

**PROCESSING AND PELLETIZING OF LOW GRADE
MALAYSIAN IRON ORE**

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PROCESSING AND PELLETIZING OF LOW GRADE MALAYSIAN IRON ORE

by

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Dedicated To the Memory of My Father Mohammed Belhaj

And

To My Mother, Who Always Supports Me To Make My Dreams Come True...

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LIST OF ABBREVIATION

ASTM	American Standard Testing Method
BET	Brunauer, Emmett and Teller
CMC	Carboxy Methyl Cellulose
EDX	Energy Dispersive X-ray spectroscopy
FBB	Fly-ash Based Binder
ICCD	International Center Diffraction Data
rpm	Revolutions per Minute
SEM	Scanning Electron Microscopy
wt%	Weight percentage
XRD	X-ray Diffraction
XRF	X-ray Fluorescence
μm	Micrometer

LIST OF SYMBOLS

N	Newton force
P_{95}	95% confidence interval for the mean
s	Standard deviation
t_{95}	t-value for the 95% confidence interval
W_a	Weight of dry pellet
W_b	Weight of pellet soaked with and suspended in the immersion fluid
W_c	Weight of pellet soaked with immersion fluid and suspended in air
ρ	Density of immersion fluid
ρ_t	True density or powder density

PEMROSESAN DAN PEMPELETAN BIJIH BESI MALAYSIA BERGRED RENDAH

ABSTRAK

Kajian telah dilakukan ke atas bijih besi bergred rendah yang diperoleh daripada KSG Resources (M) Sdn. Bhd. Sungai Temau, Pahang, Malaysia. Tujuan kajian ini dijalankan adalah untuk mengkaji kemungkinan untuk menyingkirkan bendasing daripada bijih besi melalui kaedah graviti biasa dan pengkapsulan konsentrat sebelum ia boleh digunakan sebagai bahan suapan ke dalam relau bijih besi. Kajian permulaan pencirian mineral dijalankan bersama kaedah pemprosesan fizikal merangkumi faedah yang diperolehi daripada bijih besi, teknik pengkapsulan dengan menggunakan bahan pengikat yang berbeza dan ujian fizikal telah dicapai. Perbincangan mengenai kaedah ujian dan analisis terhadap kaedah eksperimen untuk menambah nilai bijih besi yang bergred rendah dan pengkapsulan bijih besi tersebut dinyatakan secara kasar. Oleh itu, keputusan ujian dinyatakan. Keputusan menunjukkan saiz liberasi bagi partikel bijih besi adalah pada $-212 \mu\text{m}$. Penggunaan meja ayun boleh meningkatkan nilai bijih besi daripada 85% Fe_2O_3 kepada kira-kira 98% Fe_2O_3 . Kajian terhadap dua partikel bijih besi ($-212 \mu\text{m}$ and $-45 \mu\text{m}$) dijalankan untuk pengkapsulan. Dua pengikat bukan organik iaitu bentonit dan lempung bebola manakala dua pengikat organik iaitu Peridur dan lateks beramonia tinggi telah dikaji dan kajian sifat-sifat fizikal terhadap kapsul yang dihasilkan diuji. Hasil keputusan menunjukkan kapsul yang terbaik diperoleh pada saiz partikel $-45 \mu\text{m}$ dengan menggunakan pengikat bentonit dengan 2.5% berat kecuali keporosan kurang daripada piawai industri. Untuk saiz partikel $-212 \mu\text{m}$, kandungan bentonit yang sesuai untuk menghasikan keputusan yang tinggi adalah pada 2.5% berat. Walau

bagaimanapun, kapsul ini mengandungi kekuatan mampatan basah, keporosan dan indeks lelasan yang rendah berbanding yang disyorkan oleh industri. Keputusan untuk lempung bebola adalah rendah daripada yang disyorkan oleh industri untuk kedua-dua saiz partikel (-45 and -212 μm). Peridur memberikan keputusan yang baik untuk kedua-dua saiz partikel dengan 0.1% berat Peridur kecuali untuk kekuatan basah dan indeks lelasan pada saiz partikel -212 μm . Keputusan optimum untuk kapsul yang mengandungi pengikat lateks pada saiz partikel -45 μm adalah 2.5% berat pengikat dengan kekuatan mampatan kering yang tinggi dan keputusan lain hamper dengan piawaian minimum. Keputusan untuk kapsul yang diperolehi daripada -212 μm menggunakan lateks sebagai pengikat memberikan keputusan yang sangat baik dengan kekuatan mampatan kering dan kekuatan mampatan bakar. Keputusan untuk ujian lain agak rendah berbanding keperluan industri. Walau bagaimanapun, keputusan untuk kapsul -45 μm menunjukkan lateks boleh digunakan sebagai pengikat berdasarkan keputusan yang diperolehi melebihi piawaian minimum atau boleh dipertimbangkan. Secara kesimpulannya, Peridur merupakan pengikat terbaik yang mampu memberikan kebaikan terhadap sifat-sifat fizikal dan mekanikal bagi kapsul tersebut. Keputusan menunjukkan saiz partikel -45 μm lebih baik berbanding saiz -212 μm .

