UPGRADING OF WASAGU (KEBBI STATE) MANGANESE ORE TO METALLURGICAL GRADE CONCENTRATE

BY

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DECLARATION

I, declare that the work in this thesis entitled 'Upgrading of Wasagu Manganese Ore to Metallurgical grade Concentrate', has been performed by me in the Department of Metallurgical and Materials Engineering under the supervision of Prof .S.A. Yaro and Dr. D.G Thomas. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this thesis was previously presented for another degree or diploma at any university.

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CERTIFICATION

This thesis entitled 'UPGRADING OF WASAGU MANGANESE ORE TO METALLURGICAL GRADE CONCENTRATE' by Binta Hassan meets the regulations governing the award of Master of Science Degree of the Ahmadu Bello University, Zaria and is approved for its contribution to knowledge and literary presentation.

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DEDICATION

This project is dedicated to my late daughter Aisha Idris, whom I lost during the course of this pursuit and to my late friend Zulaihat Buhari. May your gentle souls rest in peace.

ACKNOWLEDGEMENT

All praise be to Allah who has spared my life to complete this work successfully. A thesis of this nature would not have been completed successfully without the assistance and co-operation of so many people. To all of them, I am grateful.

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ABSTRACT

In this work, the possibility of upgrading a locally available low grade Manganese Ore was attempted. The low grade ore deposit is located in Wasagu/Danko Local Government Area of Kebbi State, North Western Nigeria. The work involved chemical and mineralogical characterization of the ore and separation tests using gravity and magnetic Separation Techniques, while the work index of the ore was determined using the Berry and Bruce method. Results of chemical analysis using X-ray fluorescence spectrometer (XRF) revealed that the manganese ore contains 38.67%Mn on the average. Mineralogical characteristics of the ore determined using the X-ray diffraction (XRD) and Scanning Electron Microscope (SEM) revealed that the ore is predominantly spessartite with quartz and hematite as minor minerals while others are in trace amounts. Upgrading the ore using shaking table gave a concentrate of 48.89%Mn, Spiral concentrator gave a concentrate of 49.34%Mn and the Magnetic separation gave a concentrate of 52.63%Mn while their corresponding recoveries are 97.60%, 99.10% and 77.78% respectively. The results obtained from these tests showed that magnetic separation gave a better grade of the concentrate compared to the gravity concentration techniques. The grade of 52.63%Mn obtained using magnetic separation method compared favorably with 52.5%Mn required for production of ferromanganese.

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NOTATIONS

EDS	-	Energy Dispersion Spectrometer
FESEM	-	Field Emission Scanning Electron Microscope
Mn	-	Manganese
NMDC	-	National Metallurgical Development Centre
Km	-	Kilometer
Kg	-	Kilogram
Cm^3	-	Centimetre cube
Cm	-	Centimetre
µm	-	Micron (10^{-3})
SEM	-	Scanning Electron Microscope
XRF	-	X-ray Fluorescence Spectrometer
XRD	-	X-ray Diffraction
%	-	Percentage
Al_2O_3	-	Aluminium Oxide
Cao	-	Calcium Oxide
SiO_2	-	Silicon Oxide
P_2O_5	-	Phosophorous Pentoxide
Fe_2O_3	-	Iron Oxide
TiO_2	-	Titanium Oxide
M	-	Mass
V	-	Volume
N.D	-	Not Detected
BaO	-	Barium Oxide

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Manganese is a silvery grey metal that resembles iron. It is hard and brittle, very difficult to fuse but easy to oxidize. Manganese metal and it ions are paramagnetic, its specific gravity lies between 7.13 and 8, atomic weight 54.6, melting point 1230^{o}C and boiling point 1900^{o}C. Manganese belongs to group seven in the periodic chart of elements. (Wikipedia, 2010) .

Properties of some important manganese bearing minerals are presented in Table 1

The term manganese ore is used to describe ores assaying more than 35%Mn. While ores containing 10-35%Mn are termed Ferruginous manganese ores, and those containing less than 10% Mn are known as manganiferrous ores (Gupta, 2006)

Manganese ores are the source of Manganese metals, that are used in the Ferro alloy industry, in steel making for de-oxidation and desulphurization. Steels containing them in appreciable amounts, have improved hardenability, hardness, tensile strength, high temperature applicability amongst others and therefore, have greater importance from the industrial point of view. The use of Manganese in dyes, paints, battery cells, glass and textiles industries is also of great importance. Other important applications are in the production of Aluminium and cast iron. The metallurgical industries, account for over 95% of total usage. It is for this reason that manganese is listed amongst the strategic materials by most countries (Jones, 2000).

Table 1.1: Properties of Some Important Manganese Minerals

Mineral	C/Formula	Colour	Mn (%)	Hardness	Specific gravity
Pyrolusite	MnO_2	Steel Grey To Black	63.2	6-7	5
Ramdellite	MnO	Dark Grey To Black	63	3	4.7
Pollianite	Mn_2O_3	Black to Steel grey	N.A	6-6.5	5
Manganite	$Mn_2O_3H_2O$	Black to steel grey	62	4	4.3
Cryptomelane	KMn_8O_{16}	Black to steel grey	45-60	5-6	4.3
Psilomelane	$BaMn_9O_{16}2H_{2O}$	Black to dark grey	N.A	5-6	4.4-4.7
Hausmanite	Mn_3O4	Brown to black	72	4.8	4.7-5
Braunite	$3Mn_2O_3$ $AlMn(siO_3)$	Brown to black	50-60	6.0-6.5	4.7-4.9
Bixbyite	$(Mn,Fe)_2O_3$	Black	30-40	6	5
Jacobsite	$MnFe_2O_4$	Black	24	6	4.6
Hollandite	$BaMn_8O_{16}$	Black to steel grey	N.A	6	4.5-5.0
coronadite	PbM_8O_{16}	Black to	N.A	5.2-5.6	4.5-5.0
Rhodoschrosite	$MnCO_3$	steel grey. Red-rose to brown	48	3.5-4.5	3.3-3.6
Rhodonite	$MnSiO_3$	pink	42	5.5-6.5	3.4-3.6
Alabandite	MnS	Iron- black	N.A	3.5-4	3.95
Spessartite	$3Mns.Al_2O_3$	Brownish-red	33.3	4.1-4.3	7.0-7.5

Source: (Inerson, 2000). An introduction to practical Ore Microscopy

Most of the Nigeria's manganese bearing minerals deposits are found in the schist belts in the basement complex. The schist belts include: Birin Gwari in Kaduna State, Kushaka, Igarra, Maru and Maska. Available results of geological studies show that in Nigerian, most of the manganese deposits are of metamorphic origin. These include Tudun Kudu and Unguwar Mallam Ayuba in the Maska belt, Ruwan Dorawa and Maraba Hill in the Maru belt of North Western Nigeria, others are the supergene enrichment deposit of Igarra formation within the schist belt of South-Western Nigeria. (Mucke and okujeni, 1984)

Figure 1.1 is a map of Nigeria showing the location of major identified manganese deposit and showing the location of Wasagu town (National steel, Raw Materials Exploration Agency, 2010).

1.1 Wasagu Manganese Deposit.

Wasagu town is located in Wasagu/Danko Local Government Area of Kebbi state, (North-western Nigeria). The town lies on latitude 6^{o}E and longitude 11^{o}N. (Wikipeadia.org.wasagu danko) and falls within the Sokoto basin. The deposit from where a sample for this research work was obtained is about 10km from Wasagu town. The manganese deposit in Wasagu and its environs covers an area of approximately 40,000Km^2; this is estimated figure from artisanal mined out areas

