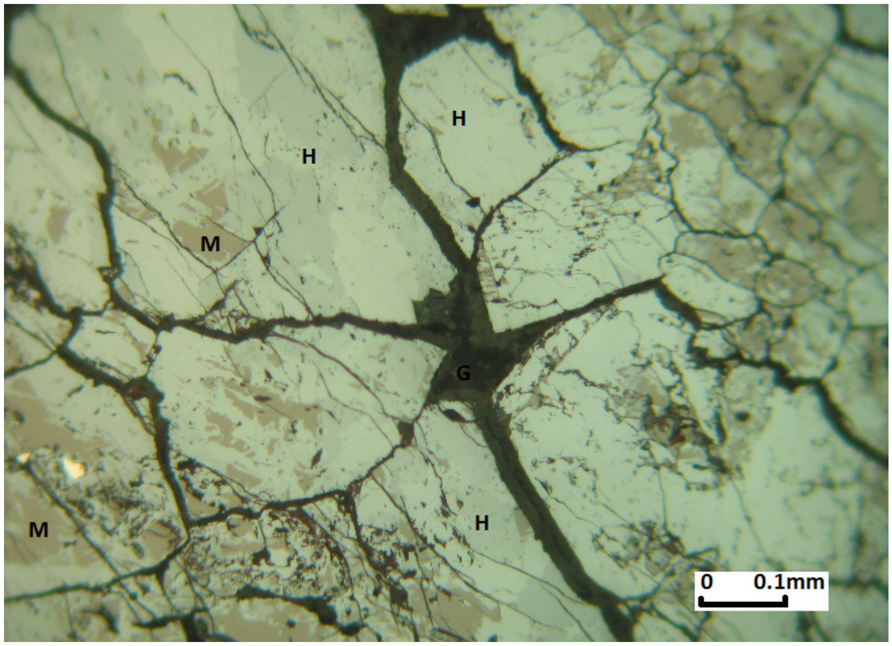


Figure 3.6 Magnetite (**M**) is intensively altered to martite (**H:** turned to hematite) Gangue minerals calcite and quartz

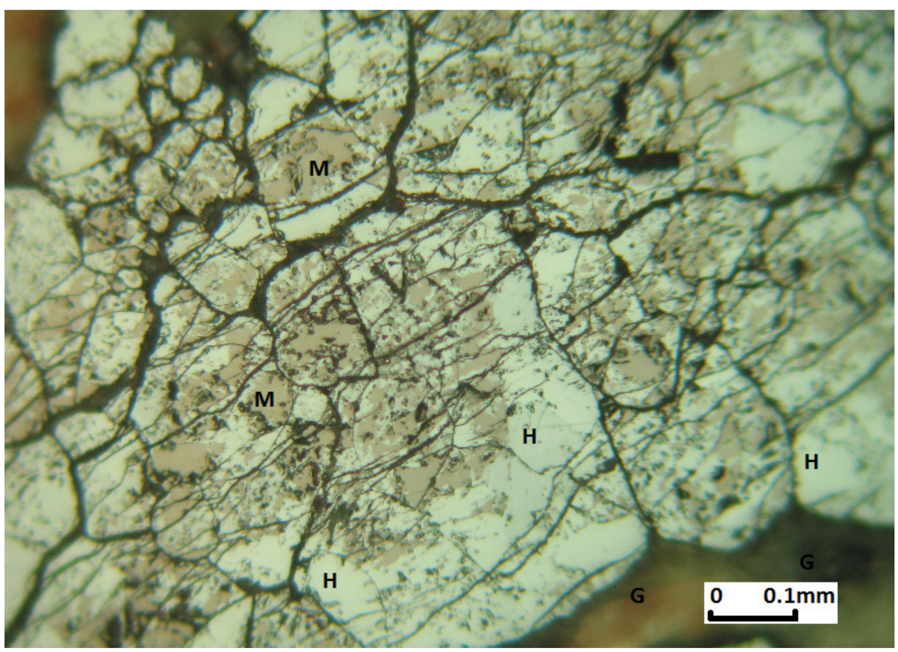


Figure 3.7 Magnetite (**M**) has cataclastic texture. Interlocked magnetite crystals are intensively martized (**H**). Gangue (**G**) minerals are calcite and quartz

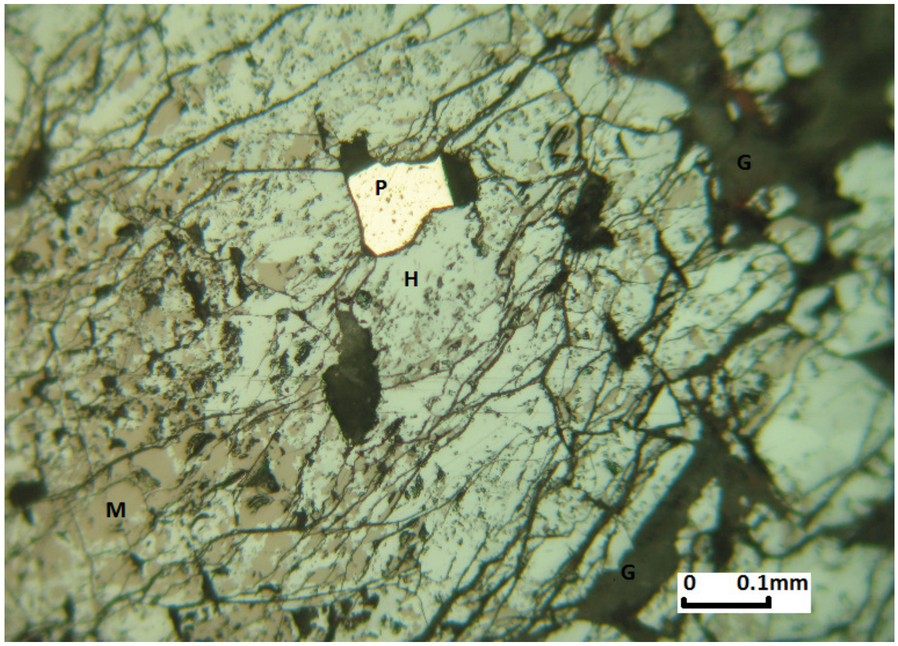


Figure 3.8 Pyrite (**P**) is observed in the fracture of martized magnetite (**H**)

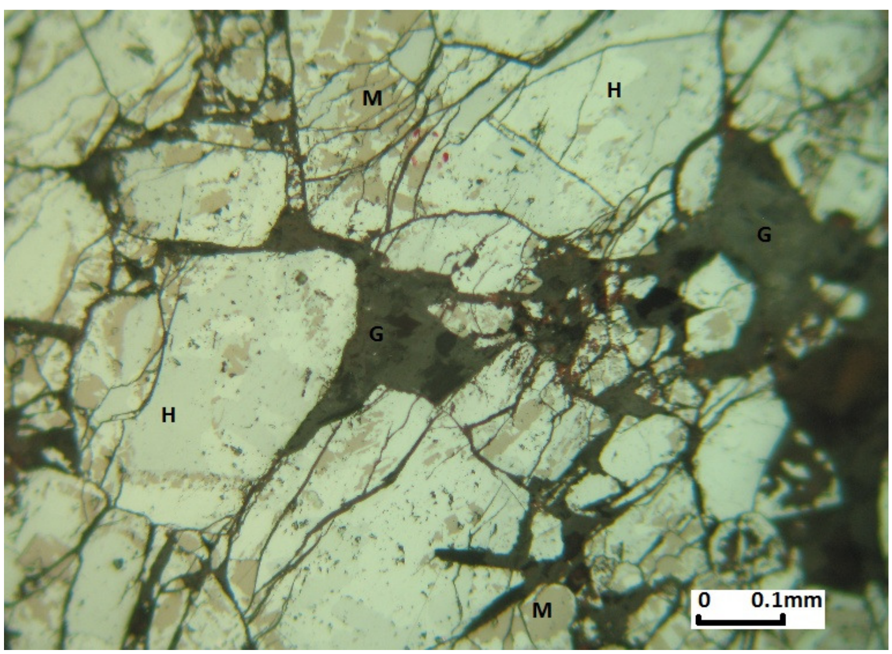


Figure 3.9 The crystals of euhedral and interlocked magnetite (**M**) are intensively altered to martite (**H**). Gangue (**G**) minerals are quartz and calcite

X-Ray Diffraction (XRD) analysis was performed on representative samples of each type tailing. XRD diagrams of each type of samples are given in Figures 3.9 -3.11. Te XRD analyses revealed that all samples comprised magnetite and hematite as major minerals together with minor amounts of pyrite and chalcopyrite, while quartz, calcite, dolomite chlorite, epidote, actinolite and tremolite were the gangue minerals.

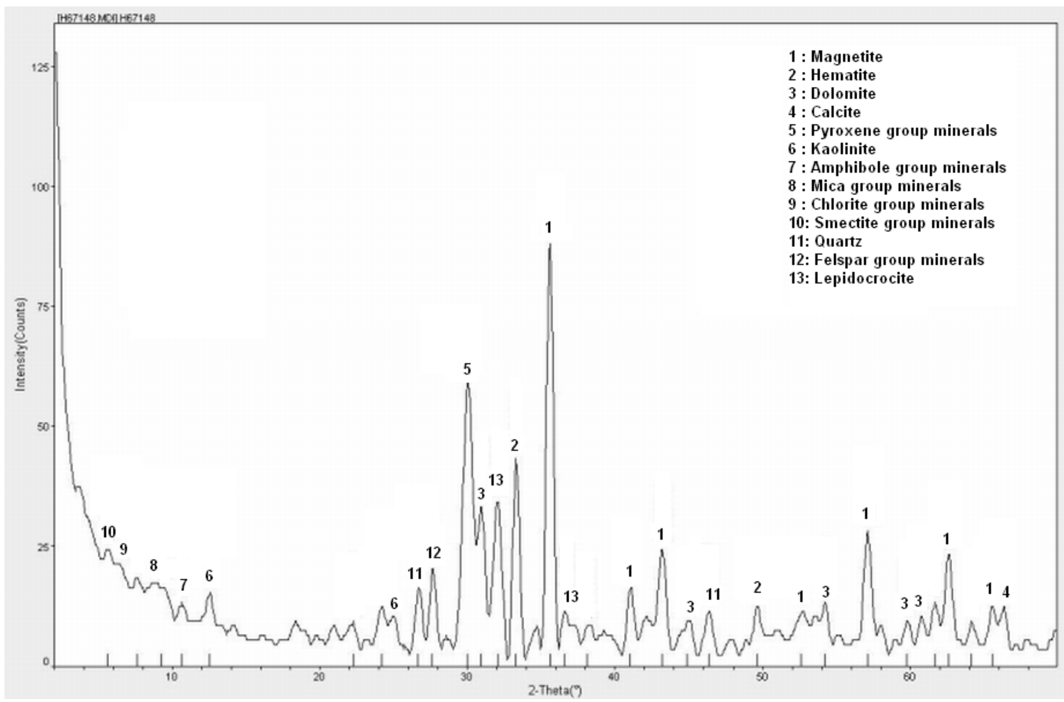


Figure 3.10 XRD pattern of high grade tailing

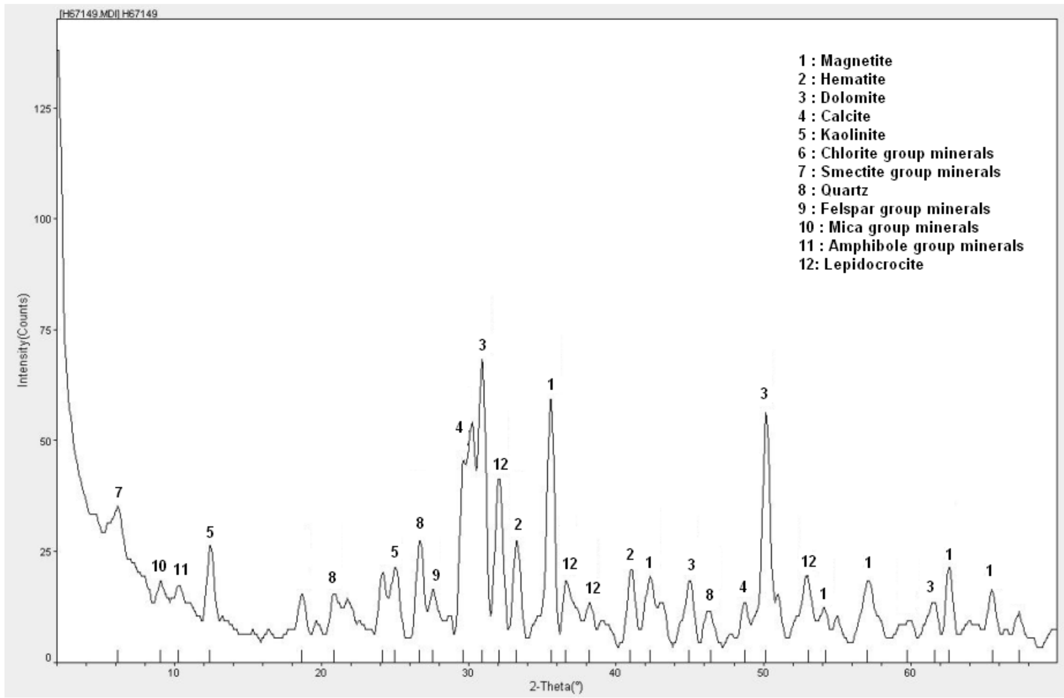


Figure 3.11 XRD pattern of medium grade tailing

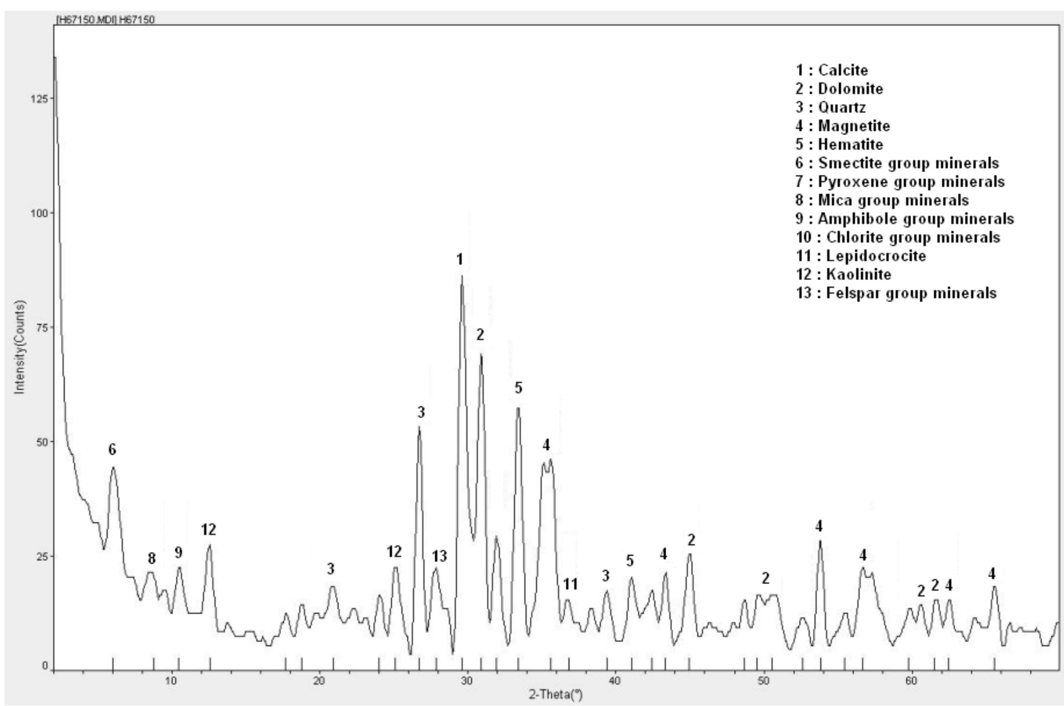


Figure 3.12 XRD pattern of low grade tailing

3.1.2. Chemical Characterization of Samples

Chemical compositions of the representative samples were determined with X-ray fluorescence method. Results of complete analyses are given in Table 3.1.