PROCESSING AND PELLETIZING OF LOW GRADE MALAYSIAN IRON ORE

ABSTRACT

Low grade iron ore obtained from KSG Resources (M) Sdn. Bhd., Sungai Temau, Pahang, Malaysia, have been studied. The purpose of this study was to investigate the feasibility of removing impurities from iron ore by simple gravity method, and the pelletization of the concentrate before it can be used as a feed material to the iron furnaces. Preliminary minerals characterisation studies together with physical processing method involved in iron ore beneficiation, pelletization techniques with different binders and physical and mechanical testing have been reviewed. The experimental procedures for upgrading the low grade iron ore and pelletizing of the iron ore are outlined and the analytical and testing methods are discussed. The result of the tests is presented. The results obtained show that the liberation size of the iron ore particles is at $-212\ \mu\text{m}$. Concentration of low grade iron ore using Mozley table can upgrade iron ore from 85% Fe_2O_3 to around 98% Fe_2O_3 . Two sizes of iron ore particles ($-212\ \mu\text{m}$ and $-45\ \mu\text{m}$) were studied for pelletization. Two inorganic binders, bentonite and ball clay and two organic binders, Peridur and high ammonia latex were studied and the physical and mechanical properties of the pellets produced were tested. The results point out the improved results of pellets for particle size $-45\ \mu\text{m}$ with bentonite binder was obtained by 2.5 wt% except the porosity was less than minimum standard proposed by the industry (20%). For particle size $-212\ \mu\text{m}$ the suitable amount of bentonite which gave optimum result was 2.5 wt%, even though these pellets had wet compressive strength, porosity and abrasion index lower than industrial proposed. For ball clay all the results were less than industrial standards for

both particle sizes (-45 μm and -212 μm). Peridur provided improved results for both particle sizes with 0.1 wt% peridur except wet strength and abrasion index for particle size -212 μm . The optimum result of pellets with latex binder for particle size -45 μm was at 2.5 wt% binder, which had high dry compressive strength and the others near to the minimum standard (22 N). Result for pellets made of -212 μm using latex as a binder give a very good result for dry compressive strength and fired compressive strength. Results for other tests were slightly lower than industries needs. However, result for pellets -45 μm shows that latex can work as a binder due to the results obtained up to the minimum standard or can be tolerated. It was concluded that, the Peridur was the suitable binder to give good physical and mechanical properties of pellets. These results were better for particle size -45 μm than particle size -212 μm .

CHAPTER 1

INTRODUCTION

1.1 Introduction

Iron is the most abundant element in the earth with about 37 weight percent. The majority of this is in the core. In the Earth crust iron is one of the top four elements with 4.6 weight percent, after oxygen, silicon and aluminum. It can be found in the native state in meteoritic masses. It is usually associated with nickel and cobalt. Native iron can also be found in the remains of eruptive rocks. Most of the iron in the crust is found combined with oxygen as iron oxide minerals such as hematite (Fe_2O_3) and magnetite (Fe_3O_4), sometimes a hydrated oxide such as goethite ($\text{FeO}(\text{OH})$) and limonite ($\text{FeO}(\text{OH})\cdot n\text{H}_2\text{O}$), beside that it also occurs as carbonate such as siderite (FeCO_3), sulphide such as pyrite (FeS_2) and as a component of a wide range of complex minerals. Other than that, iron forms red coloring matter of nature and is found in the remains of most plant and animals (Hussain, 1985, Marsden, 1990).

1.2 Geological Aspects of Iron Ore

Iron ores are found in many geological systems, actually are associated with most of the main geological ages. In Scandinavia rich ore deposit are associated with the Pre-Cambrian rocks. The same yields rich field in Canada and United States, especially around the shores of Lake Superior. The Silurian rocks of America contain bedded iron stone of the Clinton series, which are of great economic value. The Carboniferous system provided blackband and argillaceous carbonates. The Devonian or Old Red Sandstone strata yield local beds of considerable economic

importance. As indicated in the Table 1.1 (Ball et al., 1973). It can be seen that, the important deposits are associated with rocks of the oldest period, the pre-Cambrian.