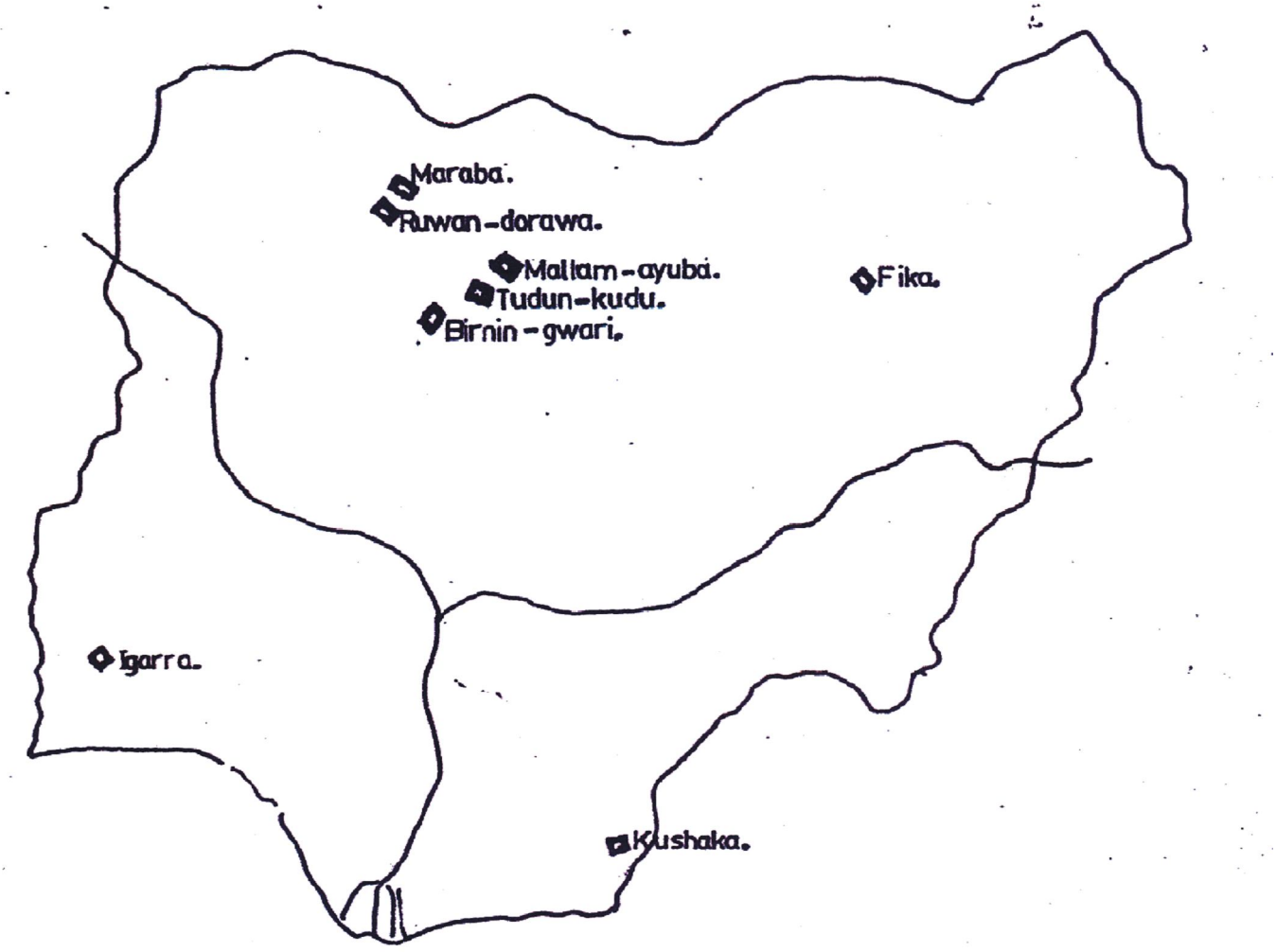


Figure 1.1 is a map of Nigeria showing the location of major identified manganese deposit and showing the location of Wasagu town (National steel, Raw Materials Exploration Agency, 2010).



Fig 1.2: Kebbi state, indicating Wasagu town

Source; www.ncocusa.com, (2010).

Manganese is never found free in nature, but generally occurs as a mineral in the form of oxides, silicates or carbonates. The genesis of these manganese minerals depends on so many factors: some of the factors include environment of deposition, tectonic setting, climate and biogenic conditions, conditions of temperature and PH and E etc.

Basically there are three main environments of manganese deposition, these include the igneous, sedimentary and metamorphic environment (Yaro, 1996).

Below, the principal Manganese bearing Minerals

Mineral	**Chemical Composition**	**% Mn**
Hausmannite	Mn_3O_4	72
Pollinate	Mn_2O_3	63.1
Pyrolusite	MnO_2	60-63
Manganite	$Mn_2O_3.H_2O$	62
Braunite	$3Mn_2O_3\ AlMnSiO_3$	62
Tephroite	$2MnO.SiO_2$	54.3

Source: Yaro, 1996

Metallurgical grade manganese ores are located in only four countries: Gabon, South Africa, Australia and Brazil and usually concentrates of up to 52.50%Mn can be accommodated for the production of ferromanganese alloys for iron and steel companies (Yaro, 1996). Hence the low grade deposits located in other countries of the world need to be beneficiated to metallurgical grade before utilization in iron and steel companies. Specification for metallurgical grade manganese ore/concentrate is presented in appendix 1 (Jacoby, 2003).

1.2 Statement of the problems

(i) The development of the process route for the Wasagu manganese ore is not available to enhance the utilization of the concentrate.

(ii) The data on the ore characteristics and the optimum concentration method for upgrading the Wasagu manganese ore to a metallurgical grade are not available; hence there is need for this research work.

1.3 Justification

1. The local steel industries have continued to depend on imported source of manganese, this is because the local manganese deposit are low grade and require upgrading before they could be used. The ever increasing demand for steel products has continued to put pressure on government to complete the construction work at the nation's steel producing plant which, will result in the need for a local manganese concentrate.
2. The Wasagu manganese ore deposit has the potential to contribute to Nigeria's steel development needs and reduce imports. However the Wasagu deposit has to be characterized and beneficiated to metallurgical grade, to meet local demand for steel producers.

1.4 Objectives of the Study

The main goal of this work is to upgrade the Wasagu manganese ore to a metallurgical grade concentrate suitable for ferromanganese production. Others are to:

1. Determine the mineralogical, chemical and physical characteristics of the ore

2. Utilize gravity – shaking table, spiral concentrator and magnetic separation methods to beneficiate Wasagu manganese ore, to metallurgical grade concentrate containing at least 52.50%Mn.
3. Determine the work index and density of the ore.

1.5 Contribution to knowledge

1. The nation and the world as a whole will be availed with the Mineralogical and chemical composition of Wasagu Manganese ore.
2. The comminution characteristics of Wasagu manganese ore have been revealed.
3. The optimum particle liberation size of the ore has been revealed.
4 The best Concentration method of the ore has been determined

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Minerals are defined as naturally occurring, homogeneous, solid substances that are generally of inorganic origin having well-defined crystalline structure and a chemical composition that lies between well-defined limits (Jones, 2000). However, due to the fact that not all materials that are classified as minerals are of inorganic origin or having fixed chemical composition amongst others, the term mineral is generally referred to as substances of economic value extracted from the earth (Wills and Munn, 2006). They are mostly inorganic in nature possessing definite chemical composition and atomic structure with some being of organic origin like coal, calcium carbonate (limestone), etc. In nature, minerals of interest exist physically and chemically combined with the host rock.

2.2 Source of Minerals

Almost all minerals are obtained directly from the earth's crust with a small proportion obtained from secondary sources such as scraps. The average crustal composition shows that the element oxygen: silicon, aluminum and iron account for nearly 90% of the total, while the economically important elements like copper, zinc, tin, lead and gold occur only in minute proportions (Jones, 2000). The rocks of the earth are however not of uniform composition. Where the minerals are potentially of economic value, these natural concentrations are called mineral deposits and it is from these quite rare crustal -features that minerals of commerce are obtained. Any mineral deposit from which it is possible to produce metallic products economically

at a profit is called an ore .Ores are also classified by nature of their gangues, such as calcareous or basic (lime rich) and siliceous or acidic (silica rich). An ore can be described as an accumulation of mineral in sufficient quantity so as to be capable of economic extraction. The minimum metal content (grade) required for a deposit to qualify as an ore varies from metal to metal. Many non- ferrous ores contain, as low as 1%, metal and often much less.

Ores of economic value can be classed as metallic or non-metallic, according to the use of the mineral. Certain minerals may be mined and processed for the more than one purpose. In one category the mineral may be a metal ore, i.e. when it is used to prepare the metal, as when bauxite (hydrated aluminium oxide) is used to make aluminium. The alternative is for the compound to be classified as non- metallic ore, i.e. when bauxite or natural aluminium is used to make material for refractory bricks or abrasives (Carr, D.D, 1994).

2.2.1 Common manganese Bearing Mineral

The Common manganese bearing minerals consist of hydro carbonates silicates and a large number of oxides, hydrated oxides and compound oxides with other metals in carbonates, for example ($MnCO_3$) and silicates e.g. Rhodonite ($MnSiO_3$) and sperssatite $Mn_3\ Al_2\ (SiO_3\ )_4$, the manganese is divalent. But in the oxides it is mostly in a higher state of oxidation mainly tetravalent (Mn^{4+}). The silicates occurrences presently are of no commercial value because they are expensive to beneficiate. The carbonates and oxides are the commercially treatable minerals (Yaro, 1996).

2.3 Ore processing

Mineral deposits have continued to drop in mineral content as well as being of more complex mixture of worthless and valuable minerals with the mixture having no immediate or readily apparent value. This complex mixture of very low mineral values therefore needs to be upgraded to make it salable. The process through which this complex mixture undergoes in order to make it salable is termed mineral processing. If the ore contains economic amounts of more than one valuable mineral it is usually the object of mineral processing to separate them. Similarly, if undesirable minerals, which may interfere with subsequent refining processes are present, it may be necessary to remove these minerals at the separation stage (Wills and Munn 2006).

2.4 Mineral Processing Operations

Mineral processing unit operations that are mostly used in the course of beneficiating mineral deposits and are as outlined below.

2.4.1 Sampling

This refers to the collection of a fraction of given material in such a way that the fraction so collected is representative of the lot: The main purpose of sampling is to obtain a small fraction of a large quantity of material for laboratory analysis and to ensure that this small fraction should represent the average composition of the bulk of the material.

A sample may be defined as a small portion of relatively large mass containing the same ingredients in the same proportion that occur in the bulk material. In

metallurgical analysis sampling is carried out in order to achieve one of the following aims:

1. To ascertain the chemical composition of the metallurgical material e.g. ores, alloys, slags etc.
2. To check whether a metallurgical product meets certain requirements.
3. For detecting impurities and contamination in metallurgical material.
4. For routine checks in metallurgical operations.

The minimum weight of samples to be collected varies with size of the particles being sampled. This is generally estimated using the expression $y=0.2116x^2$ for low and medium ores as devised by Targgat (2010) and converted to metric system klima, (2010) by where x is the particle top size in mm and y is the sample weight in Kg.

Another formula that could be used to estimate sample weight is that which is devised by GY (1979) to calculate the size of sample necessary to give the required degree of accuracy and which is mostly used for streams transported on conveyors or pulp streams rather than heap deposit (Wills and Munn, 2006).

It is expressed as $m = \frac{cd^3}{S^2}$ - - - - - - (2.1)

Where, m = minimum weight of the sample required (g).

c = Sampling constant of the material,

d = dimension of the largest piece in the material to be sampled (cm).