Table 3.1 Chemical analyses of low, medium and high grade tailings.

Tailing Grades	Total Fe %	SiO_2 %	Al_2O_3 %	CaO %	MgO %	Na_2O %	K_2O %	S %	TiO_2 %
Low	16.54	27.57	3.99	18.00	6.56	0.23	0.19	0.13	0.16
Medium	30.18	23.09	1.47	11.24	5.39	0.15	0.14	0.09	0.11
High	41.40	19.05	1.40	9.20	4.50	0.03	0.03	0.02	0.10

The distribution of iron with respect to particle size was also examined. The combined results of sieve analysis of each size fraction were tabulated in Table 3.2, Table 3.3 and Table 3.4.

Table 3.2 Size distribution, Fe_3O_4 and Fe analysis for low grade tailing

Particle Size (μm)	Weight (%)	Σ Retained Weight (%)	Fe_3O_4 (%)	Fe (%)	Fe_3O_4 Distribution (%)	Σ Fe_3O_4 Distribution (%)
-1000+833	15.46	15.46	5.36	14.21	14.03	14.03
-833+500	34.19	49.65	5.46	14.82	31.60	45.63
-500+250	21.11	70.76	6.12	17.75	21.87	67.50
-250+106	14.99	85.75	6.93	20.14	17.59	85.09
-106-75	5.57	91.32	6.91	19.89	6.51	91.60
-75+45	2.67	93.99	6.13	18.12	2.78	94.38
-45	6.01	100.00	5.53	15.43	5.62	100.00
Total	**100.00**		**5.91**	**16.55**	**100.00**	

Table 3.3 Size distribution, Fe_3O_4 and Fe analysis for medium grade tailing

Particle Size (μm)	**Weight (%)**	**Σ Retained Weight (%)**	**Fe_3O_4 (%)**	**Fe (%)**	**Fe_3O_4 Distribution (%)**	**Σ Fe_3O_4 Distribution (%)**
-1000+833	15.94	15.94	18.20	31.21	15.22	15.22
-833+500	28.31	44.26	18.56	31.72	27.57	42.80
-500+250	21.77	66.02	19.65	32.15	22.44	65.24
-250+106	16.94	82.96	20.50	32.41	18.22	83.46
-106-75	6.57	89.52	21.05	32.63	7.25	90.71
-75+45	3.30	92.82	19.75	32.25	3.42	94.12
-45	7.18	100.00	15.60	29.04	5.88	100.00
Total	**100.00**		**19.06**	**31.73**	**100.00**	

Table 3.4 Size distribution, Fe_3O_4 and Fe analysis for high grade tailing

Particle Size (μm)	**Weight (%)**	**Σ Retained Weight (%)**	**Fe_3O_4 (%)**	**Fe (%)**	**Fe_3O_4 Distribution (%)**	**Σ Fe_3O_4 Distribution (%)**
-1000+833	11.45	11.45	36.83	41.02	11.38	11.38
-833+500	32.18	43.62	36.05	40.12	31.30	42.68
-500+250	22.52	66.15	36.54	40.56	22.21	64.89
-250+106	17.23	83.38	39.63	41.66	18.43	83.31
-106-75	5.92	89.30	42.71	42.05	6.83	90.14
-75+45	2.90	92.21	39.74	41.69	3.11	93.25
-45	7.79	100.00	32.08	38.96	6.75	100.00
Total	**100.00**		**37.06**	**40.66**	**100.00**	

As it can be seen from Table 3.2, Table 3.3 and Table 3.4, although there are some differences in Fe_3O_4 and Fe grade of each fraction, there is no noticeable increase or decrease with size. Therefore, physical concentrations of samples by screening were found to be not possible.

3.2. Methods

Magnetic concentration tests with laboratory type Davis tube apparatus were carried out for the separation of magnetite mineral from the test samples. Davis tube is a test apparatus designed to separate the magnetite mineral from a small amount of test sample (Figure 3.12). It is widely used to check the suitability of an ore to magnetic separation. The cylindrical glass separation tube of the apparatus was placed at an inclined position between the conical electromagnet poles. The distance between the electromagnet poles was nearly 15 mm. Before each test, the glass separation tube was filled with water up to 5 cm below the feed end. The side inlet at the upper part of glass tube was connected to tap water with a flexible tube. By using the clamp on the flexible tube for water supply and clamp on the flexible tube connected to discharge end, a constant water level was kept in the glass tube. During the tests a 200 cc pulp with 10% solid by weight was introduced in to glass tube gradually with tap water.

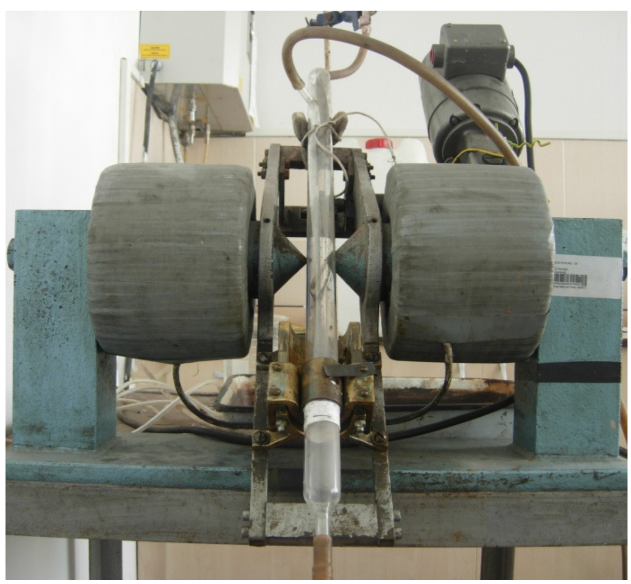


Figure 3.13 Laboratory type Davis tube magnetic concentrator

While the particles in the pulp are settling in the glass tube, the magnetics are held in the induced magnetic field zone between the electromagnet poles. During the feeding of pulp a reciprocating motion was also given to the glass tube. The magnetic field between the electromagnet poles was adjusted by changing the electrical current on coils of electromagnet.

Table 3.5 shows the relation between applied current intensity (Ampere) and induced magnetic field intensity measured by Gaussmeter between electromagnet poles. The reciprocating motion of glass tube and addition of wash water were stopped when solid free water was discharged from the discharge end of glass tube. After the removal of magnetic field by switching of electricity, the magnetic particles collected between the poles were washed down into concentrate container by opening the discharge clamp.

After drying and weighing, products were analyzed for Fe_3O_4 content by Satmagan (Saturated Magnetite Analyzer) and total Fe content by XRF (X-ray Fluorescence)

Table 3.5 Induced magnetic field intensities versus applied electrical currents

Electric current (Ampere)	**Induced magnetic field intensity (Gauss)**
0.10	400
0.25	1000
0.50	2000
0.75	3000
1.00	4000
1.25	5000
1.50	6000

CHAPTER 4

RESULTS AND DISCUSSION

The effect of feed particle size and effect of applied field intensity on iron and magnetite grade and their respective recoveries were examined throughout the study.

4.1. Concentration Studies of Low Grade Tailing

A series of magnetic separation tests were carried out separately for 100% -1000, -833, -500, -250, -106 and -75 μm size feed material at different magnetic field intensities ranging from 400 Gauss to 6000 Gauss. The effect of particle size on concentration of iron and magnetite grade and respective recoveries are shown in Figures 4.1- 4.8 and in Table A1-A8 in Appendix A.

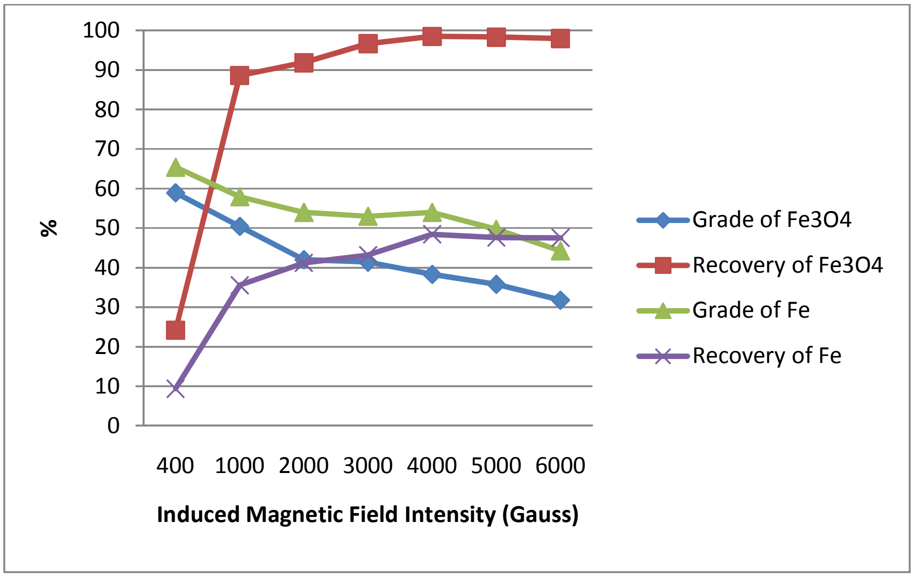


Figure 4.1 Results of the magnetic concentration test for -1000 micron material (App. A, Table A.1)

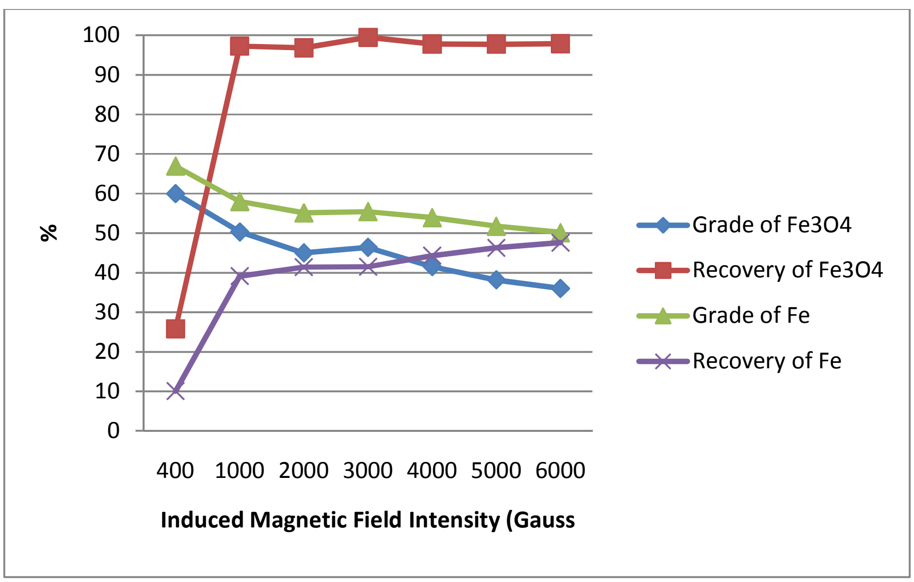


Figure 4.2 Results of the magnetic concentration test for -833 micron material (App. A, Table A.2)

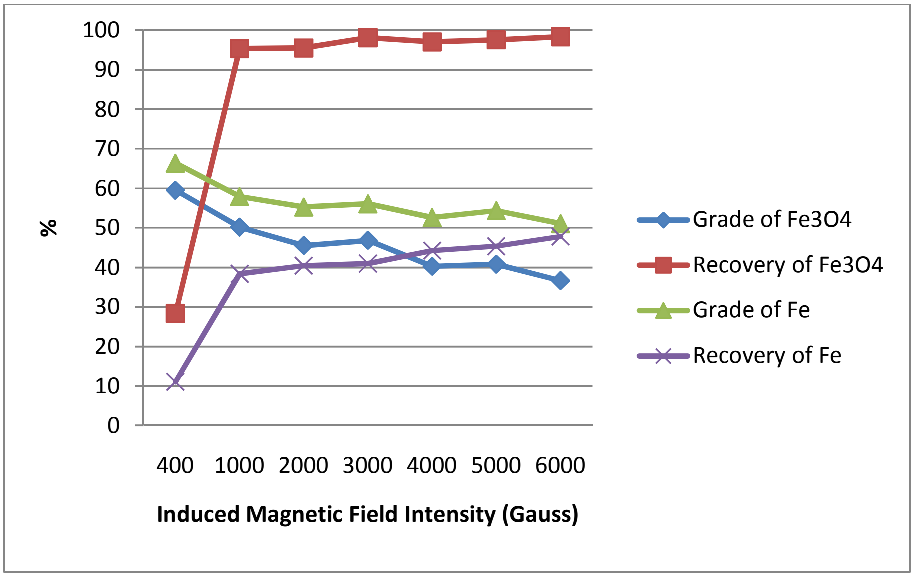


Figure 4.3 Results of the magnetic concentration test for -500 micron material (App. A, Table A.3)