Table1.1: The ore deposits associated with the main geological ages, after Ball et al. (1973)

Geological period	Deposit	Location
Tertiary Pliocene	Kerch oolitic-lionite	Crimea, Russia
Mesozoic Cretaceous	Salzgitter limestone and hematite	Germany
Jurassic	Minette ores	Western Europe
Paleozoic Carboniferous	Black band ironstones	United kingdom
Devonian	Siegerland siderite	Germany
Silurian	Clinton hematite	Alabama, U.S.A.
Ordovician	Wabana ores	Newfoundland
Pre-Cambrian	Brazilian hematites	Brazil
	Krivio Rog	Russia
	Bihar and Orissa	India
	Lake Superior ores	U.S.A
	Cerro Bolivar hematite	Venezuela
	Kiruna magnetites	Sweden

1.3 Evaluation of Iron Ore

Evaluation of the property of iron ore to determine its value or profitability is often made by a team effort involving geologists, engineers, process metallurgists, and economists. According to Bashforth (1973) and Wolf (1984) the value of an iron ore depends on many factors and several authorities have endeavored to advance

simple formula for the evaluation of iron ore. These factors can be summarized under four headings:

I- The richness or the percentage of metallic iron ore which the ore contains. Frequently this percentage is expressed in term of units, whereby an ore containing 60% Fe ore is said to contain 60 units of iron. Ore must meet the chemical and physical requirements specific to the ironmaking.

II- The location of an ore both geologically and geographically is a very important factor. A rich ore may be of little or no value if its geographical position makes it inaccessible or if its geological aspect complicates mining.

III- The composition of the gangue associated with an ore may reduce the value of a rich ore. The nature of gangue must be considered under three heading:

(a) Those substances, such as alumina, and the alkalis, should not enter into the blast furnace under any condition. The presence of alumina may produce slag difficulties, whilst the alkalis attack the furnace lining and the presence of lime reduces the iron content.

(b) Those substances which partially enter the pig iron, such as silicon, and sulphur. The amounts of these elements which enter the pig iron depend on the manner in which the furnace is burdened and operated.

(c) The whole of the phosphorus present in the ore passes into the pig iron.

VI- The treatment and preparation which the ore required to make it satisfactory for the blast furnace has a very important bearing on its value. Dense ores may require crushing or breaking up to render them more porous or to screenings from high quality lump, and the ore which contains a great deal of gangue minerals, particularly silicates, must be ground into a fine particle size that is not suitable for use in ironmaking and thus the ore must be agglomerated into large particles before it can

be used. One of the most common agglomeration techniques is pelletization, which requires a small amount of binder to be added to the powdered ore to control balling rates and hold the pellets particles together until they are hardened by sintering.

Pelletizing is a size enlargement technique employed to process fine-grained iron-bearing concentrates and powder ores. Mechanical strength of fired (at 1200-1400 °C) pellets is important for handling. When the pellets undergo metallurgical processing, their mechanical strength is a measure of their resistance to degradation by breakage due to impacts and abrasion to which they are exposed in the upper part of the blast furnace.

1.4 Problem Statement

The majority of iron ore deposits found in the world were not very high grade due to the presence of other minerals mainly silica. Therefore, the ores must be ground to a fine particle size to allow the iron oxides they can contain to be concentrated or the removal of impurities can be done promisingly. As the blast furnace can only accept particle at certain size thus, the concentrate (fine particle) must be re-agglomerated into large enough particles, so that they can be smelted in the blast furnace.

One of the agglomeration techniques is pelletization, which requires the use of binder to hold the iron oxide particles together so that the agglomerated particles can be sintered into high-strength pellets. Beside bentonite clay which is the most commonly binder, there are many other possibilities that could be competitive in a number of situations (Eisele and Kawatra, 2003).

The main objectives of this work are;

- To investigate the concentration method suitable for low grade iron ore deposit from Sungai Temau, Pahang, Malaysia.
- To investigate the performance of various types of binders that can be used to pelletize the iron ore.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

Technically and economically, iron is the most important metal of mankind. It has been known since about 4000 BC. The first utilization of iron dates back to about 2800 BC, but iron was not important before about 1350 BC when precursors to the modern steel started to replace bronze in the Middle East (Wolf, 1984; Hussain, 1985; Gregory, 2001).

Iron metal is relatively soft and is therefore not suitable for weapons and tools, but iron / carbon alloys are twice as hard as bronze. The knowledge about the use of iron alloys spread quickly and iron was adopted in Italy and Greece around 1000 BC as the dominating raw material for production of tools and weapons. Iron based tools made it possible to increase productivity, especially in agriculture and has later only increased its importance. However, its use only became widespread in the 14th century, when smelting furnaces (the forerunner of blast furnaces) began to replace forges.

Actually ,the iron ore was made feasible through the development of three processing; “steeling” the addition of carbon to ore; “quenching “ the sudden cooling of hot metal; and “tempering “ the reheating of quenched metal to correct for brittles. Iron rarely occurs in nature as the native metal except in meteorites. The pure metal is silvery white, very ductile, strongly magnetic and melts at 1528 °C. It accounts for almost 95% of all metals used by modern industrial society.