S = measure of statistical error

2.4.2 Metallurgical Analysis

Refer to the analysis of materials used in metallurgical processes which generally comprise the use of instrumental techniques or classical methods to determine the materials' chemical, 'mineralogical or phase compositions (Yaro, 1998). While the classical analytical methods rely on chemical reactions to perform an analysis, the instrumental methods generally depend on the measurement of physical property of the analyzed sample such as light absorption, fluorescence or conductivity using an apparatus which is then 'compared with the values of a reference sample to obtain a figure for the physical property so measured. Examples of instrumental methods include the Atomic absorption spectrometer, X-Ray Diffraction spectroscopy, Mineral Liberation Analyzer (MLA), Qualitative Evaluation of Minerals by Scanning Electron Microscopy (QEMSCAN), etc.

a. X-ray Flourescence (XRF)

X-ray fluorescence (XRF) spectrometer is an x-ray instrument used for routine check, relatively non-destructive chemical analyses of rocks, minerals, sediments and fluids. It works on wavelength-dispersive spectroscopic principles that are similar to an Electron Probe Micro Analyser (EPMA). However, an XRF cannot generally make analyses at the small spot sizes typical of EPMA work (2-5 microns), so it is typically used for bulk analyses of larger fractions of geological materials. The relative ease and low cost of sample preparation, and the stability and ease of use of x-ray spectrometers makes it one of the most widely used methods for analysis of major and trace elements in rocks, minerals, and sediment.

This technique works on the principle that when a material is irradiated by x-rays, electrons are ejected from the atoms making up the material. The vacancies created

by these ejected electrons are then filled with other electrons either from the higher shells within the atoms or outside the atoms. These electrons lose energy mainly in the form of radiations or x-rays. The x-rays will have a precisely defined energy and the wavelength or (velocities of the electron) are related by Plank's energy equation.

$E_1-E_2=hc$ -- - - - - - - (2.2)

Where, E_1= former energy level of electrons before filling the vacancy

E_2= new energy level of the electrons after filling the vacancy

h = planks constant

c= velocity of light

As the energies or wavelengths are characteristics of the atoms of the elements emitting the x-rays, they are used for qualitative analyses, while the intensity of these characteristics x-rays are related to the concentration of the particular element in the material and is used for quantitative elemental analyses (Karl and Macalester, 2011).

b. Scanning Electron Microscope

The SEM is an instrument that has many applications such as the investigation of the micro-structure and analyses of in homogeneity such as defects dislocation, submicroscopic precipitates inclusion etc. It produces a larger magnified image by using electrons instead of light to form an image. A beam of electrons is produced at the top of the microscope by an electron gun. The electron beam follows a vertical path through the microscope a vacuum. The beams travel through magnetic fields and lenses, which focuses the beam down towards the sample. Once the beam hits the sample, electrons and x-rays are ejected from the sample. Detectors collect these

x-rays, backscattered electrons and secondary electrons and convert them into a signal that is sent to a screen similar to television screen. This produces the final image (Iowa, state SEM, home page, 2010).

c. Powder X-ray Diffraction (XRD).

This is a non destructive method of analysis that is used for both qualitative and quantitative analysis of materials. The technique is only applicable to solids (crystalline) materials.

It is one of the primary techniques used by mineralogists and solid state physics to examine the physio-chemical makeup of unknown solids. The data is represented in a collection of single phase x-ray powder diffraction pattern for the three most intense D values, in the form of tables of inter-planar spacing (D), relative intensities (I/Io) and mineral name.

The technique is based on observing the scattered intensity of an X-ray beam hitting a sample as a function of incident and scattered angle, polarization and wavelength or energy. The X-rays are deflected by crystals and they emerge with a wavelength "n" from the crystals, a condition that satisfies the Bragg's law.

Bragg's equation is given by;

$n\lambda = 2d\sin\theta$ …… (2.3)

Where d= inter-planar (lattice) space of Bragg's angle

θ=angle between family of planes and the X-rays in the reflecting position

λ= x-ray wave length

n = is an integer. (Wills' and Munn, 2006)

d. Size Assay Analysis

The size assay analysis is usually carried out to determine the distribution of various minerals, specifically valuable and non-valuable metal bearing minerals of the ore in the various size fractions. The analysis is used to obtain information on the possibility of using waste rejection techniques so as to reject the gangue minerals at a coarse size as possible. It is also used to obtain a clue on the liberation sizes of the various mineral in the ore and their degree of associations (Yaro, 1996).

Sieve analysis is one of the oldest methods of size analysis and is accomplished by passing a known weight of sample material successfully through finer sieves and weighing the amount collected on each size fraction. Sieving is carried out with wet or dry materials and the sieves are usually agitated to expose all the particles to the openings. Sieving, when applied to irregularly shaped particles, is complicated by the fact that a particle with a size near that of the nominal aperture of the test sieve may pass only when presented in a favorable position (Wills and Munn, 2006). As .there is inevitably a variation in the size of the sieve aperture, due to irregularity of weaving, prolong sieving will cause larger apertures to exert an unduly large effect on the sieve analysis. Given time, every particle small enough could through a very few such holes. The procedure is also complicated in many cases by the presence of "near-size" particles which causes "blinding" or obstruction of the sieve apertures and reduces the effectiveness of the sieving medium. Blinding is most serious with sieves of very small aperture size (Will and Munn, 2006).

2.4.3 Work Index Determination**.**

Grinding characteristics of an ore called grindability refers to the ease with which the ore can be comminuted. It is an important factor in estimating and controlling the power requirement of industrial grinding operations. The most widely used parameter to measure grindabilty of an ore is the Bond Work Index (Wi) which is defined as the power in kilowatt hour per ton require to grind an ore from an infinite size to 80% passing 100µm. several methods have been developed for evaluation of grindabilty of ores. Most of them have not been accepted because results obtained do not correlate very well with each other or with corresponding industrial data. Probably the most widely used method is the standard Bond Method.

2.4.4 Comminution

Comminution involves the gradual reduction in size of the particles until the clean particles of the minerals can be separated by methods available. Comminution in mineral processing takes place as a sequence of crushing and grinding process (Gupta, 2006).

Liberation refers to the release of valuable mineral from the gangue Liberation of the valuable mineral from the gangue is accompanied by comminution which involves crushing, and if necessary, grinding to such a particle size that the product is a mixture of relatively clean particles of minerals and gangue. The aim of comminution is to maximize the liberation of valuable mineral from the gangue.

Grinding is often, the greatest energy consumer accounting for up to 50% of the concentration energy consumption.

The main comminution theories are outlined below.

1. Rittinger's theory of comminution which states that the energy consumed in particle breakage is proportional to the area of new surface produced.

   Rittingers energy equation is given by:

   $$E = K\left[\frac{1}{D_2} - \frac{1}{D_1}\right] \quad - \quad - \quad 2.4$$

   Where E = is the energy input

   D_1 = initial particle diameter (cm)

   D_2 = final particle diameter (cm)

   K = constant. (Wills' and Munn,2006)

2. Kick's theory of comminution: This theory states that the work required is proportional to the reduction in volume of the particles concerned. The theory is expressed as:

   $$R = \frac{f}{P} \quad - \quad - \quad - \quad 2.5$$

   Where:

   f = diameter of feed particles in cm

   p = diameter of product particles in cm. (Wills'and Munn, 2006).

3. Bond's theory of comminution

   This theory states that work input is proportional to the new crack tip length produced in the particle breakage and which equals the work represented by the product minus that represented by the feed. Bond's theory is mathematically expressed as

$$W = W_i\left[\frac{10}{\sqrt{P_□}} - \frac{10}{\sqrt{F_□}}\right] \quad - \quad - \quad 2.6$$

Where, W is the work input in kilowatt hours per short ton. W_i is the work index which is the resistance of material to crushing and grinding expressed as the kilowatt hours per short tonne required to reduce the material from theoretically infinite size to 80% passing 100µm. The work index is the widely used parameter for measuring hardness and grindability of ores (Yaro, 1996).

4. Berry and Bruce Method

Berry and Bruce (1966) developed a comparative method of the grindability of an ore. This Method employs the use of a reference ore of known work index. The reference ore is ground for a certain time and the power consumption recorded.

An identical weight of the test ore is then ground for a length of time such the power consumed is identical with that of reference ore. If r is the reference and t is the test, then from Bond''s equation

$$W_r = W_t = W_{ir}\left[\frac{10}{\sqrt{P_r}} - \frac{10}{\sqrt{F_r}}\right] = W_{it}\left[\frac{10}{\sqrt{P_t}} - \frac{10}{\sqrt{F_t}}\right] \text{.....Equation 2.7}$$

$$hence, W_{it} = W_{ir}\left[\frac{10}{\sqrt{P_r}} - \frac{10}{\sqrt{F_r}}\right] \Big/ \left[\frac{10}{\sqrt{P_t}} - \frac{10}{\sqrt{F_t}}\right] \text{.....} \quad 2.8$$

Reasonable values for the work indices are obtained by this method as long as the reference and test ores are ground to about the same product size distribution (Berry and Bruce,1996).

2.4.4.1 Denver Grindability Method

The grinding tests under this method for the determination of work index are performed for specific time intervals under uniform conditions. The amount (percentage by weight) of 75µm material produced is plotted against time in minutes, to produce a curve. The curve obtained from the grinding of the material is then compared with five standard curves on the same scale which are designated as soft (A), medium soft (B), medium (C), medium hard (D) and hard (E) as shown in Figure 2 . Ores softer than "B" are considered to be soft and ones harder than "D" are considered to be hard. Having determined the relative hardness of the ore and for a given mill feed size, desired discharge sieved size fractions and tonnage, Denver Ball Mill size and horsepower required can be determined using Denver circular slide rule (Mathur, 1985).