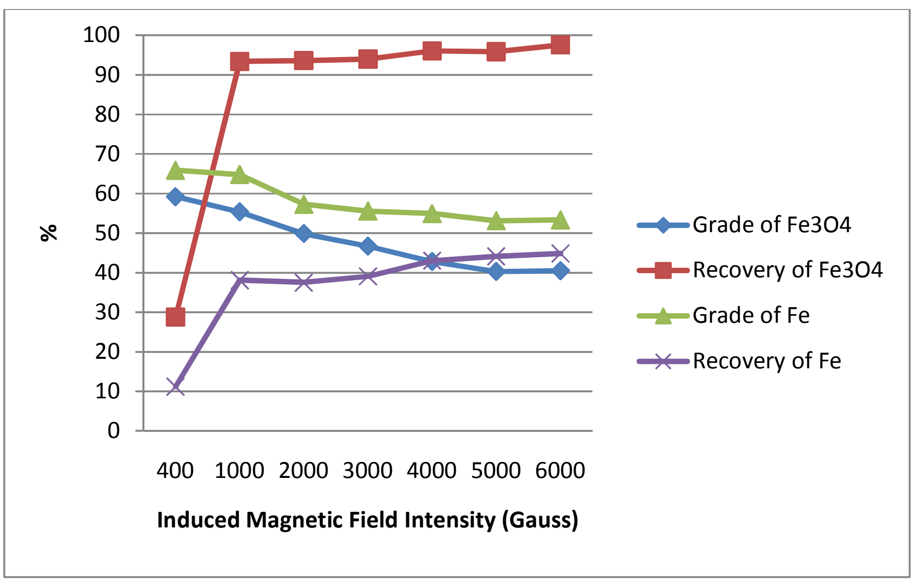


Figure 4.4 Results of the magnetic concentration test for -250 micron material (App. A, Table A.4)

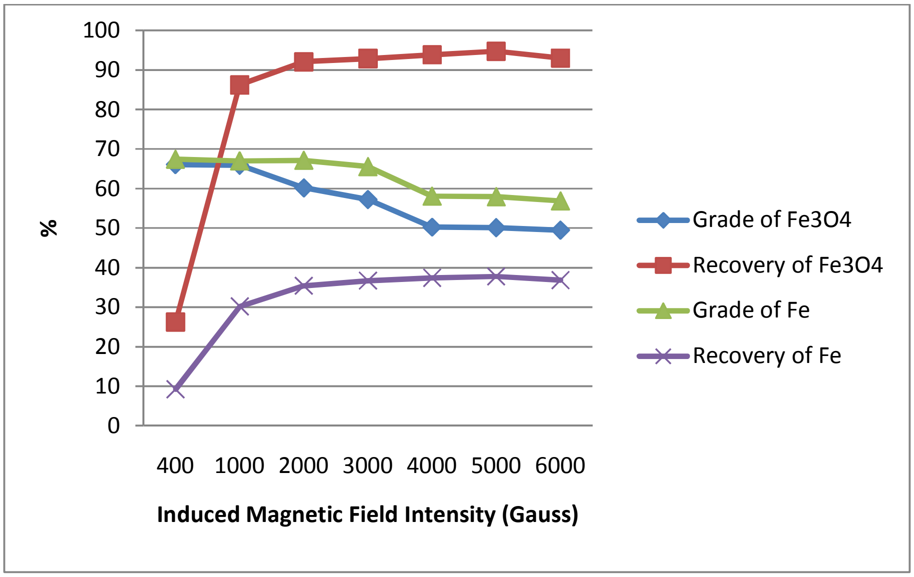


Figure 4.5 Results of the magnetic concentration test for -106 micron material (App. A, Table A.5)

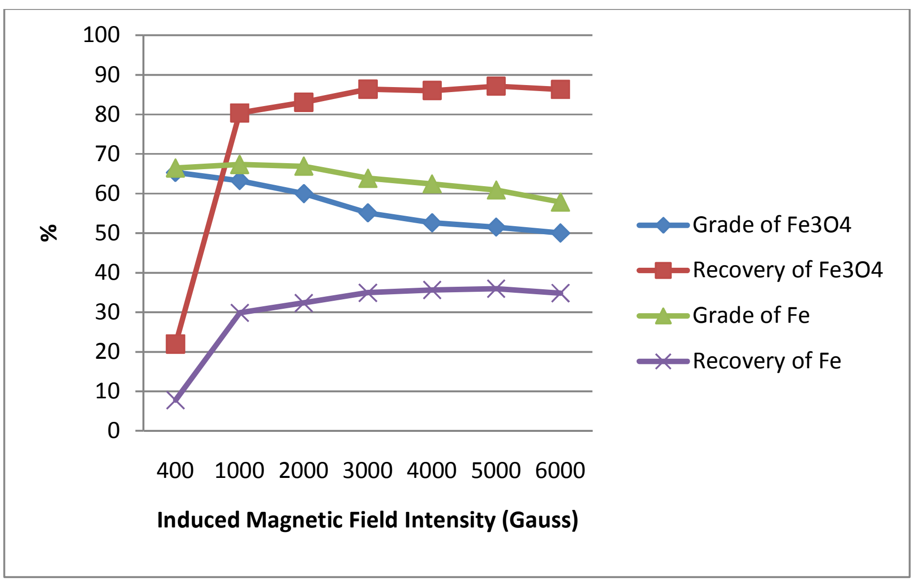


Figure 4.6 Results of the magnetic concentration test for -75 micron material (App. A, Table A.6)

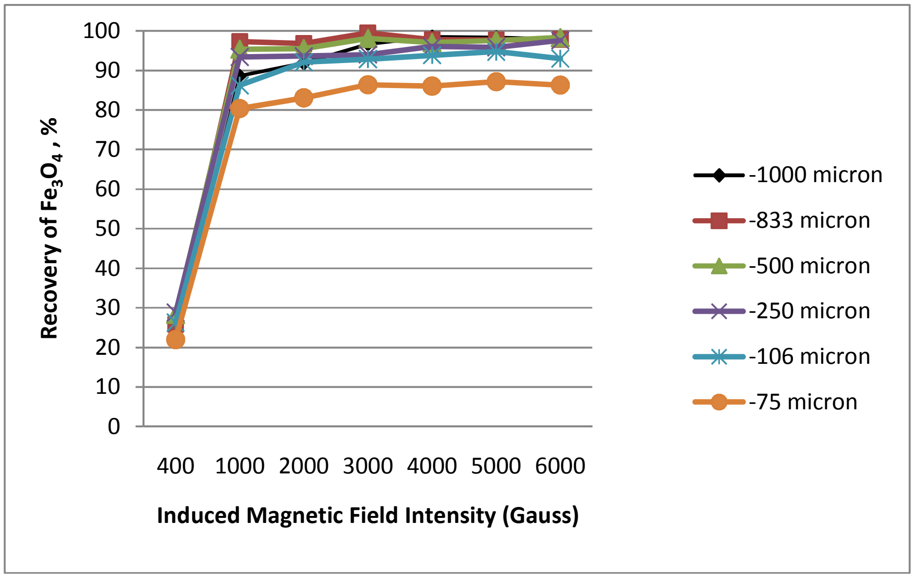


Figure 4.7 Recovery of Fe3O4% versus magnetic field intensity for low grade tailing

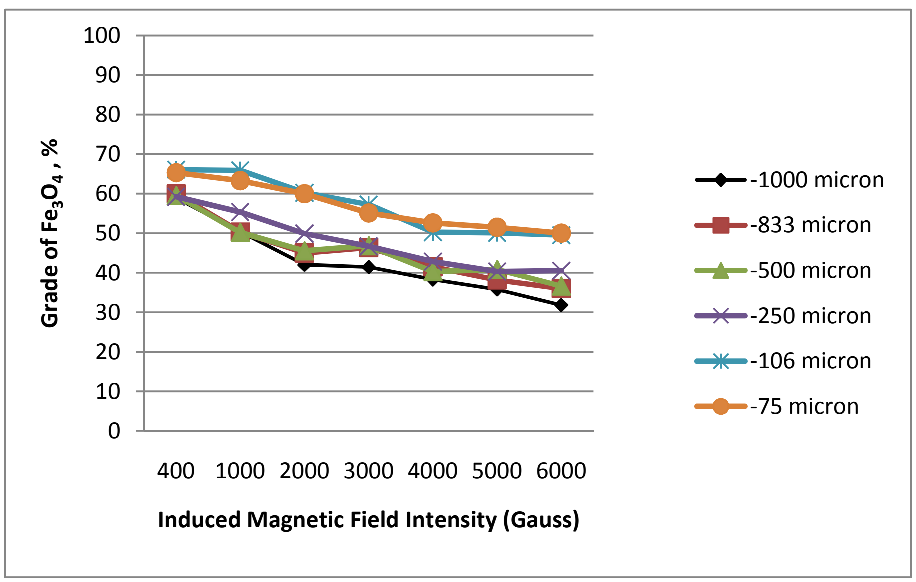


Figure 4.8 Grade of Fe3O4% versus magnetic field intensity for low grade tailing

As seen from Figures 4.1 - 4.7, the concentrate with maximum Fe_3O_4 grade was obtained at a magnetic field intensity of 400 Gauss for all sizes ranges of feed. Both Fe_3O_4 and Fe grades of concentrate decreased with increasing magnetic field intensity. At low magnetic field intensity only the particles with very high magnetic susceptibility were captured by the pole of electromagnet. It is also well known phenomena that when the particle with high magnetic susceptibility is introduced into a magnetic field, the particle gains magnetism and behaves as a magnet, and thus attracts each other. Attraction of particles causes agglomeration of particles which is called magnetic flocculation. The decrease in Fe_3O_4 content at a higher field intensity was due to magnetic flocculation which caused the entrainment of non-magnetic minerals between magnetic particles. On the other hand, minerals considered as nonmagnetic may be rendered to magnetic by elemental substitution of a small amount of a magnetic element in their crystal lattice. Such particles are easily attracted by electromagnet pole and mix with pure magnetite particles and decrease the Fe_3O_4 grade of concentrate.

As illustrated in the same Figures, the recovery of Fe and Fe_3O_4 increases with increasing magnetic field intensity. This increase was very sharp up to 1000 Gauss magnetic field intensity, and above this value, recovery of Fe_3O_4 and Fe continued to increase but gradually.

Under the constant magnetic field intensity, the Fe_3O_4 and Fe grade of concentrate increases with decreasing feed size while recoveries of Fe and Fe_3O_4 decreases slightly. The increase in grade could be explained with higher degree of liberation of particles. On the other hand, the hydrodynamic drag force of flowing water prevents the catching of very fine magnetic particles in the magnetic field zone produced by the conical poles of Davis tube. During the reciprocation of glass tube in inclined position, certain portion of very fine magnetite particles was discarded as waste together with wash water discharged from the lower end of glass tube. In this way, losses of very fine magnetite particles occurred during the concentration of fine size feed. Flocculation and coagulation of very fine magnetite particles were investigated as size enlargement process of recovering magnetite by magnetic separation (Aydoğan, 1994). Results indicated that recovery was increased by applying low intensity wet magnetic separation in combination with flocculation and coagulation process.

By using the low intensity magnetic concentration method for the low grade tailing with 6.12% Fe_3O_4 and 17.75% Fe content, a concentrate containing 65.95% Fe_3O_4 was obtained from 100% -106 microns feed with 86.21% Fe_3O_4 recovery at 1000 Gauss magnetic field intensity. Fe grade and recovery were 67.00% and 30.20%, respectively for the same concentrate.

Results of the test-work carried out with low grade tailing showed that it was not possible to produce a magnetite concentrate which will meet the specifications of magnetite concentrate suitable for preparation of dense medium regarding Fe_3O_4 content. This concentrate meets the specifications of feed for pelletizing.

4.2. Concentration Studies of Medium Grade Tailing

A series of magnetic separation tests were carried out for medium grade tailing at the same operating conditions followed during the concentration of low grade tailings. The effect of particle size and magnetic field intensities on Fe_3O_4 and Fe grade of concentrate and respective recoveries are shown in Figure 4.9 - 4.16 and in Tables B1 - B6 as shown in Appendix B.