Iron ores are rocks and minerals from which metallic iron can be extracted. It is found in varying amount in ore deposits where it occurs chiefly as the oxides, Fe_2O_3 (hematite) and Fe_3O_4 (magnetite), the sulphide, FeS_2 , the carbonate, FeCO_3 , as silicates and as many other minerals of lesser importance. Hematite is also known as "natural ore". The name refers to the early years of mining, when certain hematite ores contained 66% iron and could be fed directly into ironmaking blast furnaces. Direct ores of magnetite are relatively unimportant and are less easily reducible than hematite ores. Iron ore must be reduced by removing its oxygen to make pig iron, which is one of the main raw materials to make steel (Hussain, 1985 and Marsden, 1990).

Most blast furnaces now demand ores with definite structure and chemical specification that make crushing and screening essential. Many furnaces now specify ores of high chemical quality at more than 62% Fe which must at least be sized at about 6.35 cm as the top size, and such ore should contain a minimum of -0.95 cm fines. With high-grade ores it is only necessary for the ore to be reduced in size and graded before it is used in the steel plant. At the mine the ore is crushed to a maximum size in the region of 10-20 cm; further crushing and screening to give appropriately sized ore is carried out either at the mine, the export terminal, or at the steel plant which has taken particles ore within the size- range -3.81 cm +0.635 cm; larger particles are slow to reduce. With low-grade ores, the iron content must, where possible, be up-graded by gangue removal. This necessitates grinding to such a size that the iron-bearing mineral and the gangue are present in separate grains. Grinding is followed by mineral processing processes which separate iron-rich from the iron-deficient grains. Certain low-grade complex ores are not amenable to be concentrated

by mineral processing. These are normally crushed to -9 mm or -6 mm fine iron ore was then agglomerated into large particles because the fine ores decreases burden permeability or is blown out of the furnace as flue dust.

2.1 Iron Ore in A global Perspective

The world production of iron ore has increased from about 95 Mt in 1904 to 1,900 Mt in 2006 (U.S. Geological Survey, 2008 a). In 2007 China was the largest producer with 600 Mt. Brazil is the second largest and the largest exporter. Other major iron ore producing countries are Australia, India, Russia, Ukraine, and USA as showing in Appendix A. The world resources are estimated to exceed more than 800 billion tonnes of crude ore with more than 230 billion tonnes of iron (U.S. Geological Survey, 2008 b). Iron ore prices are therefore controlled by what the iron ore producing companies can supply compared to what the steel making companies demand and what these companies are willing to pay. In 2003 the iron ore prices increased with about 9%, while industry analysts expected a 2 to 3% increase. Due to China's high level of steel consumption, the price increase has continued and the high demand is now pushing the prices due to a supply-demand unbalance (AME, 2004). Beside that AME 2004 also expects that total Asian iron ore consumption will grow from 655 Mt in 2003 to more than one billion tonnes by 2010, providing the primary boost for global iron ore trade.

2.3 Origin of Iron Ores

Ball et al. (1973) discussed that there are two basic processes of the mechanisms of iron ores concentrated in the present deposits. The processes involved are chemical and physical, and mechanical processes.

2.3.1 Chemical and Physical Processes

In the process of crystallization from a silicate solution, the heavier iron-bearing minerals tend to segregate due to gravity or to more involved geology processes. Thus the final rock mass contains areas which are richer in iron than others. When surface water descends or when underground water ascends through rock strata, iron-bearing minerals may be deposited or gangue minerals may be leached out, in particular silica. In either case, iron enrichment takes place. Iron-bearing minerals can also be concentrated by precipitation from lakes, rivers, and seas due to chemical or bacteriology action. The iron minerals may be accompanied by other mineral deposits and then iron-rich sandstone, limestone, and other rocks are formed (Edwards and Atkinson, 1986; Dennen, 1989; Robb, 2005).

2.3.2 Mechanical Process

Weathering may break down the rocks into small particles, some of which are rich in iron. These particles were carried away by the water of the rivers or seas and later redeposited. The higher specific gravity of the iron-bearing minerals causes them to be deposited sooner than other lighter materials. This method of formation was responsible for the laying down of certain sedimentary hematite deposits and the magnetite beach sands (Edwards and Atkinson, 1986; Dennen, 1989).

2.4 Classification of Iron Ores

Bashforth (1973) stated that, a deposit of iron ore can be defined as a mineral body with sufficient size, iron content, chemical composition, physical and economic characteristic that will allow it to be a source of iron either immediately or

potentially. No definite limits can be set on the size, grade, or mineral composition. There are numerous methods of classifying iron ores that have been suggested. One method is by their appearance as shown in Table 2.1.