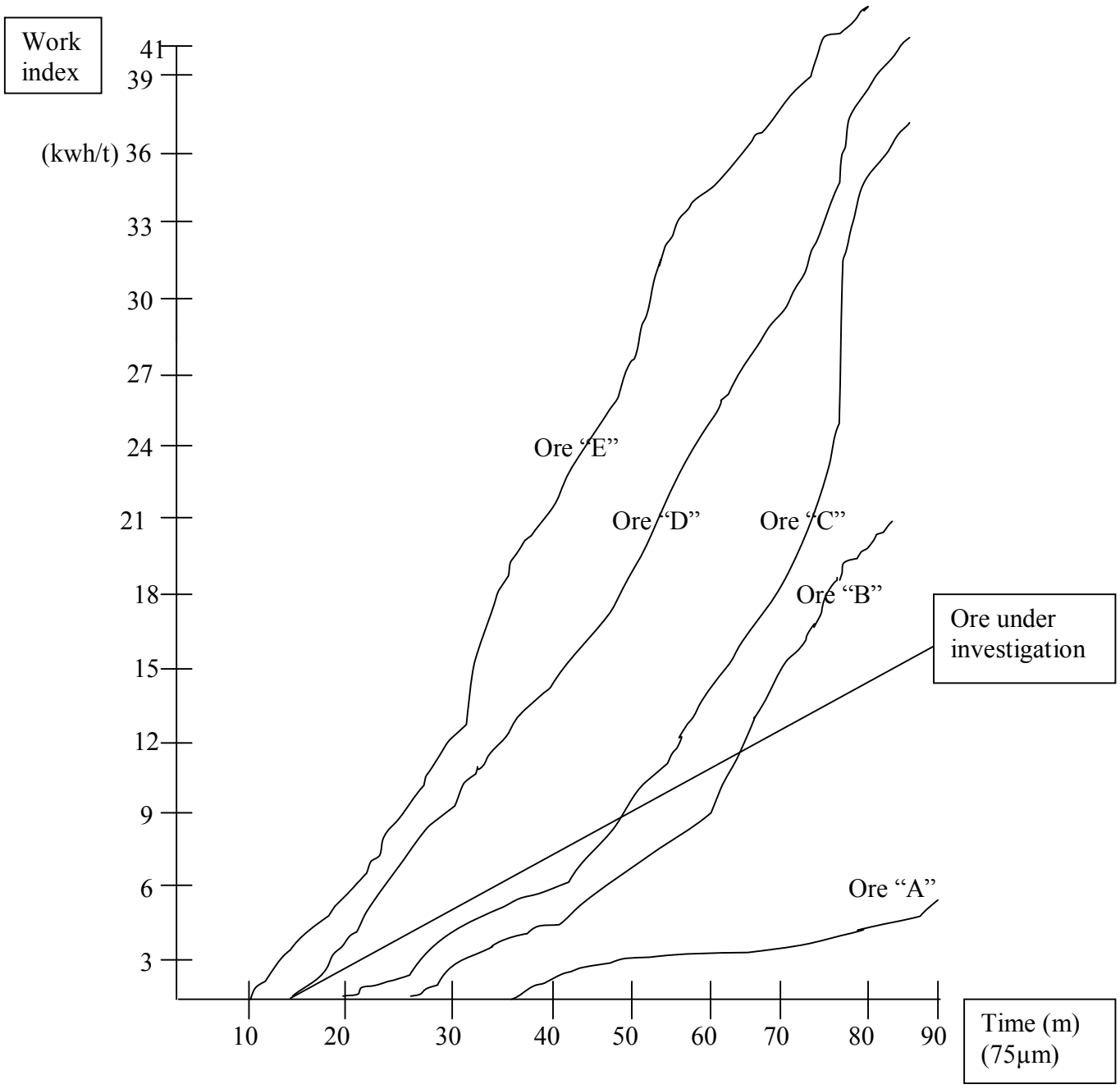


Figure 2. Denver grindability curves for classification ore types. Source (Mathur, 1985)

2.5 Mineral Separation Process.

Mineral processing in its broadest sense includes both physical and chemical separation (hydrometallurgy and pyrometallurgy) of valuable constituents from the crude ore. Ore processing is the removal of unwanted minerals (gangue) from a combination of valuable and non-valuable minerals resulting in an increase in concentration of the valuable, in an economically viable manner.

The upgrading is usually carried out using the inherent difference in the properties of the combined minerals such as colour, hardness and specific gravity (Gupta, 2006).

a. Gravity Separation

This is a separation processes that is based on difference in densities between minerals. This method separates minerals of different specific gravity by their relative movement response to gravity and resistances to motion offered by viscous fluid, such as water or air. To be effective, gravity concentration requires a difference of at least 0.5-1.0, depending on the absolute specific gravity of the lighter mineral (Wills' and Munn, 2006).

Gravity method is usually a pre-concentration process in which the valuable mineral are separated from the gangue at a coarse size as possible using a relatively cheap method. The gravity separation flow sheet usually incorporates scrubbing section to remove slimes, followed by size reduction using jigs and drums. Some examples of gravity separation techniques are: jigging, shaking concentrators and flowing film concentrators.

Gravity separation processes are effective, practical and economic in treatment of so many ores. But their applicability to the processing of any specific ore alone or in combination with other processing methods must be determined from thorough knowledge of the mineralogy of the ore (Gupta 2006).

b. Spiral Concentrator

The spiral concentrator first appeared as a production unit in 1943 in the form of the Humphrey Spiral, for the separation of chrome-bearing sands in Oregon. By the 1950's, spirals were the standard primary wet gravity separation unit in the Australian mineral sands industry. (Gupta, 2006)

In the spiral concentrator the length of the sluicing surface required to bring about segregation of light from heavy minerals is compressed into a smaller floor space by taking a curved trough and forming into a spiral about a vertical axis. The slurry is fed into the trough at the top of the spiral and allowed to flow down under gravity. The spiralling flow of pulp down the unit introduces a mild centrifugal force to the particles and fluid. This creates a flow of pulp from the centre of the spiral outwards to the edge. The heaviest and coarsest particles remain near the centre on the flattest part of the cross-section, while the lightest and finest material is washed outwards and up the sides of the launder. This separation may be assisted by the introduction of additional water flowing out from the centre of the spiral either continuously or at various locations down the length of the spiral. This wash water may be distributed through tubes or by deflection from a water channel that runs down the centre of the spiral. Some present designs have overcome the need for this wash water. Once the particle stream has separated into the various fractions, the heavy fraction can be

separated by means of splitters at appropriate positions down the spiral (Gupta, 2006).

c. Shaking Table

In the shaking table concentrator, differential motion and a riffled deck with cross flowing water is used to create a particle separation. The shaking motion is asymmetrical, being slow in the forward direction and rapid in the reverse direction. This differential motion imparts a conveying action to the table moving those particles which are in contact with the table deck, through friction, in the direction of the motion.

The Wilfley table was designed for ore concentration and since the early days of its development has been used extensively for this purpose. When the table is equipped with decks specially designed for coal washing it was known as a *Massco* table. Since the introduction of the Wilfley table many different makes of tables have been developed for use with minerals and coal.

The table consists of a slightly inclined flat surface or deck with a series of parallel ridges or riffles along the direction of motion. The riffles are tapered towards the opposite end to the reciprocating drive. Feed is introduced at the corner of the table at about 25% solids (by mass) and with the shaking motion, the particles spread out over the table. Wash or dressing water is introduced along the top edge of the deck to assist in segregation and transport of particles on the table. The coarse lighter particles take the shortest path across the feed box and the fine heavy particles are the last to arrive at end of the riffles, affected more by the shaking action and

frictional than by the water film. Abowzied, (1990). The net effect is that the particles move diagonally across the deck from the feed end (Gupta, 2006).

d. Magnetic Separation Method

This method employs separation of minerals based on their difference in magnetic properties. This concentration is achieved by passing a mixture of the mineral particles through a non-homogeneous magnetic field which result in either preferential retention or deflection of the magnetisable particles (Wills et al 2006).

The basic principle of the magnetic separator is that the mineral is being acted upon by several external forces with a dominant magnetic force. The separation of one mineral from another depends on their motion in respond to the dominant force and other competing forces, namely frictional, gravitational, centrifugal and inertia. In the case of separation involving ferromagnetic minerals in the magnetic separation, the magnetic force acting upon the particles must be greater than the sum of all competing forces, and hence the minerals will be attracted to the magnet. The non-magnetic mineral will be repelled from the magnetic field.

2.6 Previous work on Manganese Ores.

As stated earlier, there are many promising local manganese ores, the importance of exploiting these ores to produce manganese concentrate for ferromanganese production has also been discussed and cannot be overemphasized.

Yaro (1996) worked on the Mallam Ayuba manganese ore with chemical composition of 23.00% Mn_3O_4, 36.40% SiO_2, 14.80% Fe_2O_3 and other associated compounds. He upgraded the ore and produced a concentrate assaying 38.30% Mn_3O_4 using magnetic clinker process.

He used his findings to develop a process route for the beneficiation of Mallam Ayuba manganese ore and was able to use the process route to produce ferromanganese feed grade.

In 2008, the Gusau Raw materials exploration agency camp, in Zamfara State, carried out a reconnaissance geological investigation on the Kaoje, Darene manganese deposit, however not much has been done beyond the initial surveyed. The same agency also carried out another investigation on Maikujeri manganese deposit of Bukuyyum local government of Zamfara State, the result reveals that the deposit has low phosphorous and silica content which is good for metallurgical purposes.

Elsewhere Mishra et al (2010) upgraded low siliceous manganese ore from Bonia Keonjhar belt in India. The result reveals that a feed assay 26%Mn could be upgraded to more than 45% Mn by using a dry belt magnetic separator with a recovery of 69%.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Materials

The materials employed for this work include: a composite sample of Wasagu manganese ore. The equipments used were small size laboratory jaw crusher, cone crusher, pulverizing machine, standard sieve shakers, Wifley shaking table, spiral concentrator high intensity magnetic separator, X- ray spectrometer (XRF), Scanning Electron Microscope (SEM) and X- ray Diffraction microscope(XRD) .