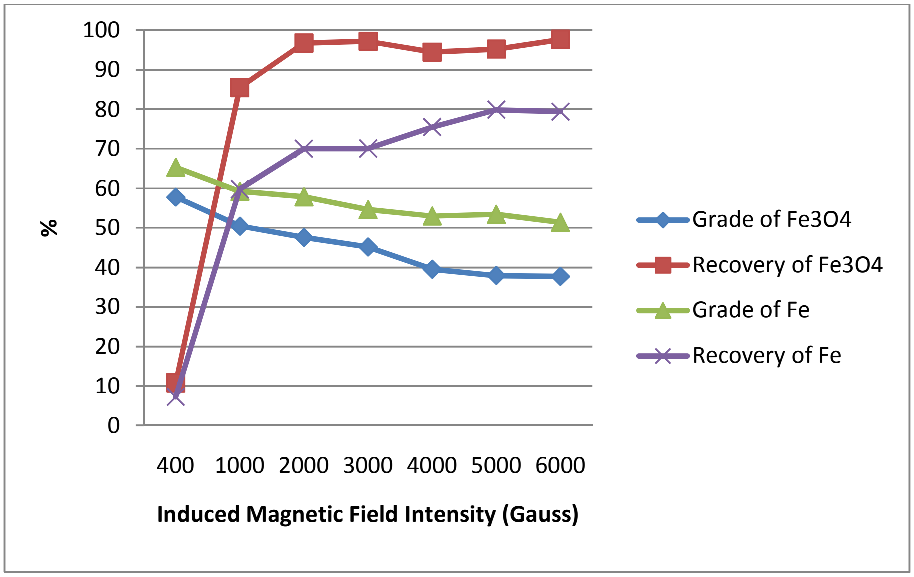


Figure 4.9 Results of the magnetic concentration test for -1000 micron material (App. B, Table B.1)

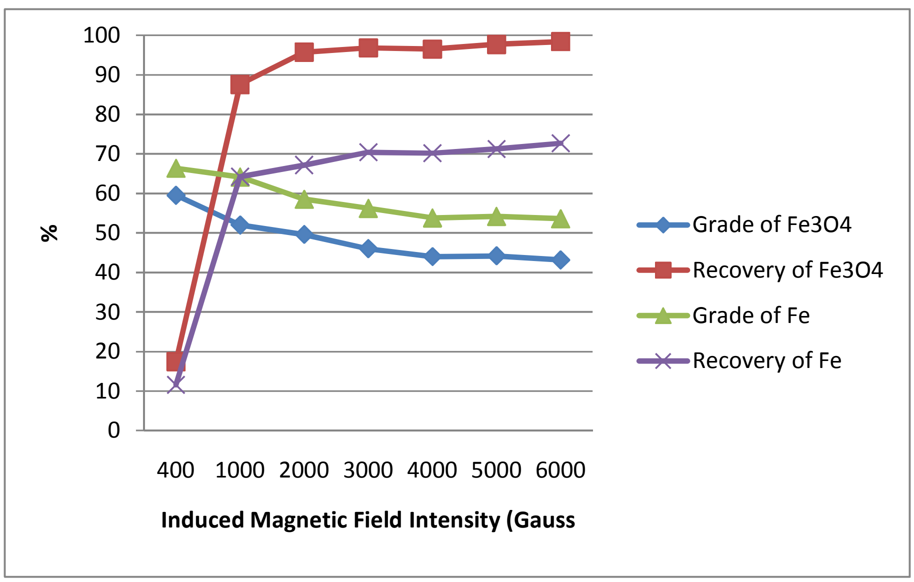


Figure 4.10 Results of the magnetic concentration test for -833 micron material (App. B, Table B.2)

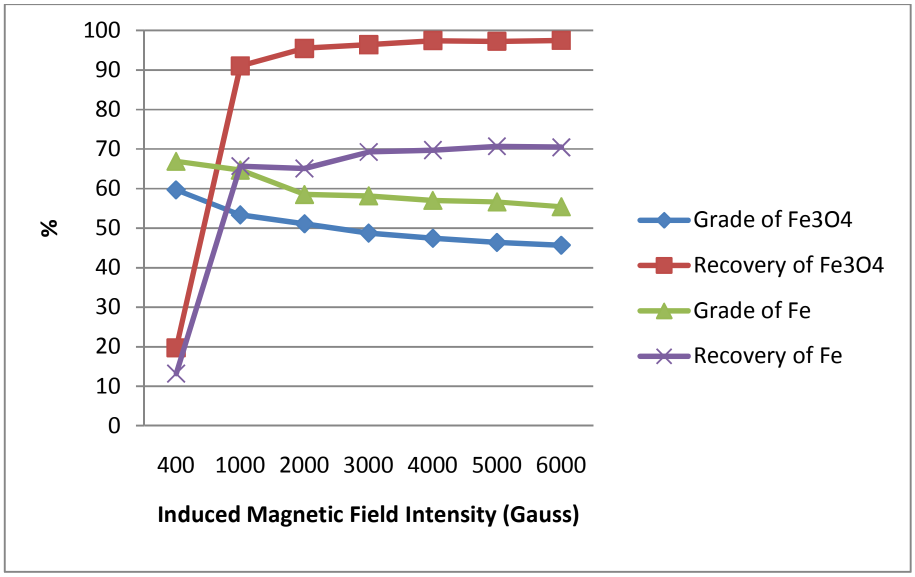


Figure 4.11 Results of the magnetic concentration test for -500 micron material (App. B, Table B.3)

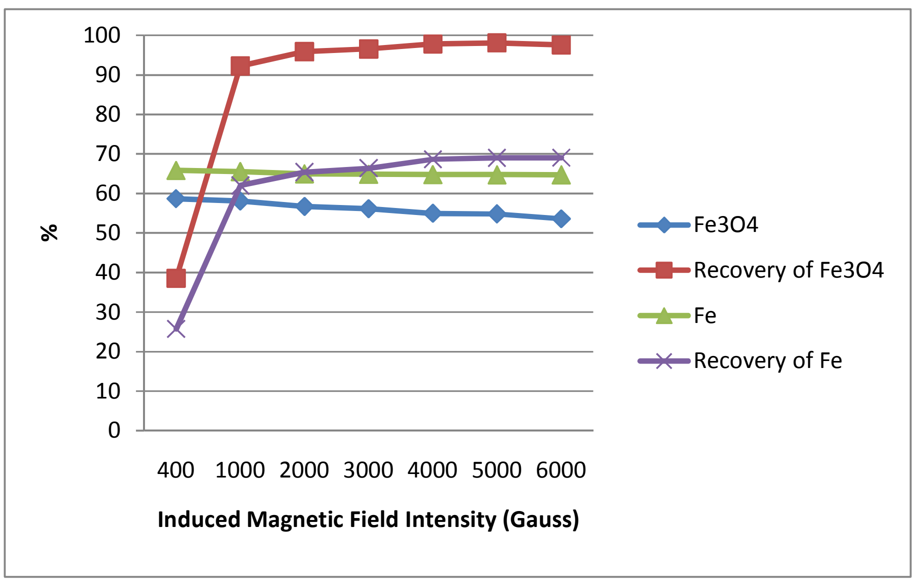


Figure 4.12 Results of the magnetic concentration test for -250 micron material (App. B, Table B.4)

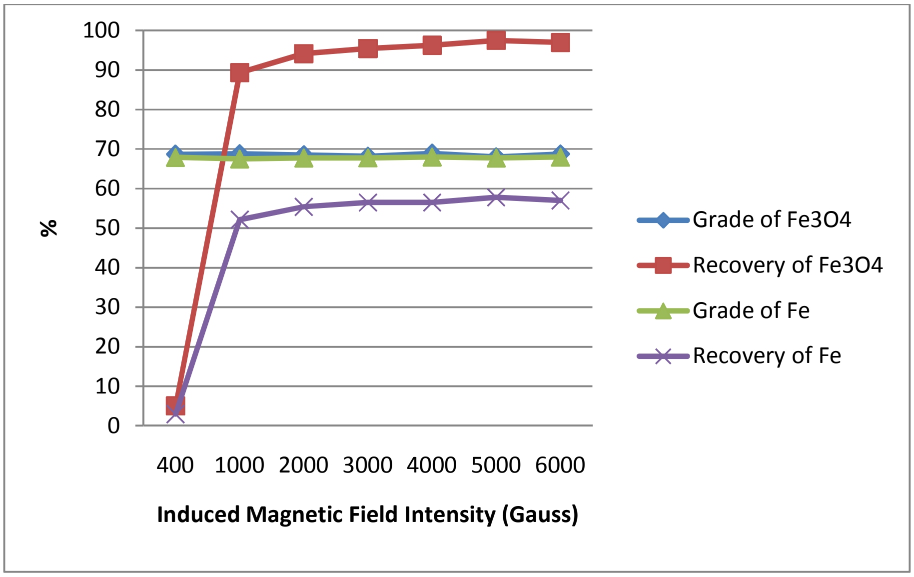


Figure 4.13 Results of the magnetic concentration test for -106 micron material (App. B, Table B.5)

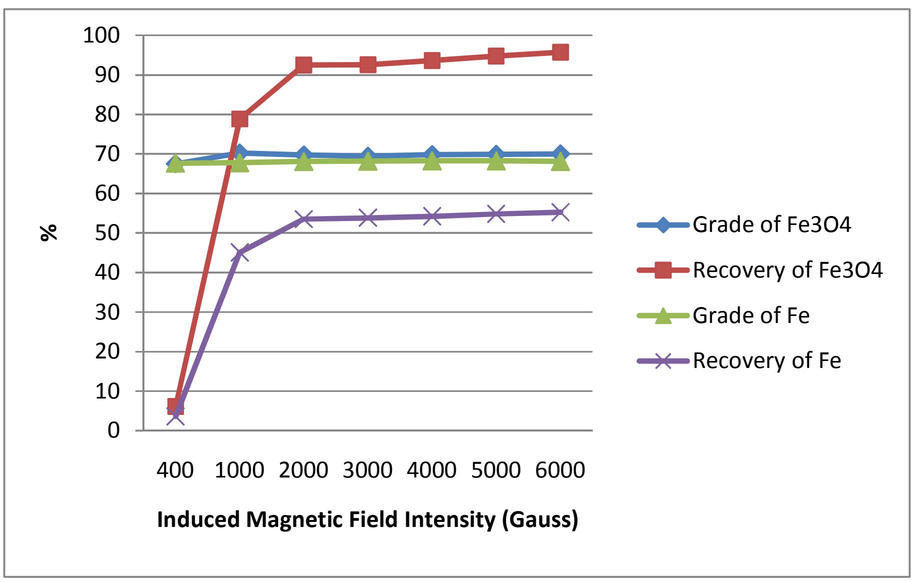


Figure 4.14 Results of the magnetic concentration test for -75 micron material (App. B, Table B.6)

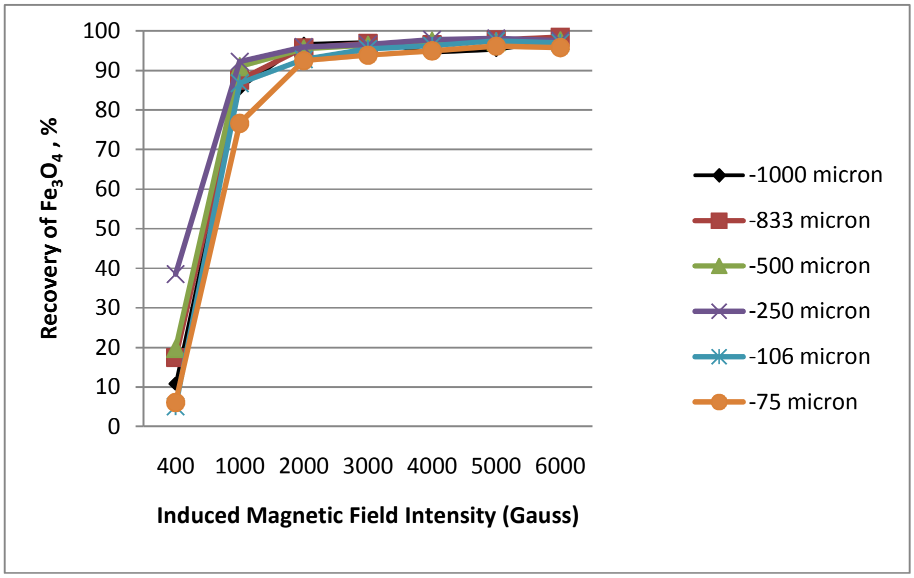


Figure 4.15 Recovery of Fe_3O_4% versus magnetic field intensity for medium grade tailing

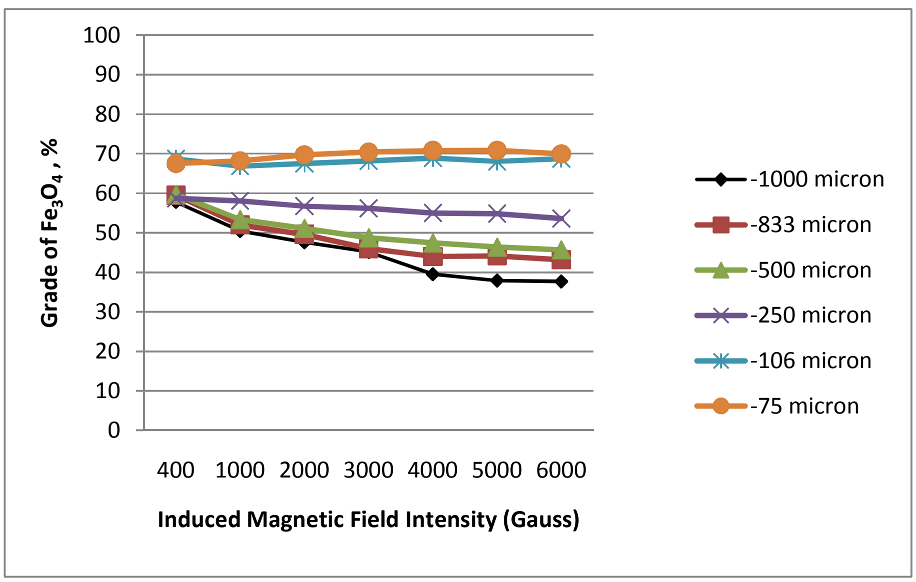


Figure 4.16 Grade of Fe_3O_4% versus magnetic field intensity for medium grade tailing

As seen from Figures 4.8 - 4.16, similar relations were observed between the Fe and Fe_3O_4 grades and respective recoveries and operating parameters of concentration process namely feed size and induced magnetic field intensity.

The concentrate with maximum Fe_3O_4 content was obtained at magnetic field intensity of 400 Gauss. The decrease in both Fe_3O_4 and Fe grade with increased magnetic field intensity were due to magnetic flocculation of magnetic particles which causes entrainment of particles other than magnetic particles. Presence of intimately interlocked hematite and magnetite particles also resulted in a decrease in Fe_3O_4 grade of concentrate. The increase in grade with decreasing particle size was due to better liberation of minerals at finer sizes. The slight decrease in recovery of magnetite minerals was due to hydrodynamic drag force of flowing water. This drag force has a negative effect on capturing of fine magnetite particles by the magnetic poles of Davis Tube.

By using the magnetic concentration method for the medium grade tailing with 18.85% Fe_3O_4 and 31.82% Fe content, a concentrate containing 70.23% Fe_3O_4 was obtained from 100% -75 microns feed with 78.87% recovery at 1000 Gauss magnetic field intensity. Fe grade and recovery were 67.80% and 45.11% respectively for the same concentrate.

Results of the test-work carried out with medium grade tailing show that it was not possible to produce a magnetite concentrate which will meet the specifications of magnetite concentrate suitable for preparation of dense medium. The grade and size of concentrate was suitable for production of magnetite pellets.

4.3. Concentration Studies of High Grade Tailing

A series of magnetic separation tests were carried out for high grade tailing at the same operating conditions followed during the concentration of both low and medium grade tailings. The effect of particle size and magnetic field intensities on Fe_3O_4 and Fe grade of concentrate and respective recoveries are shown in Figure 4.17-4.24 and in Tables C1-C6 as shown in Appendix C.