Table 2.1: Mineral and their appearances, after Bashforth (1973)

Mineral	Appearance
Magnetite	Black ores
Hematite	Red ores
Limonite	Brown ores
Carbonates	Carbonates ores

Iron ore deposits can also be classified according to their mode of origin as stated by Bashforth (1973); Hendrickson and Sandoval (1980); and Marsden (1990).

Lake Superior type

This is the large and most important group of ores which all resemble the ores of the Lake Superior region in the United States of America. The original, sedimentary mother-rock typically consists of alternative bands of iron oxide and silica. This type of ore is also known by different names in the world.

Minette type

These ores were precipitated from shallow waters and the iron ore salt crystallized around granules, often of foreign matter, to produce the egg-shaped “ooliths” of which they are composed.

Laterite type

This type of ore is formed by the decomposition of basic igneous rocks under tropical conditions. With alternating wet and dry seasons silica and alkalis were leached out, leaving mainly iron oxide and alumina, any chromium, nickel and cobalt in the parent rock also can be found in this ore.

Kiruna type

This type of ore is derived from igneous material of volcanic origin and consists mainly of magnetite.

Magnitnaya type

This, like the Kiruna type, was derived from igneous material, but gases and hydrothermal solutions may have played an important role in modifying the nature of the ore deposit. These ores are mainly magnetites.

Bilbao type

These ores are replacements of limestone. Circulating water has removed limestone, usually depositing iron carbonate in its place. Subsequent surface weathering has oxidized part of the iron carbonate to oxide or hydrated oxide. These types of ore may be classified according to the gangue with which they are associated, thus:

- i. Siliceous ores, in which the gangue is predominantly silica; such ores are found in Cumberland, North Lancaster and in many parts in Spain.
- ii. Calcareous Ores, where the gangue is limey in nature, such as the Campanil and some of the Lincolnshire ores.

- iii. Aluminous Ores, whose gangue consist largely of alumina, such as the Belfast ores.
- iv. Bituminous Ores, which contain a large amount of bituminous or coaly material, such as the Blackband Ironstone.
- v. Argillaceous Ores, in which the gangue is composed chiefly of clayey matter, such as the Clay and Ironstone.

2.5 Nature of Iron Ore

Iron ore can only be considered to be an iron ore if the total cost of extracting iron from it is comparable with the cost of extracting iron from other ores. This will be governed by the many factors, of which the iron content of the mineral, the nature of the impurities and the location of the deposit are of particular importance.

The more economically important iron ores are the following (Hussain, 1985).

2.5.1 Hematite

Hematite is widely distributed and is the most important source of iron. When pure, it contains 70% of iron. Much of the hematite mined is high grade, with 64-68% iron and only small quantities of impurity, mainly silica and alumina. Sulphur and phosphorus contents if any are normally very low. There are also very large deposits of low grade hematite containing only 20-40 % iron with high silica contents, some of which are now being mined. Much of the silica is removed by mineral processing and the product obtained can contains 60-69 % of iron (Hussain, 1985; Podolosky and Keller, 1994).

2.5.2 Magnetite

Deposits of high grade magnetites occur in a number of places in the world. Pure magnetite contains 72.4% iron, whereas the high grade ore normally contains more than 60% iron with some impurities such as silica, phosphorus and apatite, as a common impurity (El Habaak, 2004). Low grade magnetite deposits are also worked in many places, and a product is obtained after mineral processing which has iron content in excess of 60% (Hussain, 1985; Podolosky and Keller, 1994).

2.5.3 Limonite, Goethite, Hydrogoethite

These are all hydrated iron oxides containing up to 60-63% iron. They can occur as primary minerals and always formed relatively near to the surface as a result of weathering of the exposed ore (Hussain, 1985).

2.5.4 Siderite

This mineral constitutes only a small proportion of the total world iron ore reserves. When pure, it contains 48.3% iron, but it is easily decomposed by heat (calcined) to hematite with 70% iron, siderite is still a commercially important source of ore in some countries (Hussain, 1985).

2.5.5 Chamosite

This mineral occurs, together with limonite and siderite, in the relatively low grade. This ore usually contains some sulphur and phosphorus and other minerals such as quartz and calcite (Ball et al., 1973; Podolosky and Keller, 1994).

2.6 Impurities

All iron ores contain impurities, which are collectively known as gangue. The complex mineral chamosite can be regarded as a mixture of iron oxide (FeO) and gangue (SiO₂ and Al₂O₃). These impurities may be divided into two categories as indicated by Ball et al. (1973).