3.1.2 Sample preparation

A composite sample of Wasagu manganese ore weighing 50kg, collected from four (4) pits spaced at a distance of 5m and a depth of 6m. The pits were dug by local artisanal miners. The average size of a sample is about 8cm. After the composite sample was collected, it was dried, crushed, using the cone crushers to sizes ranging from 0.5cm to 0.2cm and was finally pulverized to 1400µm + 63µm.

3.2 Methodology

3.2.1 Determination of Specific Gravity

The density of the manganese ore was determined using a dried 50ml density bottle (pycnometer). The empty bottle was first weighed (w). The manganese ore grains were then introduced into the density bottle and the bottle plus the sample were weighed (w_1). The bottle plus mineral was then filled with water and weighed again (w_2). Finally the manganese rocks grains were removed; the bottle was filled with water and weighed (w_3).

The density of the manganese ore is given by the expression

Density = $\frac{\text{Mineral weight}}{\text{Mineral volume}}$

Where mineral weight = $(w_1 - w)$ and

Mineral volume = mass of water displaced

By mineral = $(w_3 - w) - (w_2 - w_1)$

Density $(w_1 - w) \times 1000 / (w_3 - w) - (w_2 - w_1)$

The result is given in Table 4.1.

3.2.2 Chemical and Mineralogical Characteristics

Chemical and mineralogical characteristics of the ore were investigated using the X- ray Florescent (XRF), X-Ray Diffraction (XRD) and Scanning Electron Microscope (SEM).

a. X-Ray Diffraction (XRD)

The XRD was done at the Faculty of Natural and Agricultural Science, Geology Department, University of Pretoria, Pretoria South Africa. The samples were prepared for XRD analysis using a back loading preparation method.

They were analyzed using a PAN analytical X'pert pro powder diffractometer with X'celerator detector and a variable divergence slit with Fe filtered Co-Kα radiation. The phases were identified using the X'pert Highscore plus software. The relative phase amounts (weights %) were estimated using the Rietveld method (Autoquan program). Errors are on the 3 sigma.

b. Scanning Electron Microscope (SEM)

The analysis was conducted at the centre for Scientific and Industrial Research (CSIR), building in Pretoria, South Africa, using the Field Emission Scanning Electron Microscope equipped with Energy Dispersion Spectrometer (FESEM-EDS) and a sparter coating machine.

c. Size/Assay analysis

Size-assay analysis of the composite sample was carried out in order to determine the 80% passing and the distribution of manganese within the size fractions. The various size fractions retained on each sieve was weighed and assayed for %Mn content using the XRF spectrometer.

d. X- ray Flourescence Spectrometer (XRF)

The investigation was carried out at the National Metallurgical Centre Jos. Before the analysis, the ore was first milled to -63µm each sample was to plates and each sample was placed in the machine for one hour thirty minutes.

3.2.3 Work Index Determination

The work index of the manganese ore was determined using the Berry-Bruce method (1996). A reference ore of known work index (granite with a work index of 14.39kwh/t) and the manganese ore were milled using the same quantity of energy. By using the Bond's energy equation, the work index of the manganese ore was calculated by equating the energy consumed in grinding a reference ore and the manganese test ore. The result is given in Table 5.2a to d.

3.2.4 Concentration Test Using Shaking Table

This test was carried out using laboratory scale shaking table, on some sample of manganese ore ground to the following particle sizes -710+500µm, -500+355µm, -355+250µm, -250+180.µm,-180+125µm,-125+90µm,-90+63µm. Each particle size fraction was prepared using 25% solid by weight and was used for each batch of concentration test. The result is given in Table 5. 3

3.2.5 Concentration Test Using Spiral Concentrator

This test was carried out on representative samples of manganese ore ground to the following particle sizes -710+500µm, -500+355µm, -355+250µm, -250+180µm, -180+125µm, -125+90µm, -90+63µm. Each particle size fraction was prepared using 25% solid by weight and was used for each batch of concentration test. The result is given in Table 5.4.

3.2.6 Concentration Test Using Magnetic Separator

The main aim of this test is to separate the magnetic minerals from the non magnetic. A representative sample of the grounded ore was used, which was sized into various size fractions ranging -710+500µm, -500+355µm, -355+250µm, -250+180.µm,-180+125µm,-125+90µm,-90+63µm. These various size fractions were subjected to magnetic separation, using a dry belt high intensity magnetic separator. After which two products (concentrate and tailings) were produced for analysis. The result is given in Table 5.5.

CHAPTER FOUR

RESULTS

4.1 Specific Density Determination

The result of specific density is presented in Table 4.1. The test was carried out at the National Metallurgical Development Centre Jos. The density of the ore was found to be 4.0

Table 4.1: Table of values for the volume of water displaced

Number	Initial volume (cm^3)	Find volume (cm^3)	Difference in volume (cm^3)
1	20	23	3
2	20	23	3
3	20	23	3

Using the relationship

Sp.gr = $\frac{M}{V}$ = density of water (ρ(

Where m = weight of the sample = 12g

ρ = density of water = $1g/cm^3$

V = volume

$V = V_f - V_i$

V_i= initial volume

V_f = final volume

$$\text{Sp.gr} = \frac{\text{ıM}}{\text{V x density of water}}$$

$$\text{Sp.gr} = \frac{12g \times 1cm^3}{(23 - 20)\ cm^3 \times 1g} = \frac{12}{3} = 4$$

4.2 Chemical and Mineralogical Analysis of the Head sample

The chemical and mineralogical analysis of the head sample is given in Tables 4.2, 4.2a and Figures 4a, 4b and plate 1.0 respectively.

Table 4.2: Chemical Analysis of the head sample using XRD

SAMPLE	Al_2O_3	SiO_2	SO_3	K_2O	CaO	TiO_2	Cr O_3	MnO	FeO	NiO	CuO	ZnO	SrO	ZrO_2	MoO_3	BaO
H/sample	6.6	7.5	ND	0.36	0.73	0.36	0.09	50.14	14.3	0.1	0.06	0.07	0.07	ND	0.12	0.19

4.3: XRD Result.

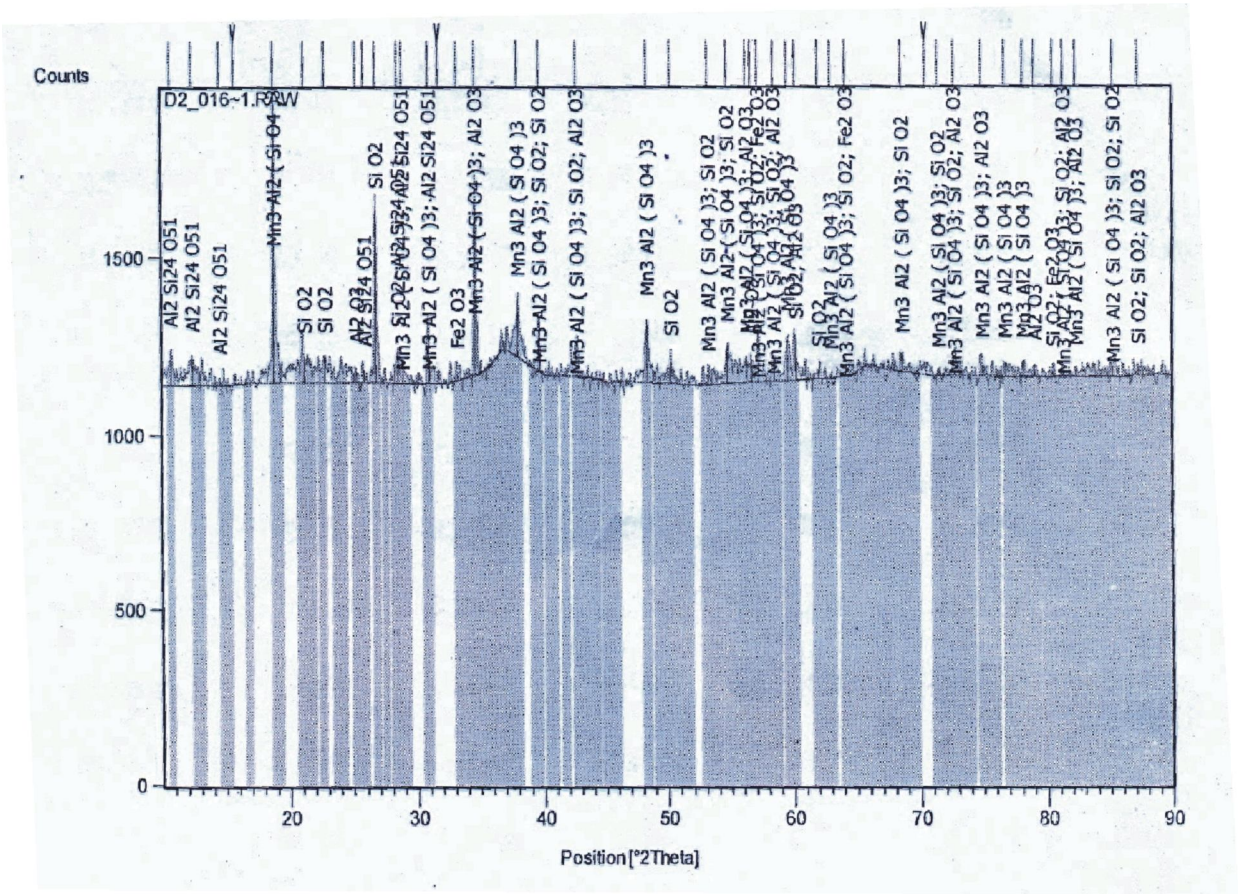
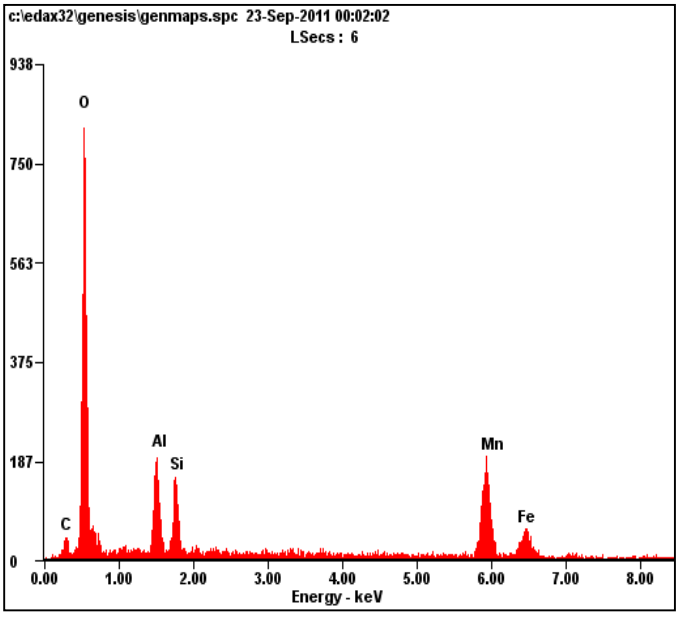