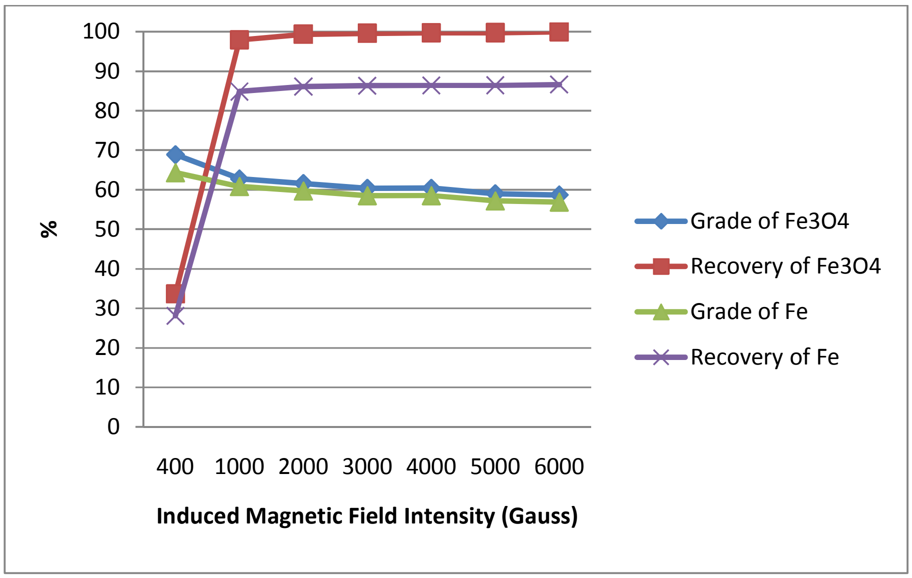


Figure 4.17 Results of the magnetic concentration test for -1000 micron material (App. C, Table C.1)

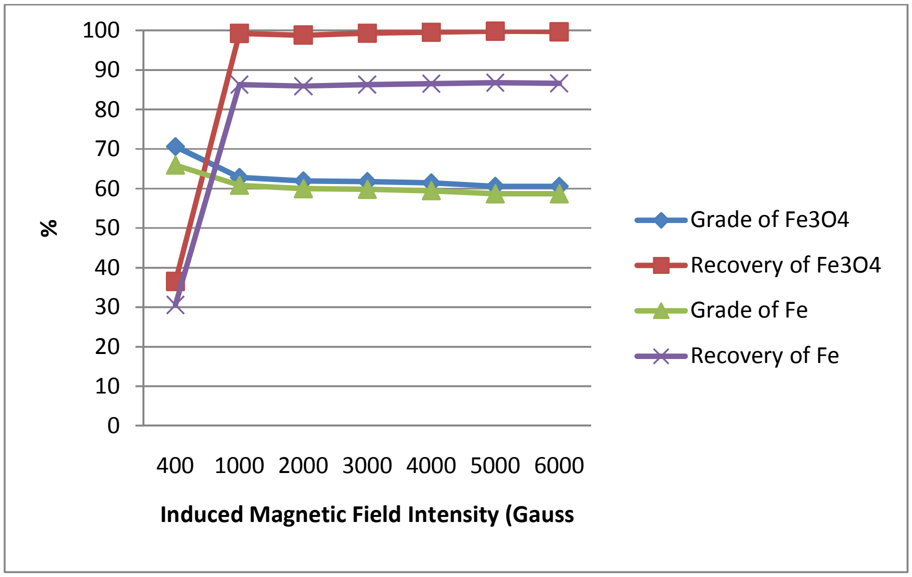


Figure 4.18 Results of the magnetic concentration test for -833 micron material (App. C, Table C.2)

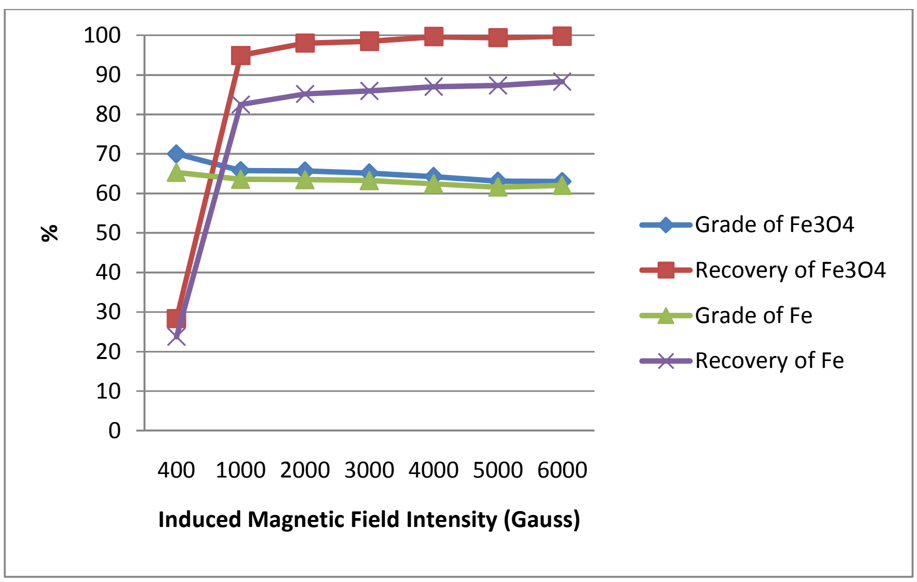


Figure 4.19 Results of the magnetic concentration test for -500 micron material (App. C, Table C.3)

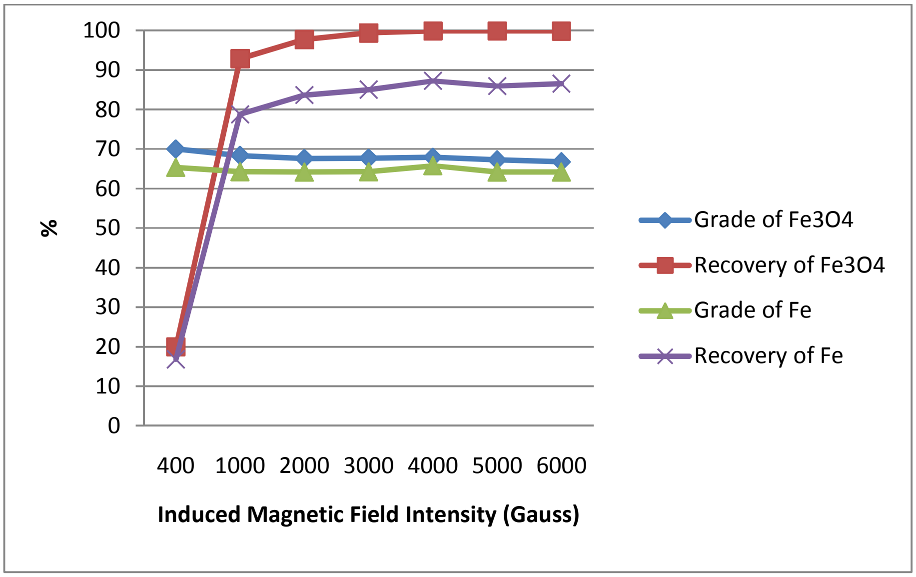


Figure 4.20 Results of the magnetic concentration test for -250 micron material (App. C, Table C.4)

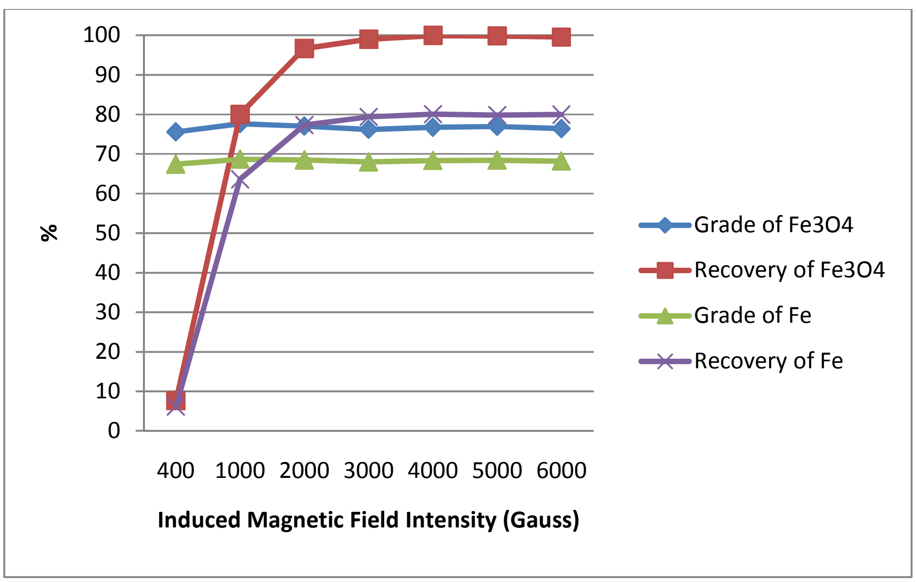


Figure 4.21 Results of the magnetic concentration test for -106 micron material (App. C, Table C.5)

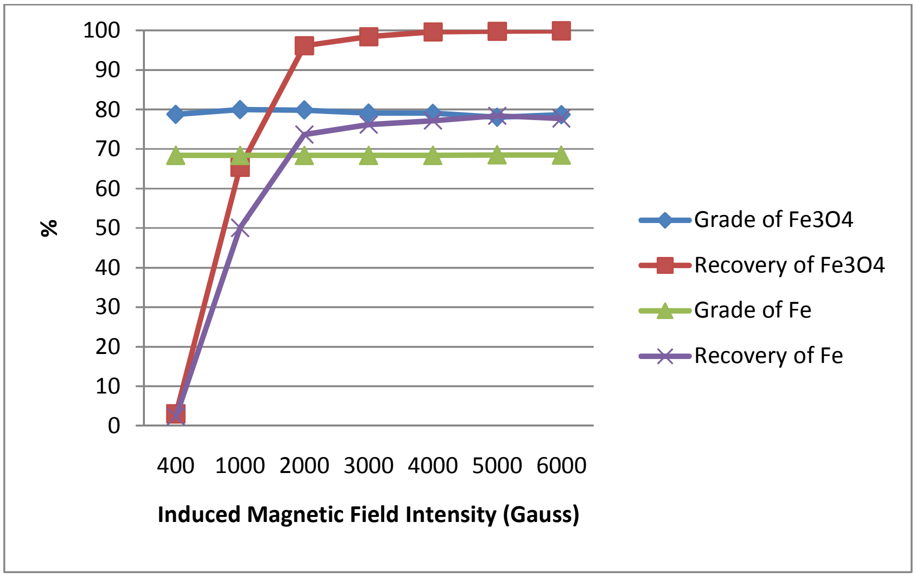


Figure 4.22 Results of the magnetic concentration test for -75 micron material (App. C, Table C.6)

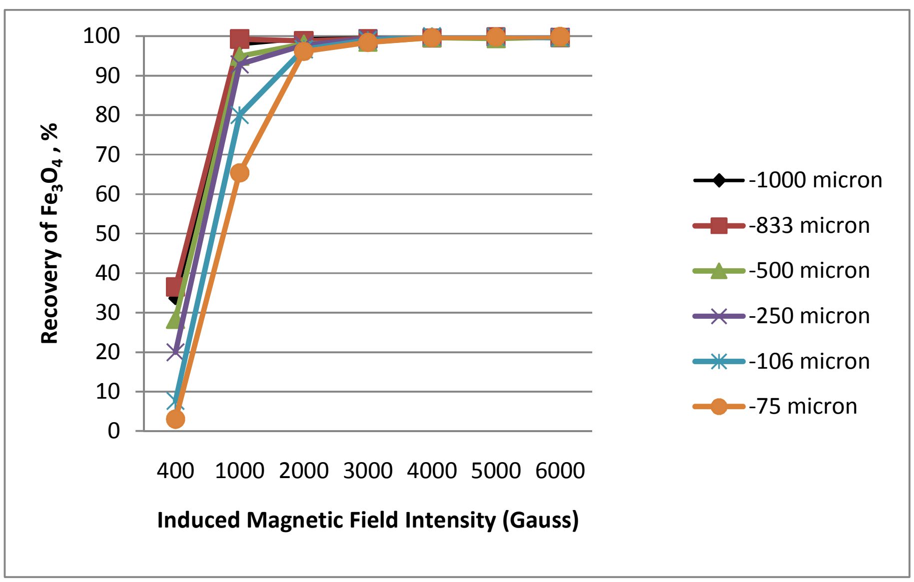


Figure 4.23 Recovery of Fe_3O_4% versus magnetic field intensity for high grade tailing

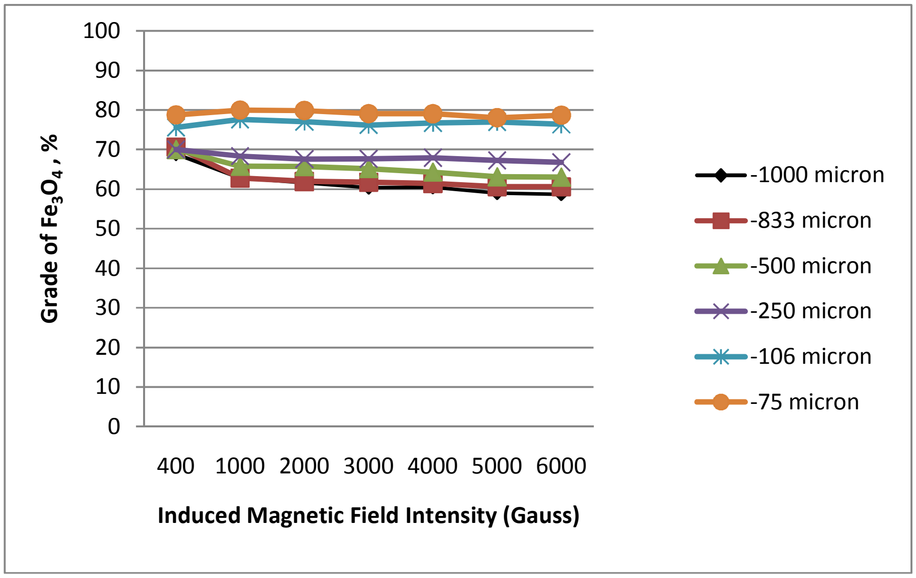


Figure 4.24 Grade of Fe_3O_4% versus magnetic field intensity for high grade tailing

As seen from Figures 4.17 - 4.24, similar relations as for low grade and medium grade tailings were observed between the Fe and Fe_3O_4 grades and respective recoveries and operating parameters of concentration process namely feed size and induced magnetic field intensity.