2.6.1 Slag Forming

These are four main oxides namely silica and alumina which are acidic and lime and magnesia which are basic. Of these oxides, only SiO₂ can be reduced during ironmaking and usually only to a very limited extent. In conventional ironmaking by the blast furnace process, a liquid slag is formed in which the slag is formed in which the ratio by weight of bases (CaO + MgO) to acids (SiO₂ + Al₂O₃), called the basicity. Most ores have an excess of SiO₂ and Al₂O₃ and the ash of the coke used for fuel is mainly composed of these oxides, so a basic flux, e.g. limestone must be added (Bashforth, 1973; Bennett, 1985). As Man-sheng et al. (2007) stated that the low content of SiO₂, Al₂O₃ and of FeO and high porosity, affect the production of high-reducibility in blast furnace.

2.6.2 Metallic Oxides

Metallic oxides which are largely reduced to metal during ironmaking. Manganese oxides are the most common, other of chromium and nickel. Some metal oxides, e.g. nickel, are more easily reduce than iron oxide, while others, such as manganese and chromium, are less easily reduced so that only a proportion of them go to the metal, the reminder going, as oxide, to the slag. A manganese content of

around 1% in the metal is advantageous but small proportions of other metal such as zinc are undesirable. The large deposits of lateritic ores, which consist predominantly of hydrated oxides, contain appreciable quantities of chromium, nickel, and cobalt (Ball et al., 1973 and Bennett, 1985).

2.7 Deleterious Impurities

Both sulphur and phosphorus impart undesirable properties to steel and must be kept below certain maximum levels. Sulphur can be reduced to the desired level during ironmaking but an increased sulphur intake increases the cost of ironmaking. Normally most of the sulphur enters the ironmaking processes from the coke used as fuel, but some ores have relatively high sulphur content. These can be given some pretreatment to reduce the sulphur level; when iron is extracted from pyrite or pyrrhotite the sulphur is first removed by roasting, the ore being converted to an oxide. Phosphorus cannot be removed during ironmaking but this can, if necessary, be done when the iron is refined to steel. However, the most economic modern steelmaking process, basic oxygen steelmaking, can only be used if the phosphorus content of the iron is low. This means that low phosphorus ores, with a phosphorus/iron weight ratio of 0.002 or less, are preferred (Bennett, 1985).

2.8 Ore Preparation and Concentration Methods

Marsden (1990) mentioned that the iron ore mining methods vary by the type of ore being mined. There are four main types of iron ore deposits worked currently, depending on the mineralogy and geology of the ore deposits. These are magnetite, titanomagnetite, massive hematite and pisolitic ironstone deposits.

2.8.1 Iron Ore Mining

According to U.S geological survey (2008a) iron ore mining is carried out on a very large scale. A modern mine can produce ten million tons or more of ore per year, almost all iron ore (98%) mined is used in steelmaking, specifically, as a feed to the blast furnace. Mining commences as an open cast operation which may eventually change to underground mining if the ore body dips steeply. Most of the newer mines, for both high and low grade ore, are open cast and are likely to remain so as very large reserves are available close to the surface. Large tonnages of ore are mined underground; however, underground mining is normally more expensive than open-pit working, as the development costs are higher and labor productivity is lower. However, if the scale of the operation is large and other circumstances are favorable, ore mined underground can be competitive with ore mined by open-pit working.

2.8.1.1 Open Pit Mining

Open pit mining is the process of mining any near-surface deposit by means of a surface pit excavated using one or more horizontal benches. Both the overburden (if present) ,which has low ore content ,and the ore are typically removed in benches that vary from 9 m to 30 m in height (9 m to 15 m for iron ore). A thick deposit requires many benches and may resemble an inverted cone, with the higher benches being larger than the lower benches. The individual benches are designed to accommodate the materials-handling equipment utilized. The reach of the excavator equipment limits the high of the bench. The width of bench must be sufficient to contain most of the fly rock from a bench blast (18 m to 30 m for iron ore). The broken ore, which is shattered by explosive charged set in the holes, which are

drilled behind the face of bench, is loaded into dumper trucks or any transporting methods to carry the ore (Dennen, 1989; Hartman and Mutmanky, 2002).

2.8.1.2 Underground Mining

Iron ore is mined underground by methods similar to those used for other metals, but generally on a far large scale. In vertical ore bodies, access is achieved by sinking shafts or inclined roadway in the adjacent barren rock. These roadways are connected to the ore body by a series of cross-cuts carrying longitudinal drifts. This network serves to collect the ore and deliver it to the hoisting shaft. Between each drift, sub-levels are driven, spaced usually around 9 m. These sub-level carry the stopes from which the ore is won. The precise method of extracting the ore depends on the angle of dip of the body, its width, the strength of the surrounding rocks, and regularity of the ore.