Figure 4a: XRD Result, indicating the Major Diffraction peaks of the Minerals in the Ore.

Table 4.2a:

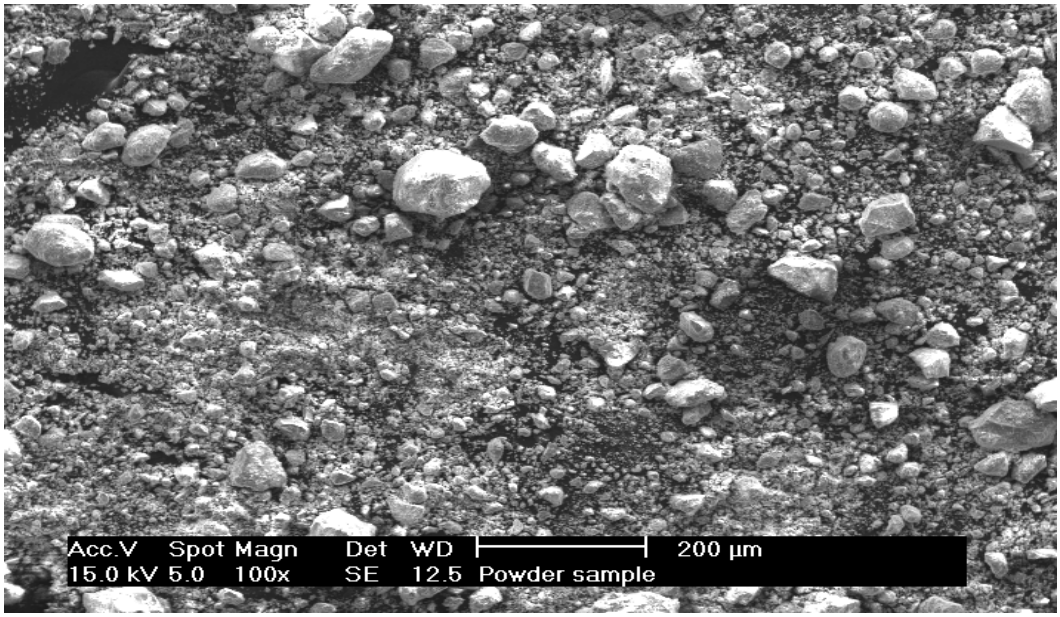
Visible	Ref. Code	Score	Compound Name	Displacement [°2Th.]	Scale Factor	Chemical Formula
*	01-087-1717	58	Spessartine, syn	0.140	0.802	Mn3 Al2 (Si O4)3
*	01-083-0539	46	Quartz	0.156	0.732	Si O2
*	01-079-1914	29	Quartz	0.205	0.112	Si O2
*	01-071-1684	31	Aluminum Oxide	0.086	0.225	Al2 O3
*	00-024-0072	14	Hematite	0.011	0.079	Fe2 O3
*	00-046-0748	19	Aluminum Silicate	-0.359	0.076	Al2 Si24 O51

XRD Result, revealing the major compounds found in the ore and their corresponding chemical formulas



Element	*Wt%*	*At%*
CK	07.10	15.32
OK	30.52	49.43
AlK	07.12	06.84
SiK	05.39	04.97
MnK	38.57	18.19
FeK	11.30	05.24
Matrix	Correction	ZAF

Figure 4b: SEM/EDX pattern and the major elements present in the Wasagu Manganese ore.



SEM; Plate i: Micrograph of Wasagu Manganese ore sample x100

Description: the white particles are free silica embedded in the matrix of spessartite indicated by the dark patches

CHAPTER FIVE

DISCUSSION

5.1 Analysis of the Head Sample

The chemical analysis of the head sample shows that the average manganese content is 50.14%MnO (38.67%Mn) with FeO content of 14.30% and a silica content of 7.50%. The result compared favorably with the 35%Mn sighted in the literature and makes the Wasagu manganese ore another potential deposit. The silica and iron contents can be easily removed during beneficiation and slag formation (Wills' and Munn, 2006). The proportions of other components in the manganese ore are within acceptable limits (Kudrin et al, 1985). Tables 5.2 to 5.2a show chemical analysis EDX-XRF results.

5.2 Mineralogical Analysis

The results obtained from SEM and XRD confirms that the manganese ore is intimately associated with other minerals and cannot be separated by any physical means, hence other complex techniques need to be employed. Complete mineralogical analysis carried out by;

a. X-ray Diffraction Spectrometer Results

The XRD pattern in Figure 4a reveals that, the major diffraction peaks are spessartite, quartz, Aluminum oxide, Hematite, and Aluminum silicate while others are in traces. Each of these phases has a score of 58, 46, 31, 14 and 19 (see Table 4.1a). The XRD pattern (see Figure 4a) reveals that the major diffraction peaks are 74.857, 72.744, 71.462, 70.440 and 68.563 degrees and their inter-planar distances are 1.268, 1.300, 1.320, 1.336 and 1.368 ´.

The XRD result shows that there is no free MnO_2 mineral in the ore, the manganese is in complex combination with Al_2O_3 and SiO_3. Only little free silica and Al_2O_3 are present in the ore. The major manganese bearing mineral is spessartine/Almandine as indicated (Mn_3Al_2 $(SiO_4)_3$.) This manganese bearing mineral is similar to the manganese ore found in Mallam Ayuba in Kaduna State (Yaro, 1996). In this mineral it is very difficult to isolate the manganese using any known mineral processing technique except by thermal decomposition.

b. SEM/EDS Results

Surface morphology of the manganese ore shows manganese containing quartz, as obtained from SEM results Indicates silver colour characteristics crystals and pure black patches (matrix) which is a characteristic feature of quartz mineral (SiO_2) (Kerr, 1995). The SEM/EDS microstructure of Wasagu manganese is presented in Fig 4b. The understanding of the mineralogy of an ore provides an insight into the liberation size of the ore and the separation technique likely to be employed in the concentration of the valuable minerals.

5.3 Specific Density Determination.

The density of the ore was found to be 4.0 which is below the standard specific gravity. This low density can be due to inclusion of silica and others; the result is presented in Table 4.1.

Most of the well known manganese minerals have specific gravity much higher than this value. The manganese bearing mineral is spessartite / almadine, a complex compound of SiO_2, $A1_2O_3$ and MnO_2.

5.4 Size/assay Analysis

The result of the distribution of manganese bearing mineral in Table 5.1 revealed that manganese bearing minerals are evenly distributed in each size fractions. This implies that manganese silica and aluminum and Fe are interlocked hence making the liberation of the mineral difficult by physical processes. Fig 5.1 showed the graph of distribution versus size fraction of Wasagu manganese ore where the %Mn content decreases as the size fraction reduces an indication that the manganese bearing minerals shows a degree of liberation as the ore mineral size is reduced.

Table 5.1: Size Assay Analysis of Wasagu Manganese Ore.

Sieve Size (µm)	Weight (g)	Mn (%) Assay	Mn Unit	Distribution (%)	Cumulative Distribution (%)
+1400	37.31	39.89	1488.2	38.67	38.67
-1400+1000	9.24	40.35	372.2	9.67	48.34
-1000+710	7.50	39.38	295.35	7.68	56.62
-710+500	8.50	39.83	338.56	8.81	64.83
-500+355	7.03	40.24	282.89	7.35	72.18
-355+250	5.73	38.97	218.37	5.68	77.86
-250+180	11.50	38.11	448.16	11.66	89.52
-180+ 125	3.14	36.90	115.87	3.01	92.83
-125+90	5.45	36.13	196.91	5.12	97.65
-90+63	1.65	35.38	58.37	1.52	99.17
-63	0.89	33.95	30.56	0.79	99.96

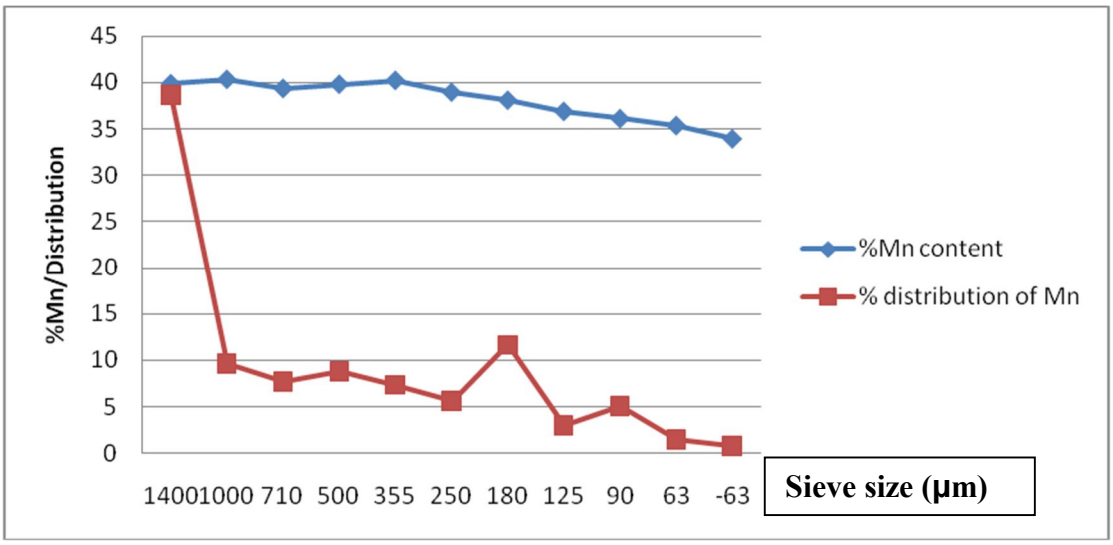


Figure 5.1: The percentage of Mn and its distribution in the various size fractions.