The concentrate with maximum Fe_3O_4 content was obtained at magnetic field intensity of 400 Gauss. The decrease in both Fe_3O_4 and Fe grade with increased magnetic field intensity were due to magnetic flocculation of magnetite particles which causes entrainment of particles other than magnetite particles. Presence of intimately interlocked hematite and magnetite particles also resulted in a decrease in Fe_3O_4 grade of concentrate. The increase in grade with decreasing particle size was due to better liberation of minerals at finer sizes. The slight decrease in recovery of magnetite minerals was due to hydrodynamic drag force of flowing water. This drag force has a negative effect on capturing of fine magnetite particles by the magnetic poles of Davis Tube.

By using the magnetic concentration method for the high grade tailing with 35.70% Fe_3O_4 and 39.90% Fe content, a concentrate containing 79.98% Fe_3O_4 was obtained from 100% -75 microns feed with 65.42% recovery at 1000 Gauss magnetic field intensity. Fe grade and recovery were 68.40% and 50.06% respectively for the same concentrate. At the same operating conditions a concentrate containing 76.5% Fe_3O_4 was obtained with 96.6% recovery by using a low intensity wet magnetic drum separator. The separator was constructed with a permanent magnet and manufactured by Boxmag Rapid Limited, England and the dimensions of the drum 19 * 19 cm (Figure 4.25).

Results of the test-work carried out with medium grade tailing show that it was not possible to produce a magnetite concentrate which will meet the specifications of magnetite concentrate suitable for preparation of dense medium. The grade and size of concentrate was suitable for production of magnetite pellets.

Figure 4.25 Low intensity wet magnetic drum separator

4.3.1 Regrinding of Rougher Concentrate

The rougher concentrate obtained from the feed of -75 μm size was subjected to another magnetic separation after regrinding the material to -45 μm. By following the flowsheet given in Figure 4.26, the final clean concentrate with 82.00% Fe_3O_4 content was obtained with 61.94% Fe_3O_4 recovery. The complete chemical analysis of this final concentrate was given in Table 4.1. The decrease in recovery was due to effect of hydrodynamic drag force of flowing water on very fine magnetite particles. Further increase in the grade of concentrate was not possible due to mineralogical texture of test sample. Microscopical examination of final magnetite concentrate indicated that there were no free hematite or gangue mineral particles. All particles were either free magnetite particle or intimately interlocked particle of magnetite and hematite. The measured specific gravity 4.97 of the final magnetite concentrate confirms these findings.

Although the magnetite content (Fe_3O_4) of produced concentrate was less than 90%, all particles in the concentrate will behave like a magnetite particle at low magnetic field intensity due to their mineralogical texture and will not create problem during their regeneration in heavy medium separation circuit. Therefore, to reach a final decision about the suitability of produced concentrate as suspension solid for heavy media, a pilot scale test should be carried out.

Table 4.1 Chemical analysis of the final clean concentrate

Total Fe %	**SiO_2 %**	**Al_2O_3 %**	**CaO %**	**MgO %**	**Na_2O %**	**K_2O %**	**S %**	**TiO_2 %**
68.44	0.70	0.10	0.25	0.25	0.02	0.02	0.005	<0.05

Size reduction (crushing + grinding) cost will be the main component of operating cost of magnetite concentrate from the iron ore tailings. The required energy for the size reduction operation from 80% passing from 10 cm to 80% passing 35 μm (100% -45 μm) can be calculated by using Bond index equation of

$$\boldsymbol{W = 10 * w_i * \left(\frac{1}{\sqrt{P}} - \frac{1}{\sqrt{F}}\right) * 1.1}$$

Where;

W : Work input in kWh/ton

w_i : Work index value of ore (for iron ore 15.44 kWh/ston)

P : The particles size which 80% of the product passes from 35 μm

F : The particles size which 80% of the feed passes from 10 cm (=100000 μm)

$$\boldsymbol{W = 10 * 15.44 * \left(\frac{1}{\sqrt{35}} - \frac{1}{\sqrt{100000}}\right) * 1.1}$$

$$\boldsymbol{W = 10 * 15.44 * \left(\frac{1}{5.9160} - \frac{1}{316.2277}\right) * 1.1}$$

$$\boldsymbol{W = 10 * 15.44 * (0.1658) * 1.1}$$

$$\boldsymbol{W = 28.17\ kWh/ton}$$

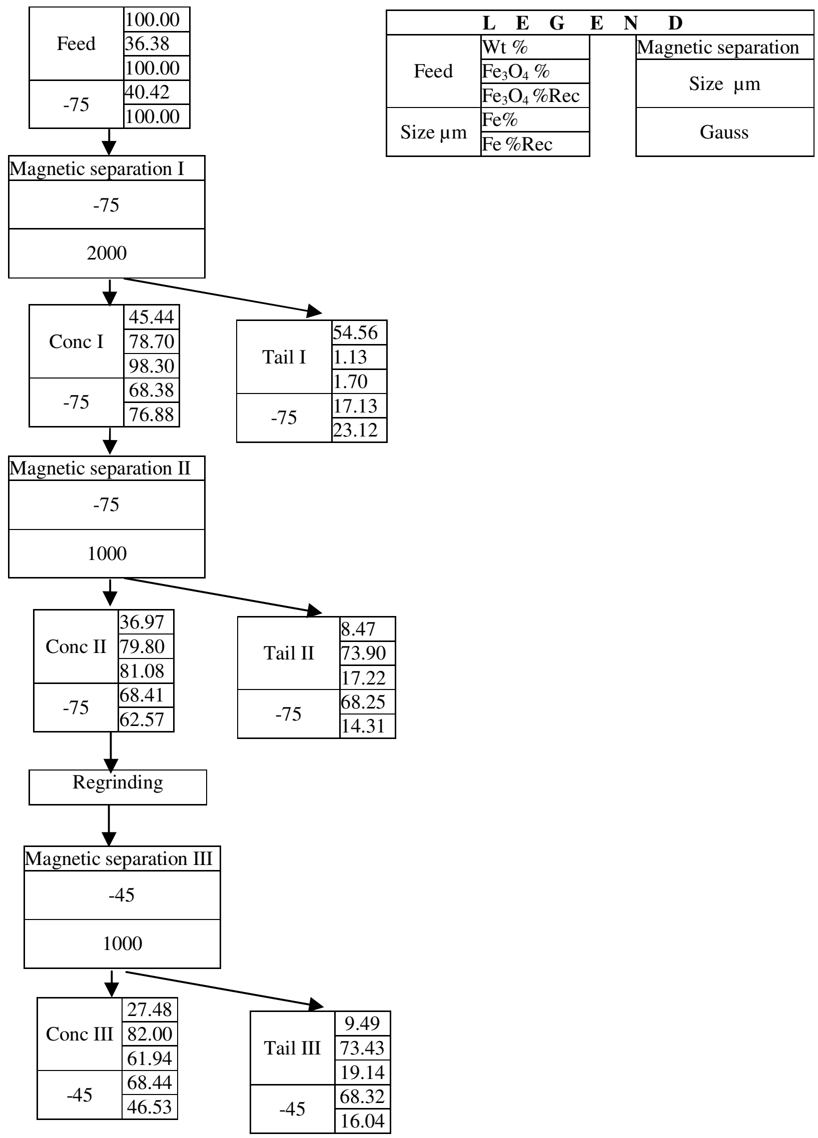


Figure 4.26 Flowsheet followed during the cleaning of magnetite preconcentrate

CHAPTER 5

CONCLUSION

In view of the results obtained in this research the following conclusions are derived;

- Mineralogical analysis of test samples showed that magnetite and hematite were the major ore minerals while pyrite and chalcopyrite were found in trace amounts. Actimolite, tremolite, epidote, chlorite, quartz, calcite, and dolomite were the gangue minerals in all test samples.

- A concentrate with 65.95% Fe_3O_4 grade with 86.21% recovery was obtained from 100% -106 μm size feed of low grade tailing at 1000 Gauss magnetic field intensity. Therefore low grade iron ore tailing was not suitable for the production of magnetite concentrate which will be used in preparation of heavy medium. This concentrate was suitable for production of magnetite pellets.

- A concentrate with 70.23% Fe_3O_4 content was obtained with 78.87% recovery from 100% -75 μm size feed of medium grade iron ore tailings at 1000 Gauss magnetic field intensity. Magnetite concentrate with this grade was not suitable for preparation of heavy medium. This concentrate was suitable for production of magnetite pellets.

- A concentrate with 79.98% Fe_3O_4 was obtained with 65.42% recovery from 100% -75 μm size feed of high grade iron ore tailings at 1000 Gauss magnetic field intensity. Magnetite concentrate with this grade was not suitable for preparation of heavy medium. This concentrate was suitable for production of magnetite pellets.

- Final concentrate with 82.00% Fe_3O_4 content was obtained with 61.94% Fe_3O_4 recovery from high grade iron ore tailings at 1000 Gauss magnetic field intensity after re-grinding of magnetite pre-concentrate to minus 45 μm. This concentrate was suitable for the production of magnetite pellets. Decision should be given about the suitability of produced concentrate as suspension solid for heavy media preparation after carrying out a pilot scale test.

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APPENDIX A

TABLES FOR LOW GRADE TAILINGS

Table A.1 Results of the magnetic concentration for -1000 μm

Particle Size (μm)	Magnetic Field Intensity (Gauss)	Products	Weight (%)	Fe_3O_4 (%)	Recovery of Fe_3O_4 (%)	Fe (%)	Recovery of Fe (%)
-1000	400	Concentrate	2.44	58.90	24.15	65.40	9.35
		Tailing	97.56	4.63	75.85	15.85	90.65
		Feed	**100.00**	**5.95**	**100.00**	**17.06**	**100.00**
	1000	Concentrate	10.46	50.41	88.62	57.96	35.54
		Tailing	89.54	0.76	11.38	12.28	64.46
		Feed	**100.00**	**5.95**	**100.00**	**17.06**	**100.00**
	2000	Concentrate	13.01	42.00	91.84	54.00	41.18
		Tailing	86.99	0.56	8.16	11.54	58.82
		Feed	**100.00**	**5.95**	**100.00**	**17.06**	**100.00**
	3000	Concentrate	13.89	41.40	96.65	53.02	43.17
		Tailing	86.11	0.23	3.35	11.26	56.83
		Feed	**100.00**	**5.95**	**100.00**	**17.06**	**100.00**
	4000	Concentrate	15.31	38.28	98.50	54.00	48.46
		Tailing	84.69	0.11	1.50	10.38	51.54
		Feed	**100.00**	**5.95**	**100.00**	**17.06**	**100.00**
	5000	Concentrate	16.34	35.80	98.31	49.72	47.62
		Tailing	83.66	0.12	1.69	10.68	52.38
		Feed	**100.00**	**5.95**	**100.00**	**17.06**	**100.00**
	6000	Concentrate	18.33	31.80	97.97	44.25	47.54
		Tailing	81.67	0.15	2.03	10.96	52.46
		Feed	**100.00**	**5.95**	**100.00**	**17.06**	**100.00**

Table A.2 Results of the magnetic concentration for -833 µm

Particle Size (µm)	Magnetic Field Intensity (Gauss)	Products	Weight (%)	Fe_3O_4 (%)	Recovery of Fe_3O_4 (%)	Fe (%)	Recovery of Fe (%)
-833	400	Concentrate	2.60	60.00	25.83	66.95	10.06
		Tailing	97.40	4.60	74.17	15.97	89.94
		Feed	**100.00**	**6.04**	**100.00**	**17.30**	**100.00**
	1000	Concentrate	11.68	50.30	97.27	58.00	39.16
		Tailing	88.32	0.19	2.73	11.92	60.84
		Feed	**100.00**	**6.04**	**100.00**	**17.30**	**100.00**
	2000	Concentrate	13.00	45.00	96.85	55.10	41.40
		Tailing	87.00	0.22	3.15	11.65	58.60
		Feed	**100.00**	**6.04**	**100.00**	**17.30**	**100.00**
	3000	Concentrate	12.95	46.40	99.48	55.46	41.51
		Tailing	87.05	0.04	0.52	11.62	58.49
		Feed	**100.00**	**6.04**	**100.00**	**17.30**	**100.00**
	4000	Concentrate	14.22	41.53	97.77	53.93	44.33
		Tailing	85.78	0.16	2.23	11.23	55.67
		Feed	**100.00**	**6.04**	**100.00**	**17.30**	**100.00**
	5000	Concentrate	15.47	38.17	97.76	51.76	46.28
		Tailing	84.53	0.16	2.24	10.99	53.72
		Feed	**100.00**	**6.04**	**100.00**	**17.30**	**100.00**
	6000	Concentrate	16.42	36.00	97.87	50.14	47.59
		Tailing	83.58	0.15	2.13	10.85	52.41
		Feed	**100.00**	**6.04**	**100.00**	**17.30**	**100.00**

Table A.3 Results of the magnetic concentration for -500 µm

Particle Size (µm)	Magnetic Field Intensity (Gauss)	Products	Weight (%)	Fe_3O_4 (%)	Recovery of Fe_3O_4 (%)	Fe (%)	Recovery of Fe (%)
-500	400	Concentrate	2.86	59.50	28.36	66.39	11.04
		Tailing	97.14	4.42	71.64	15.75	88.96
		Feed	**100.00**	**6.00**	**100.00**	**17.20**	**100.00**
	1000	Concentrate	11.40	50.20	95.38	**57.91**	38.38
		Tailing	88.60	0.31	4.62	11.96	61.62
		Feed	**100.00**	**6.00**	**100.00**	**17.20**	**100.00**
	2000	Concentrate	12.58	45.57	95.55	**55.26**	40.42
		Tailing	87.42	0.31	4.45	11.72	59.58
		Feed	**100.00**	**6.00**	**100.00**	**17.20**	**100.00**
	3000	Concentrate	12.56	46.86	98.09	56.10	40.97
		Tailing	87.44	0.13	1.91	11.61	59.03
		Feed	**100.00**	**6.00**	**100.00**	**17.20**	**100.00**
	4000	Concentrate	14.46	40.27	97.05	52.60	44.22
		Tailing	85.54	0.21	2.95	11.22	55.78
		Feed	**100.00**	**6.00**	**100.00**	**17.20**	**100.00**
	5000	Concentrate	14.34	40.83	97.58	54.39	45.35
		Tailing	85.66	0.17	2.42	10.97	54.65
		Feed	**100.00**	**6.00**	**100.00**	**17.20**	**100.00**
	6000	Concentrate	16.10	36.64	98.32	51.08	47.81
		Tailing	83.90	0.12	1.68	10.70	52.19
		Feed	**100.00**	**6.00**	**100.00**	**17.20**	**100.00**