The ore is recovered by mechanical methods and dropped by chutes to the main haulage level, where it is collected into railway cars or trucks and dropped down into bins situated at the bottom haulage level. These bins usually feed a series of underground crusher and the ore is reduced in sized to 100-150 mm before being hoisted up to the surface (Dennen ,1989; Hartman and Mutmanky, 2002).

2.8.2 Iron Ore Processing

Ball et al. (1973) stated that, the ore loaded at the mine face is in the form of lumps whose maximum size can be up to 1.0-1.25 m with high grade ores it is only necessary for the ore to be reduced in size and graded before it is used in the ironmaking. At the mine the ore is crushed to a maximum size in the region 100-200

mm; further crushing and screening to give appropriately sized ore is carried out either at the mine, the export terminal, on receipt at the import terminal, or at the ironmaking, before shipment to the steel works, the fine material may be further treated to give a sized product, such as pellets.

The product shipped to the consumer should have as uniform a composition as possible. At times it may come not only from different faces of the same mine but from different mines in the same locality. In order to minimize variation in composition, the ore may be blended. With low grade ores, the iron ore content must, where possible, be up graded by gangue removal. This necessitates grinding to such a size that the iron bearing mineral and the gangue are present in separate grains. Grinding is followed by mineral processing steps which separate the iron rich from the iron deficient iron grains. Certain low grade complex ores are not amenable to concentration by mineral processing. These are normally crushed to -9 or -6 mm and then sintered.

2.8.2.1 Crushing and grinding (comminution)

The 1.0-1.25 m lumps excavated at the mine must be reduced to a maximum size of the order of 25-37 mm for rich ores and to a size which may be as small as 45 μm for certain low grade ores, to enable high grade concentrate to be obtained. The first stage of crushing produces a material which is predominately in the size range 150-250 mm. Both gyratory and jaw crushers can be used as primary crusher. Most open pits now usually prefer gyratories because trucks can dump into the crusher from several sides, rather than from one side only onto the pan feeder required for a jaw crusher.

The second stage of crushing, which is usually carried out using cone or gyratory crusher, may be carried out in a single operation if the aim is to produce material in the size range 27-55 mm. If the ore must be ground fine for concentration, this is usually done by rod or ball mills or combination of both down to approximately 10-25 mm. Rod mills grind the larger particles preferentially and so produce a smaller proportion of very fine particles, followed by an initial concentration, after which further grinding in ball mill is carried out.

As Denne (1989) stated that an alternative method that has come into increasing use in the recent years is the substitution of autogenous mills. This change has come about because the flow sheet is simpler, one machine can take the place of several units, less labor is required and there may be substantial saving in iron ore wear. However, it is not suited for grinding all types of iron ore.

2.8.2.2 Concentration

Until now most of the world's iron ore was simply dug, sometimes crushed, and then shipped. Most blast furnaces now demand ores with definite structure and chemical specification that make crushing and screening essential. Many furnaces specify ores of high chemical quality which must at least be sized. Most furnaces specify the top size at about 38.1 mm and such ore should contain a minimum of -9.5 mm. These fines may be pelletized at the mine, or, if shipped to the furnace sintered or pelletized there.

A low grade ore need to be crushed to a liberation size, therefore iron ore can be separated from gangue minerals with appropriate processing method. There are

many methods normally used to separate iron oxide from gangue minerals such as, gravity method, magnetic separator, reduction roasting and followed by magnetic separator, floatation and electrostatic. In addition to these methods, some degree of concentration can be achieved by washing (Devaney, 1985a). Olubambi and Potgieter (2005) mentioned that the concentration of the valuable minerals from the gangue involves exploitation of the differences in the mineral properties of the ore after effective comminution.

a) Washing

Sometimes ores can be enriched by the simple process of washing such ores that consist of coarse and fine particles of clean ore minerals mixed with either barren sand or clay. In general, clay minerals increase the alumina in iron ore which is easily reduced by washing. Separation of clay minerals consists of a simple scrubbing operation in a log-washer or classifier followed by a screening operation to remove the coarser iron particles, whereas the overflow usually is the waste product (Narayanan, 1964; Ball et al., 1973; Devaney1985a).

b) Gravity Separation

The common iron oxides are usually sufficiently heavy so that they can be separated, if they are structurally free from the lighter waste minerals with minimum metal loss in tailing, by machine that utilized these specific gravity differences. The common iron ore minerals and gangue minerals are as shown in Table 2.2.

For coarse particles 6-40 mm, heavy media separation using a ferrosilicon suspension in a rotary drum are most commonly used or magnetite in water with a density between that of the iron oxides and the gangue.