5.5 Work Index

Table 5.2a and 5.2b gives the result of particle size analysis of the feed and the discharge of the ball mill, for the reference ore (granite), while Table 5.2c and 5.2d gives the particle size distribution of the feed and discharge for the ball mill for the test ore (manganese). From these Tables, the 80% passing products and feeds for both reference ore (granite) and the test ore were calculated. The work index of the manganese ore was found to be 9.2kwh/tone. This value of work index indicates that the ore is medium soft grade B manganese ore type (Mathur, 1985). The graphs are presented below in Figures 5.2a and 5.2b

Table 5.2A: Particle Size Analysis of Feed to the Ball Mill (reference ore)

Sieve Size(µm)	Weight (gm)	Percentage Weight Retained (%)	Cumulative Percentage Weight Retained(%)	Cumulative Percentage Passing (%)
+1400	22.54	22.61	22.61	77.39
+1000	14.75	14.79	37.40	62.60
+710	14.90	14.94	52.34	47.66
+500	13.94	13.98	66.32	33.68
+355	8.70	8.72	74.04	24.96
+250	7.70	7.72	82.76	17.24
+180	6.88	6.90	89.66	10.34
+125	4.02	4.03	93.69	6.31
+90	3.96	3.97	97.66	2.34
+63	0.92	0.92	98.58	1.42
-63	1.34	1.34	99.98	0.02
	99.68			

1400 = 77.9%

X = 80%

1400 x 80

77.39

X = 1447.21 µm = F, is the 80% passing of the feed (Reference ore)

Table 5.2b: Particle Size Analysis of Ball Mill Discharge (reference ore)

Sieve Size (µm)	Weight Retained (g)	Percentage Weight Retained (%)	Cumulative Percentage Weight Retained	Cumulative Percentage Passing (%)
+710	0.27	0.27	0.27	99.73
+500	19.46	19.66	19.93	80.07
+355	0.39	0.39	20.32	79.68
+250	52.24	52.70	73.02	26.98
+180	15.91	16.05	89.07	10.93
+125	2.82	2.84	91.91	8.09
+90	6.12	6.17	98.08	1.92
+63	0.90	0.91	98.99	0.01
-63	0.98	0.99	99.99	0.01

500 = 80.7%

X = 80%

X = $\frac{500 \times 80}{80.07}$ = 499.56µm = P_r, is the 80% passing of product (Reference ore).

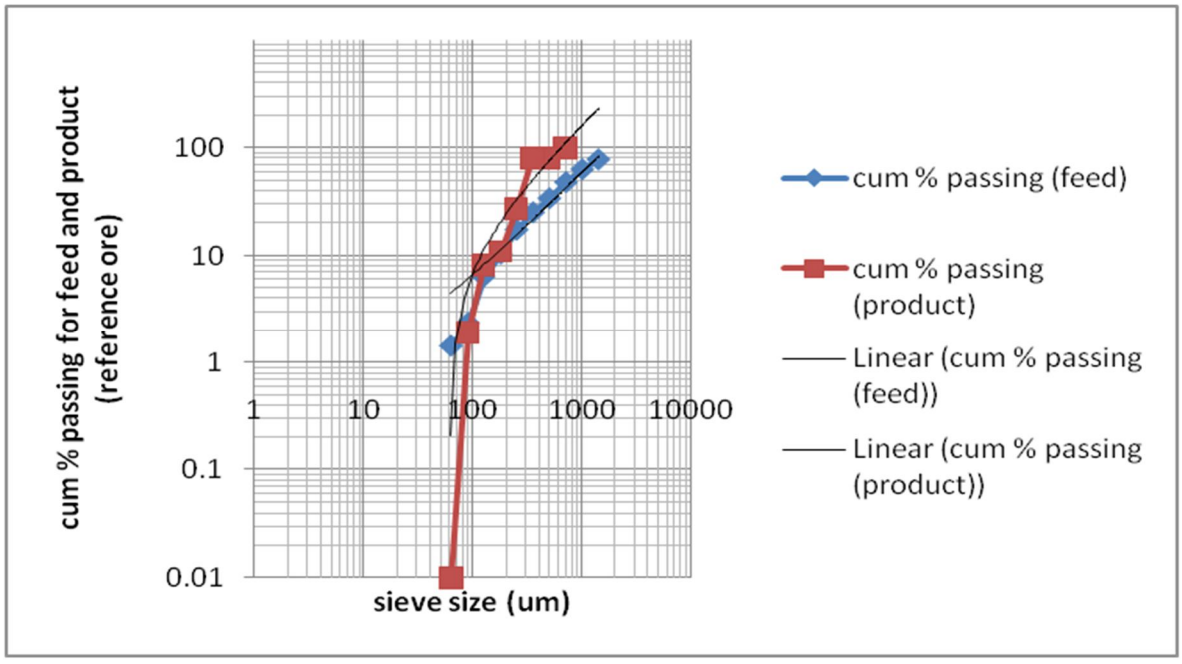


Fig 5.2a: Semi- log graph for the reference ore

Table 5.2c: Particle Size Analysis of Feed to the Ball Mill (test ore.)

Sieve Size (μm)	Weight Retained (gm)	Percentage Weight Retained (%)	Cumulative Percentage Weight Retained (%)	Cumulative Percentage Passing (%)
+1400	33.08	33.09	33.09	66.91
+1000	8.48	8.48	41.57	58.43
+710	7.72	7.72	49.29	50.71
+500	7.25	7.25	56.54	43.46
+355	5.93	5.93	62.47	37.53
+250	5.77	5.77	68.24	31.76
+180	6.81	6.81	75.05	24.95
+125	6.89	6.89	81.94	18.06
+90	6.87	7.04	88.96	11.05
+63	5.95	6.09	95.05	4.05
-63	2.83	2.90	97.05	2.05

1400 = 66.91

X = 80%

$$\frac{1400 \times 80}{66.91}$$

= 1673.89 μm $=F_{t,}$ is the 80% passing of the feed (Test ore).

Table 5.2d: Particle Size Analysis of Ball Mill Discharge (test ore)

Sieve Size (µm)	Weight Retained(g)	Percentage Weight Retained (%)	Cumulative Percentage Weight Retained (%)	Cumulative Percentage Passing (%)
+500	9.67	9.67	9.67	90.33
+355	9.97	9.97	19.64	80.36
+250	40.15	40.16	59.80	40.20
+180	21.39	21.40	81.20	18.80
+125	6.25	6.25	87.45	12.55
+90	6.21	6.21	93.66	6.34
+63	3.47	3.47	97.13	2.87
-63	2.85	2.85	99.98	0.02
			100	

355 = 80.36%

X = 80%

355 x 80

80.36

= 28400 = 353.41 µm = P_t , is the 80% passing of the product (Test ore).

80.36

Since the same quantity of energy is used in grinding both the reference and the test ore, then, Using the Berry and Bruce method of comparison

$$W_r = W_t = W_{ir}\left[\frac{10}{\sqrt{P_r}} - \frac{10}{\sqrt{F_r}}\right] = W_{it}\left[\frac{10}{\sqrt{P_t}} - \frac{10}{\sqrt{F_t}}\right] \quad \text{.....4.1}$$

$$hence, W_{it} = W_{ir}\left[\frac{10}{\sqrt{P_r}} - \frac{10}{\sqrt{F_r}}\right] \Big/ \left[\frac{10}{\sqrt{P_t}} - \frac{10}{\sqrt{F_t}}\right] \quad \text{..... 4.2}$$

w_{it}= 10 x 14.39{1/22.35-1/38.04}/10{1/18.798-1/40.913}= The work index of the wasagu manganese ore was found to be 9.2kwh/tonne.