Table A.4 Results of the magnetic concentration for -250 μm

Particle Size (μm)	Magnetic Field Intensity (Gauss)	Products	Weight (%)	Fe_3O_4 (%)	Recovery of Fe_3O_4 (%)	Fe (%)	Recovery of Fe (%)
-250	400	Concentrate	2.92	59.20	28.81	65.90	11.19
		Tailing	97.08	4.40	71.19	15.74	88.81
		Feed	**100.00**	**6.00**	**100.00**	**17.20**	**100.00**
	1000	Concentrate	10.12	55.37	93.39	64.80	38.13
		Tailing	89.88	0.44	6.61	11.84	61.87
		Feed	**100.00**	**6.00**	**100.00**	**17.20**	**100.00**
	2000	Concentrate	11.26	49.90	93.65	**57.30**	37.51
		Tailing	88.74	0.43	6.35	12.11	62.49
		Feed	**100.00**	**6.00**	**100.00**	**17.20**	**100.00**
	3000	Concentrate	12.08	46.70	94.02	55.61	39.06
		Tailing	87.92	0.41	5.98	11.92	60.94
		Feed	**100.00**	**6.00**	**100.00**	**17.20**	**100.00**
	4000	Concentrate	13.46	42.83	96.08	54.95	43.00
		Tailing	86.54	0.27	3.92	11.33	57.00
		Feed	**100.00**	**6.00**	**100.00**	**17.20**	**100.00**
	5000	Concentrate	14.28	40.28	95.87	53.15	44.13
		Tailing	85.72	0.29	4.13	11.21	55.87
		Feed	**100.00**	**6.00**	**100.00**	**17.20**	**100.00**
	6000	Concentrate	14.46	40.50	97.61	53.34	44.84
		Tailing	85.54	0.17	2.40	11.09	55.16
		Feed	**100.00**	**6.00**	**100.00**	**17.20**	**100.00**

Table A.5 Results of the magnetic concentration for -106 µm

Particle Size (µm)	Magnetic Field Intensity (Gauss)	Products	Weight (%)	Fe_3O_4 (%)	Recovery of Fe_3O_4 (%)	Fe (%)	Recovery of Fe (%)
-106	400	Concentrate	2.43	66.10	26.25	67.44	9.23
		Tailing	97.57	4.63	73.75	16.51	90.77
		Feed	**100.00**	**6.12**	**100.00**	**17.75**	**100.00**
	1000	Concentrate	8.00	65.95	86.21	67.00	30.20
		Tailing	92.00	0.92	13.79	13.47	69.80
		Feed	**100.00**	**6.12**	**100.00**	**17.75**	**100.00**
	2000	Concentrate	9.36	60.20	92.07	67.17	35.42
		Tailing	90.64	0.54	7.93	12.65	64.58
		Feed	**100.00**	**6.12**	**100.00**	**17.75**	**100.00**
	3000	Concentrate	9.93	57.25	92.89	65.57	36.68
		Tailing	90.07	0.48	7.11	12.48	63.32
		Feed	**100.00**	**6.12**	**100.00**	**17.75**	**100.00**
	4000	Concentrate	11.43	50.24	93.83	**58.11**	37.42
		Tailing	88.57	0.43	6.17	12.54	62.58
		Feed	**100.00**	**6.12**	**100.00**	**17.75**	**100.00**
	5000	Concentrate	11.57	50.11	94.73	57.96	37.78
		Tailing	88.43	0.36	5.27	12.49	62.22
		Feed	**100.00**	**6.12**	**100.00**	**17.75**	**100.00**
	6000	Concentrate	11.50	49.50	93.01	**56.89**	36.86
		Tailing	88.50	0.48	6.99	12.66	63.14
		Feed	**100.00**	**6.12**	**100.00**	**17.75**	**100.00**

Table A.6 Results of the magnetic concentration for -75 µm

Particle Size (µm)	Magnetic Field Intensity (Gauss)	Products	Weight (%)	Fe_3O_4 (%)	Recovery of Fe_3O_4 (%)	Fe (%)	Recovery of Fe (%)
-75	400	Concentrate	1.97	65.30	21.99	66.47	7.81
		Tailing	98.03	4.66	78.01	15.77	92.19
		Feed	**100.00**	**5.85**	**100.00**	**16.77**	**100.00**
	1000	Concentrate	7.43	63.30	80.40	67.34	29.84
		Tailing	92.57	1.24	19.60	12.71	70.16
		Feed	**100.00**	**5.85**	**100.00**	**16.77**	**100.00**
	2000	Concentrate	8.10	60.00	83.08	66.95	32.34
		Tailing	91.90	1.08	16.92	12.35	67.66
		Feed	**100.00**	**5.85**	**100.00**	**16.77**	**100.00**
	3000	Concentrate	9.17	55.10	86.37	**63.87**	34.92
		Tailing	90.83	0.88	13.63	12.01	65.08
		Feed	**100.00**	**5.85**	**100.00**	**16.77**	**100.00**
	4000	Concentrate	9.57	52.60	86.05	62.43	35.63
		Tailing	90.43	0.90	13.95	11.94	64.37
		Feed	**100.00**	**5.85**	**100.00**	**16.77**	**100.00**
	5000	Concentrate	9.90	51.50	87.15	60.88	35.94
		Tailing	90.10	0.83	12.85	11.92	64.06
		Feed	**100.00**	**5.85**	**100.00**	**16.77**	**100.00**
	6000	Concentrate	10.10	50.00	86.32	**57.84**	34.84
		Tailing	89.90	0.89	13.68	12.16	65.16
		Feed	**100.00**	**5.85**	**100.00**	**16.77**	**100.00**

APPENDIX B

TABLES FOR MEDIUM GRADE TAILINGS

Table B.1 Results of the magnetic concentration for -1000 μm

Particle Size (μm)	Magnetic Field (Gauss)	Products	Weight (%)	Fe_3O_4 (%)	Recovery of Fe_3O_4 (%)	Fe (%)	Recovery of Fe (%)
-1000	400	Concentrate	3.57	57.80	10.79	65.28	7.26
		Tailing	96.43	17.70	89.21	30.87	92.74
		Feed	**100.00**	**19.13**	**100.00**	**32.10**	**100.00**
	1000	Concentrate	32.43	50.45	85.53	59.20	59.81
		Tailing	67.57	4.10	14.47	19.09	40.19
		Feed	**100**	**19.13**	**100.00**	**32.10**	**100.00**
	2000	Concentrate	38.87	47.60	96.72	57.85	70.05
		Tailing	61.13	1.03	3.28	15.73	29.95
		Feed	**100.00**	**19.13**	**100.00**	**32.10**	**100.00**
	3000	Concentrate	41.17	45.16	97.19	54.63	70.07
		Tailing	58.83	0.91	2.81	16.33	29.93
		Feed	**100.00**	**19.13**	**100.00**	**32.10**	**100.00**
	4000	Concentrate	45.73	39.52	94.47	53.01	75.52
		Tailing	54.27	1.95	5.53	14.48	24.48
		Feed	**100.00**	**19.13**	**100.00**	**32.10**	**100.00**
	5000	Concentrate	48.00	37.95	95.22	53.42	79.88
		Tailing	52.00	1.76	4.78	12.42	20.12
		Feed	**100.00**	**19.13**	**100.00**	**32.10**	**100.00**
	6000	Concentrate	49.57	37.70	97.69	51.40	79.37
		Tailing	50.43	0.88	2.31	13.13	20.63
		Feed	**100.00**	**19.13**	**100.00**	**32.10**	**100.00**

Table B.2 Results of the magnetic concentration for -833 µm

Particle Size (µm)	Magnetic Field (Gauss)	Products	Weight (%)	Fe_3O_4 (%)	Recovery of Fe_3O_4 (%)	Fe (%)	Recovery of Fe (%)
-833	400	Concentrate	5.57	59.50	17.44	66.39	11.57
		Tailing	94.43	16.61	82.56	29.92	88.43
		Feed	**100.00**	**19.00**	**100.00**	**31.95**	**100.00**
	1000	Concentrate	32.00	52.00	87.58	64.16	64.26
		Tailing	68.00	3.47	12.42	16.79	35.74
		Feed	**100.00**	**19.00**	**100.00**	**31.95**	**100.00**
	2000	Concentrate	36.67	49.60	95.73	58.53	67.18
		Tailing	63.33	1.28	4.27	16.56	32.82
		Feed	**100.00**	**19.00**	**100.00**	**31.95**	**100.00**
	3000	Concentrate	40.00	46.00	96.84	56.24	70.41
		Tailing	60.00	1.00	3.16	15.76	29.59
		Feed	**100.00**	**19.00**	**100.00**	**31.95**	**100.00**
	4000	Concentrate	41.67	44.00	96.50	53.82	70.19
		Tailing	58.33	1.14	3.50	16.33	29.81
		Feed	**100.00**	**19.00**	**100.00**	**31.95**	**100.00**
	5000	Concentrate	42.00	44.20	97.71	54.22	71.28
		Tailing	58.00	0.75	2.29	15.82	28.72
		Feed	**100.00**	**19.00**	**100.00**	**31.95**	**100.00**
	6000	Concentrate	43.33	43.15	98.40	53.62	72.72
		Tailing	56.67	0.53	1.60	15.38	27.28
		Feed	**100.00**	**19.00**	**100.00**	**31.95**	**100.00**

Table B.3 Results of the magnetic concentration for -500 μm

Particle Size (μm)	Magnetic Field (Gauss)	Products	Weight (%)	Fe_3O_4 (%)	Recovery of Fe_3O_4 (%)	Fe (%)	Recovery of Fe (%)
-500	400	Concentrate	6.30	59.70	19.74	66.94	13.17
		Tailing	93.70	16.32	80.26	29.66	86.83
		Feed	**100.00**	**19.05**	**100.00**	**32.01**	**100.00**
	1000	Concentrate	32.5	53.35	91.02	64.72	65.71
		Tailing	67.50	2.54	8.98	16.26	34.29
		Feed	**100.00**	**19.05**	**100.00**	**32.01**	**100.00**
	2000	Concentrate	35.60	51.10	95.49	58.53	65.09
		Tailing	64.40	1.33	4.51	17.35	34.91
		Feed	**100.00**	**19.05**	**100.00**	**32.01**	**100.00**
	3000	Concentrate	37.68	48.74	96.41	58.19	69.25
		Tailing	62.32	1.10	3.59	15.62	30.75
		Feed	**100.00**	**19.05**	**100.00**	**31.66**	**32.01**
	4000	Concentrate	39.15	47.42	97.45	57.04	69.76
		Tailing	60.85	0.80	2.55	15.91	30.24
		Feed	**100.00**	**19.05**	**100.00**	**32.01**	**100.00**
	5000	Concentrate	39.98	46.36	97.30	56.64	70.74
		Tailing	60.02	0.86	2.70	15.60	29.26
		Feed	**100.00**	**19.05**	**100.00**	**32.01**	**100.00**
	6000	Concentrate	40.69	45.66	97.53	55.43	70.46
		Tailing	59.31	0.79	2.47	15.94	29.54
		Feed	**100.00**	**19.05**	**100.00**	**32.01**	**100.00**

Table B.4 Results of the magnetic concentration for -250 μm

Particle Size (μm)	Magnetic Field (Gauss)	Products	Weight (%)	Fe_3O_4 (%)	Recovery of Fe_3O_4 (%)	Fe (%)	Recovery of Fe (%)
-250	400	Concentrate	12.53	58.70	38.51	65.83	25.73
		Tailing	87.47	13.43	61.49	27.22	74.27
		Feed	**100.00**	**19.10**	**100.00**	**32.06**	**100.00**
	1000	Concentrate	30.33	58.1	92.26	65.55	62.01
		Tailing	69.67	2.12	7.74	17.48	37.99
		Feed	**100.00**	**19.10**	**100.00**	**32.06**	**100.00**
	2000	Concentrate	32.27	56.75	95.88	65.00	65.43
		Tailing	67.73	1.16	4.12	16.37	34.57
		Feed	**100.00**	**19.10**	**100.00**	**32.06**	**100.00**
	3000	Concentrate	32.83	56.18	96.56	64.86	66.42
		Tailing	67.17	0.98	3.44	16.03	33.58
		Feed	**100.00**	**19.10**	**100.00**	**32.06**	**100.00**
	4000	Concentrate	33.97	55.00	97.82	64.79	68.65
		Tailing	66.03	0.63	2.18	15.22	31.35
		Feed	**100.00**	**19.10**	**100.00**	**32.06**	**100.00**
	5000	Concentrate	34.17	54.85	98.13	64.75	69.01
		Tailing	65.83	0.54	1.87	15.09	30.99
		Feed	**100.00**	**19.10**	**100.00**	**32.06**	**100.00**
	6000	Concentrate	34.77	53.60	97.57	64.74	69.05
		Tailing	65.23	0.71	2.43	15.47	30.95
		Feed	**100.00**	**19.10**	**100.00**	**32.60**	**100.00**