Table 2.2: Iron ore minerals and gangue mineral

Iron ore minerals	Specific gravity	Gangue minerals	Specific gravity
Hematite	5.1	Quartz or Chert	2.65
Magnetite	5.17	Calcite or Limestone	2.75
Goethite	4.2		
Siderite	3.85		

Jigging is one of the oldest methods of gravity concentration in which its feed is kept in motion by water pulsing vertically through it. The heavier grains move downwards to the bottom of the bed and are removed. Since the weight of the grain is governed by its size as well as its specific gravity, it is necessary for the feed to be sized within close limits. Many kinds of jig are in existing according to the size and the nature of the ore. The output of an individual jig is low (Alderman, 2002).

The feed moves over inclined, shaking table washed with a cross-stream of water. This method now is little used for iron ore concentration. The capital and operating costs are high and the output of individual tables is small. For fine ore 1.0-1.5 mm, Humphreys spirals are now largely used and have taken the place of the shaking tables, because of have relatively high capacity and also low maintenance requirements. This method is becoming widely used in the treatment of hematite

ores. The ore is washed down a spiral launder with a curved bottom. The heavier concentrate moves to the bottom of the curved track whilst the lighter tailings climb toward the outer rim (Slyke, 1985 and Alderman, 2002).

c) Magnetic separation

Magnetic separators exploit the difference in magnetic properties between the ore minerals and are used to separate magnetic mineral (magnetite), in some application hematite, from non-magnetic gangue such as quartz. Magnetic separators can be classified into low- and high-intensity machines, which may be further classified into dry-feed and wet-feed separators (Norrgran and Mankosa, 2002).

When the mineral is magnetite, low- intensity (500-1200 oersteds) separation is normally practiced because it is very cheap and effective. If the particles are of comparatively large size, greater than 6 mm, dry magnetic separations are used. When the particles are less than 100 μm wet magnetic separation is used. If the size of the ore is intermediate, it is possible to use either method. High-intensity (1200-22000 oersteds) separators can be used to separate weakly magnetic materials, such as hematite and hydrated hematite, from gangue materials. This process is suitable for use with dry ores. Wet high-intensity magnetic separation has its greatest use in the concentration of low grade iron ores containing hematite, which frequently replaces flotation methods, although the trend towards magnetic separation has been slow in the North America, mainly due to the very high capital cost of such separators (Hernlund and McDermott, 1985).

d) Froth Flotation

Froth floatation is a selective process and can be used to achieve specific separation from complex ores. This process utilizes the differences in physico-chemical surface properties of particles of various minerals. After treatment with reagents, such differences in surface properties between the minerals within the floatation pulp become apparent and, for floatation to take place, an air-bubble must be able to attach itself to a particle, and lift it to the water surface. Froth floatation can be used effectively to separate general type of iron ore to upgrade certain types of iron ore concentrates. For floatation to take place, the particles should be at least 250 μm . In order to float iron ore, anionic floatation by using fatty acids or petroleum sulfonates as collector can be applied to float fine iron oxides, such as magnetite, hematite, or siderite; away from waste minerals such as quartz or chert. Cationic floatation may be used to upgrade fine concentrate by floating the gangue minerals away from the iron minerals. However, the efficiency of froth floatation process decreases when slime is apparent (Kelly and Spottiswood, 1989; Lindroos and Keranen, 1985).

Yang et al. (2003) found that the magnetic separation and flotation are the most widely accepted technologies for the concentrating of iron ore particles. However, these processes result in iron concentrate with high amounts of very fine and/or interlocked silica particles.

e) Electrostatic separation

This method of separation is limited to relatively few iron ores. The major process makes use of the differences in electrical conductivity between iron oxides

and gangue minerals. It works best on crystalline, nonmagnetic iron oxides finer than about 1.7 mm and coarser than 75 μm . The minerals surfaces should be free from slime or dust coating (Devaney, 1985a).

2.9 Fine Iron Ore

Fine ores, which are usually occurred or produced from concentration methods used, are to be agglomerated before it can be fed into blast furnace. Fine iron ores are not suitable as feed to the blast furnace, both because fines tend to pack into a nonpermeable bed and because the fine particles are likely to be carried away as dust by the high gas flow rates. The powders are must therefore be agglomerated into larger particles that will be improve permeability of the furnace burden, increase the rate reduction, and reduce the amount of material blown out of the furnace as dust.

2.9.1 Agglomeration Technique

This term is used to describe processes whose goal is to form balls, briquettes, nodules, sinter, and pelletizing or other sized and shaped particles from loose, usually fine, incoherent particles. Fine sized ore concentrates are usually pelletized to give the industry a chemically controlled, closely sized product that increases the production rate and reduces the cost considerably. Because of their fine size they could not be sintered efficiently, nodulizing was not attractive because of high fuel requirement and briquetting more expensive than other agglomeration processes due to wear of briquetting surfaces and the energy required to compress.