Table B.5 Results of the magnetic concentration for -106 μm

Particle Size (μm)	Magnetic Field (Gauss)	Products	Weight (%)	Fe_3O_4 (%)	Recovery of Fe_3O_4 (%)	Fe (%)	Recovery of Fe (%)
-106	400	Concentrate	1.40	68.70	5.05	67.90	2.97
		Tailing	98.60	18.35	94.95	31.50	97.03
		Feed	**100.00**	**19.05**	**100.00**	**32.01**	**100.00**
	1000	Concentrate	24.73	68.83	89.35	67.50	52.15
		Tailing	75.27	2.69	10.65	20.35	47.85
		Feed	**100.00**	**19.05**	**100.00**	**32.01**	**100.00**
	2000	Concentrate	26.17	68.53	94.14	67.75	55.39
		Tailing	73.83	1.51	5.86	19.34	44.61
		Feed	**100.00**	**19.05**	**100.00**	**32.01**	**100.00**
	3000	Concentrate	26.67	68.18	95.45	67.78	56.47
		Tailing	73.33	1.18	4.55	19.00	43.53
		Feed	**100.00**	**19.05**	**100.00**	**32.01**	**100.00**
	4000	Concentrate	26.60	68.93	96.25	68.00	56.51
		Tailing	73.40	0.97	3.75	18.97	43.49
		Feed	**100.00**	**19.05**	**100.00**	**32.01**	**100.00**
	5000	Concentrate	27.30	68.03	97.49	67.76	57.79
		Tailing	72.70	0.66	2.51	18.59	42.21
		Feed	**100.00**	**19.05**	**100.00**	**32.01**	**100.00**
	6000	Concentrate	26.87	68.75	96.97	67.95	57.04
		Tailing	73.13	0.79	3.03	18.80	42.96
		Feed	**100.00**	**19.05**	**100.00**	**32.01**	**100.00**

Table B.6 Results of the magnetic concentration for -75 µm

Particle Size (µm)	Magnetic Field (Gauss)	Products	Weight (%)	Fe_3O_4 (%)	Recovery of Fe_3O_4 (%)	Fe (%)	Recovery of Fe (%)
-75	400	Concentrate	1.70	67.50	6.09	67.70	3.62
		Tailing	98.30	18.01	93.91	31.20	96.38
		Feed	**100.00**	**18.85**	**100.00**	**31.82**	**100.00**
	1000	Concentrate	21.17	70.23	78.87	67.80	45.11
		Tailing	78.83	5.05	21.13	22.16	54.89
		Feed	**100.00**	**18.85**	**100.00**	**31.82**	**100.00**
	2000	Concentrate	25.00	69.73	92.48	68.10	53.50
		Tailing	75.00	1.89	7.52	19.73	46.50
		Feed	**100.00**	**18.85**	**100.00**	**31.82**	**100.00**
	3000	Concentrate	25.13	69.40	92.52	68.20	53.86
		Tailing	74.87	1.88	7.48	19.61	46.14
		Feed	**100.00**	**18.85**	**100.00**	**31.82**	**100.00**
	4000	Concentrate	25.27	69.83	93.61	68.30	54.24
		Tailing	74.73	1.61	6.39	19.48	45.76
		Feed	**100.00**	**18.85**	**100.00**	**31.82**	**100.00**
	5000	Concentrate	25.57	69.87	94.78	68.25	54.84
		Tailing	74.43	1.32	5.22	19.30	45.16
		Feed	**100.00**	**18.85**	**100.00**	**31.82**	**100.00**
	6000	Concentrate	25.80	69.98	95.78	68.15	55.26
		Tailing	74.20	1.07	4.22	19.19	44.74
		Feed	**100.00**	**18.85**	**100.00**	**31.82**	**100.00**

APPENDIX C

TABLES FOR HIGH GRADE TAILINGS

Table C.1 Results of the magnetic concentration for -1000 μm

Particle Size (μm)	Magnetic Field (Gauss)	Products	Weight (%)	Fe_3O_4 (%)	Recovery of Fe_3O_4 (%)	Fe (%)	Recovery of Fe (%)
-1000	400	Concentrate	18.10	68.90	33.67	64.30	28.11
		Tailing	81.90	30.00	66.33	36.34	71.89
		Feed	**100.00**	**37.04**	**100.00**	**41.40**	**100.00**
	1000	Concentrate	57.77	62.78	97.92	60.80	84.84
		Tailing	42.23	1.83	2.08	14.86	15.16
		Feed	**100.00**	**37.04**	**100.00**	**41.40**	**100.00**
	2000	Concentrate	59.73	61.62	99.37	59.68	86.10
		Tailing	40.27	0.58	0.63	14.29	13.90
		Feed	**100.00**	**37.04**	**100.00**	**41.40**	**100.00**
	3000	Concentrate	61.07	60.40	99.58	58.50	86.29
		Tailing	38.93	0.39	0.42	14.58	13.71
		Feed	**100.00**	**37.04**	**100.00**	**41.40**	**100.00**
	4000	Concentrate	61.13	60.42	99.72	58.51	86.39
		Tailing	38.87	0.27	0.28	14.49	13.61
		Feed	**100.00**	**37.04**	**100.00**	**41.40**	**100.00**
	5000	Concentrate	62.60	59.02	99.75	57.16	86.43
		Tailing	37.40	0.25	0.25	15.02	13.57
		Feed	**100.00**	**37.04**	**100.00**	**41.40**	**100.00**
	6000	Concentrate	63.03	58.73	99.94	56.88	86.60
		Tailing	36.97	0.06	0.06	15.01	13.40
		Feed	**100.00**	**37.04**	**100.00**	**41.40**	**100.00**

Table C.2 Results of the magnetic concentration for -833 µm

Particle Size (µm)	Magnetic Field (Gauss)	Products	Weight (%)	Fe_3O_4 (%)	Recovery of Fe_3O_4 (%)	Fe (%)	Recovery of Fe (%)
-833	400	Concentrate	19.13	70.65	36.51	65.96	30.59
		Tailing	80.87	29.06	63.49	35.40	69.41
		Feed	**100.00**	**37.02**	**100.00**	**41.25**	**100.00**
	1000	Concentrate	58.53	62.80	99.29	60.82	86.30
		Tailing	41.47	0.63	0.71	13.63	13.70
		Feed	**100.00**	**37.02**	**100.00**	**41.25**	**100.00**
	2000	Concentrate	59.07	61.94	98.83	59.99	85.91
		Tailing	40.93	1.06	1.17	14.20	14.09
		Feed	**100.00**	**37.02**	**100.00**	**41.25**	**100.00**
	3000	Concentrate	59.53	61.76	99.31	59.81	86.31
		Tailing	40.47	0.63	0.69	13.95	13.69
		Feed	**100.00**	**37.02**	**100.00**	**41.25**	**100.00**
	4000	Concentrate	60.02	61.42	99.58	59.48	86.55
		Tailing	39.98	0.39	0.42	13.88	13.45
		Feed	**100.00**	**37.02**	**100.00**	**41.25**	**100.00**
	5000	Concentrate	60.98	60.60	99.82	58.69	86.76
		Tailing	39.02	0.17	0.18	13.99	13.24
		Feed	**100.00**	**37.02**	**100.00**	**41.25**	**100.00**
	6000	Concentrate	60.89	60.60	99.67	58.69	86.63
		Tailing	39.11	0.31	0.33	14.10	13.37
		Feed	**100.00**	**37.02**	**100.00**	**41.25**	**100.00**

Table C.3 Results of the magnetic concentration for -500 μm

Particle Size (μm)	Magnetic Field (Gauss)	Products	Weight (%)	Fe_3O_4 (%)	Recovery of Fe_3O_4 (%)	Fe (%)	Recovery of Fe (%)
-500	400	Concentrate	14.97	70.00	28.32	65.35	23.77
		Tailing	85.03	31.19	71.68	36.89	76.23
		Feed	**100.00**	**37.00**	**100.00**	**41.15**	**100.00**
	1000	Concentrate	53.40	65.78	94.94	63.57	82.49
		Tailing	46.60	4.02	5.06	15.46	17.51
		Feed	**100.00**	**37.00**	**100.00**	**41.15**	**100.00**
	2000	Concentrate	55.23	65.68	98.04	63.47	85.19
		Tailing	44.77	1.62	1.96	13.62	14.81
		Feed	**100.00**	**37.00**	**100.00**	**41.15**	**100.00**
	3000	Concentrate	55.93	65.18	98.53	63.24	85.95
		Tailing	44.07	1.24	1.47	13.12	14.05
		Feed	**100.00**	**37.00**	**100.00**	**41.15**	**100.00**
	4000	Concentrate	57.37	64.28	99.67	62.43	87.04
		Tailing	42.63	0.29	0.33	12.51	12.96
		Feed	**100.00**	**37.00**	**100.00**	**41.15**	**100.00**
	5000	Concentrate	58.30	63.10	99.43	61.61	87.29
		Tailing	41.70	0.51	0.57	12.55	12.71
		Feed	**100.00**	**37.00**	**100.00**	**41.15**	**100.00**
	6000	Concentrate	58.60	63.02	99.81	62.02	88.32
		Tailing	41.40	0.17	0.19	11.61	11.68
		Feed	**100.00**	**37.00**	**100.00**	**41.15**	**100.00**

Table C.4 Results of the magnetic concentration for -250 µm

Particle Size (µm)	Magnetic Field (Gauss)	Products	Weight (%)	Fe_3O_4 (%)	Recovery of Fe_3O_4 (%)	Fe (%)	Recovery of Fe (%)
-250	400	Concentrate	10.50	70.00	19.97	65.35	16.82
		Tailing	89.50	32.91	80.03	37.92	83.18
		Feed	**100.00**	**36.80**	**100.00**	**40.80**	**100.00**
	1000	Concentrate	50.00	68.36	92.88	64.27	78.76
		Tailing	50.00	5.24	7.12	17.33	21.24
		Feed	**100.00**	**36.80**	**100.00**	**40.80**	**100.00**
	2000	Concentrate	53.17	67.62	97.70	64.18	83.64
		Tailing	46.83	1.81	2.30	14.25	16.36
		Feed	**100.00**	**36.80**	**100.00**	**40.80**	**100.00**
	3000	Concentrate	54.02	67.70	99.38	64.24	85.06
		Tailing	45.98	0.50	0.62	13.26	14.94
		Feed	**100.00**	**36.80**	**100.00**	**40.80**	**100.00**
	4000	Concentrate	54.10	67.94	99.88	65.81	87.26
		Tailing	45.90	0.10	0.12	11.32	12.74
		Feed	**100.00**	**36.80**	**100.00**	**40.80**	**100.00**
	5000	Concentrate	54.63	67.26	99.85	64.18	85.94
		Tailing	45.37	0.12	0.15	12.65	14.06
		Feed	**100.00**	**36.80**	**100.00**	**40.80**	**100.00**
	6000	Concentrate	55.03	66.76	99.83	64.18	86.56
		Tailing	44.97	0.14	0.17	12.19	13.44
		Feed	**100.00**	**36.80**	**100.00**	**40.80**	**100.00**

Table C.5 Results of the magnetic concentration for -106 µm

Particle Size (µm)	Magnetic Field (Gauss)	Products	Weight (%)	Fe_3O_4 (%)	Recovery of Fe_3O_4 (%)	Fe (%)	Recovery of Fe (%)
-106	400	Concentrate	3.67	75.60	7.64	67.45	6.13
		Tailing	96.33	34.82	92.36	39.36	93.87
		Feed	**100.00**	**36.32**	**100.00**	**40.39**	**100.00**
	1000	Concentrate	37.40	77.68	79.99	68.70	63.61
		Tailing	62.60	11.61	20.01	23.48	36.39
		Feed	**100.00**	**36.32**	**100.00**	**40.39**	**100.00**
	2000	Concentrate	45.59	77.04	96.70	68.50	77.32
		Tailing	54.41	2.20	3.30	16.84	22.68
		Feed	**100.00**	**36.32**	**100.00**	**40.39**	**100.00**
	3000	Concentrate	47.17	76.22	98.99	67.98	79.39
		Tailing	52.83	0.69	1.01	15.76	20.61
		Feed	**100.00**	**36.32**	**100.00**	**40.39**	**100.00**
	4000	Concentrate	47.30	76.76	99.97	68.37	80.07
		Tailing	52.70	0.02	0.03	15.28	19.93
		Feed	**100.00**	**36.32**	**100.00**	**40.39**	**100.00**
	5000	Concentrate	47.13	76.96	99.87	68.43	79.85
		Tailing	52.87	0.09	0.13	15.39	20.15
		Feed	**100.00**	**36.32**	**100.00**	**40.39**	**100.00**
	6000	Concentrate	47.33	76.40	99.56	68.24	79.97
		Tailing	52.67	0.30	0.44	15.36	20.03
		Feed	**100.00**	**36.32**	**100.00**	**40.39**	**100.00**

Table C.6 Results of the magnetic concentration for -75 μm

Particle Size (μm)	Magnetic Field (Gauss)	Products	Weight (%)	Fe_3O_4 (%)	Recovery of Fe_3O_4 (%)	Fe (%)	Recovery of Fe (%)
-75	400	Concentrate	1.37	78.80	3.02	68.44	2.35
		Tailing	98.63	35.10	96.98	39.50	97.65
		Feed	**100.00**	**35.70**	**100.00**	**39.90**	**100.00**
	1000	Concentrate	29.20	79.98	65.42	68.40	50.06
		Tailing	70.80	17.44	34.58	28.15	49.94
		Feed	**100.00**	**35.70**	**100.00**	**39.90**	**100.00**
	2000	Concentrate	42.97	79.88	96.15	68.40	73.66
		Tailing	57.03	2.41	3.85	18.43	26.34
		Feed	**100.00**	**35.70**	**100.00**	**39.90**	**100.00**
	3000	Concentrate	44.43	79.08	98.42	68.41	76.18
		Tailing	55.57	1.02	1.58	17.11	23.82
		Feed	**100.00**	**35.70**	**100.00**	**39.90**	**100.00**
	4000	Concentrate	45.00	79.06	99.66	68.42	77.17
		Tailing	55.00	0.22	0.34	16.57	22.83
		Feed	**100.00**	**35.70**	**100.00**	**39.90**	**100.00**
	5000	Concentrate	45.63	78.06	99.77	68.55	78.39
		Tailing	54.37	0.15	0.23	15.86	21.61
		Feed	**100.00**	**35.70**	**100.00**	**39.90**	**100.00**
	6000	Concentrate	45.30	78.72	99.89	68.48	77.75
		Tailing	54.70	0.07	0.11	16.23	22.25
		Feed	**100.00**	**35.70**	**100.00**	**39.90**	**100.00**