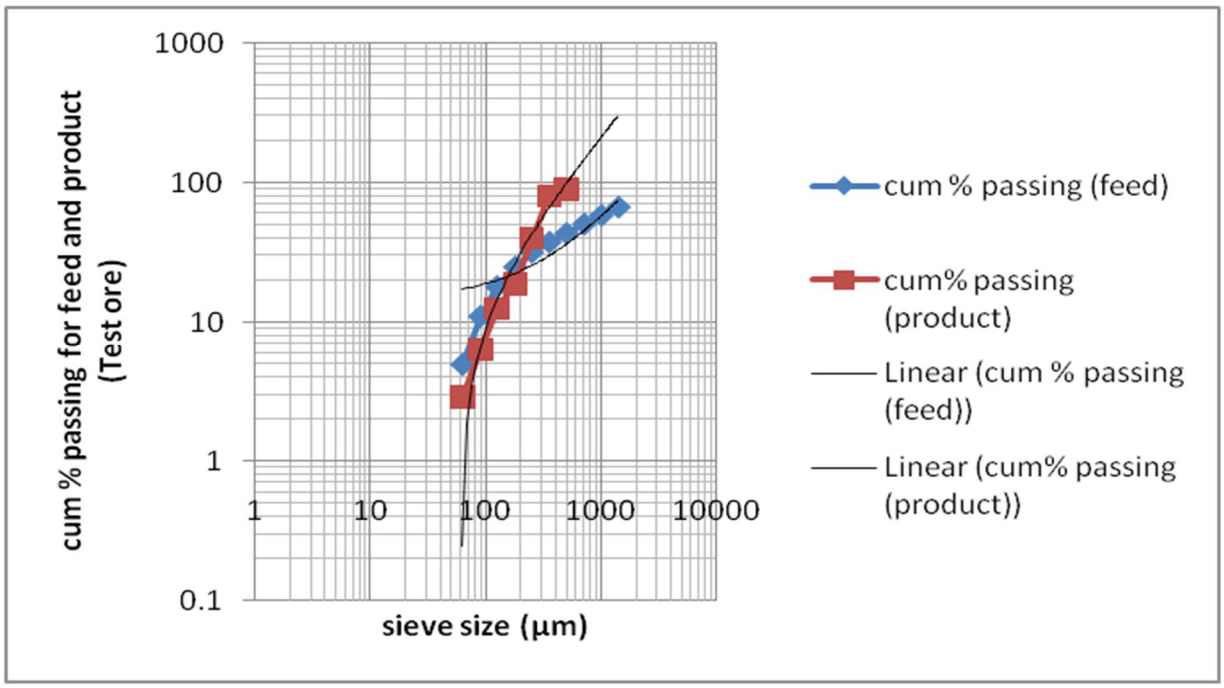


Figure 5.2b Semi- log graph for the test ore

5.6 Separation Test Using Shaking Table Technique

Table 5.3 gives the result of separation test using shaking table for particle sizes ranging -710 to +63µm. The assay of manganese and recoveries in each size fractions were computed. It was found that a concentrate with a maximum grade of 48.89%Mn and a highest recovery of 97.6% was obtained, at this sieve size -355+250µm. This grade of manganese obtained do not meet the stated literature value of 52.5%Mn required for ferromanganese alloys production. This implies that much of the manganese bearing minerals are liberated at this size fraction. The graph of percentage recovery was plotted against sieve size and is shown in figure 5.3

Table 5.3 Metallurgical Balance for Shaking Table

Sample	**Feed**			**Concentrate**			**Recovery**
Sieve Size(µm)	Weight (g) F	Mn(%) Assay f	Mn Unit Ff	Weight (g) C	Mn(%) Assay C	Mn Unit Cc	Recovery Cc/Ff x 100
-710+ 500	978.79	39.83	38985	955.90	44.53	42566	91.59
-500+355	962.10	40.24	38715	775.76	48.64	37732	97.50
-355+ 250	962.22	38.97	37450	747.88	48.89	36564	97.60
-250+180	945.60	38.11	36037	627.63	47.50	29815	82.70
-180+125	933.60	36.90	34450	604.06	45.89	27720	80.50
-125+90	937.80	36.13	33883	458.45	46.48	21309	62.90
-90+63	958.6	35.38	33915	377.40	47.33	17862	52.70

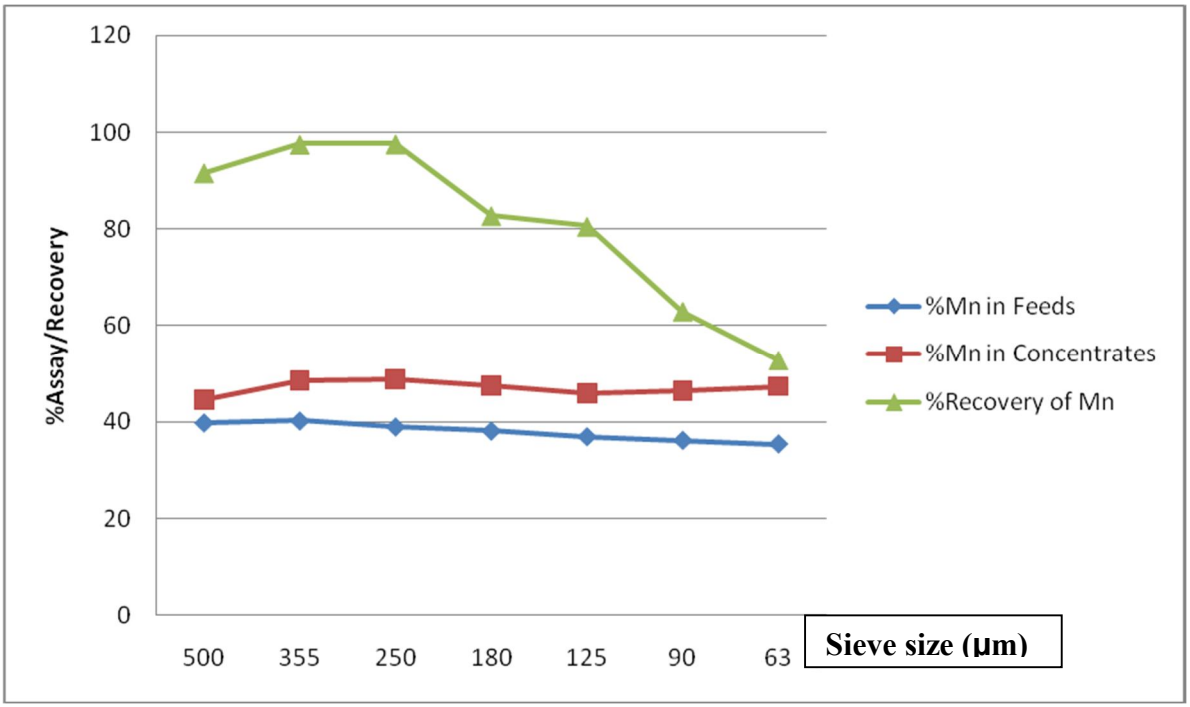


Figure 5.3: The percentages of Mn in the feeds, concentrates and its recoveries for the various size fractions using the Shaking Table.

5.7 Separation Test Using Magnetic Separator

Table 5.4 gives the results of concentration test using magnetic separator technique. Concentration test using the Denver magnetic separator was conducted. It was found that a maximum recovery of 77.8%Mn and a concentrate with a highest grade of 52.63%Mn was achieved at a size fraction of -355 + 250 μm. This grade of manganese met the stated literature value of 52.5%Mn required for the production of ferromanganese alloys. The graph of percentage recovery plotted against size fraction using the magnetic separation technique is shown in Figure 5.4

Table 5.4: Metallurgical Balance for Magnetic Separator

Sample	**Feed**			**Concentrate**			**Recovery**
Sieve Size (µm)	Weight (g) F	Mn(%) Assay F	Mn Unit Ff	Weight (g) C	Mn(%) Assay C	Mn Unit Cc	Recovery Cc/Ff x 100
-710+500	499.50	39.83	19895	175.07	51.02	8932	44.90
500+355	498.00	40.24	20039	193.82	51.33	9945	49.63
-355+250	497.00	38.97	19368	286.26	52.63	15065	77.78
-250+180	506.00	38.11	19284	222.02	51.20	11367	58.95
-180+125	497.80	36.90	17986	90.70	50.66	4595	25.55
-125+90	4497.50	36.13	17602	73.79	48.62	3588	20.38
-90+63	494.41	35.38	166785	143.40	48.94	7018	41.81

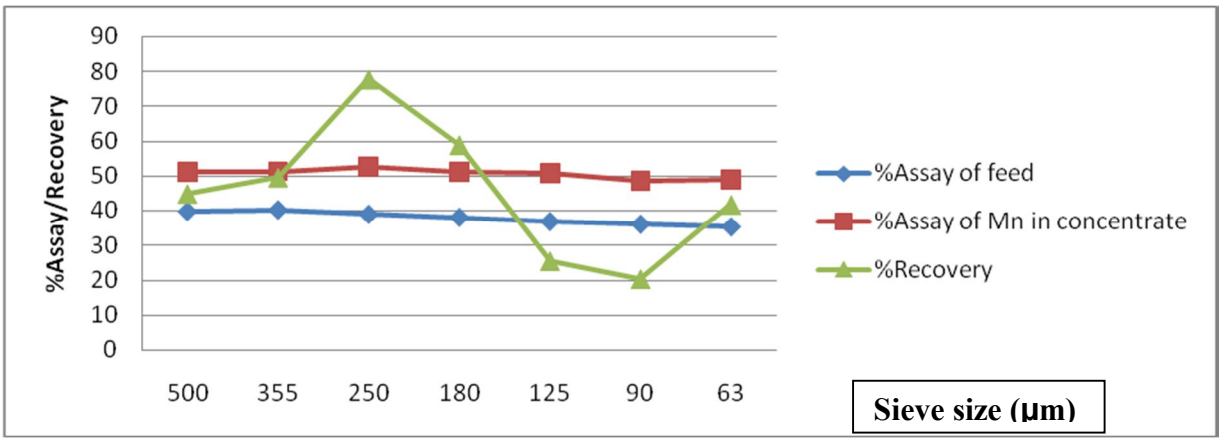


Figure 5.4: The percentages of Mn in the feeds, concentrates and its recoveries for the various size fractions, using the Magnetic separator.

5.8 Separation Test Using Spiral Concentrator

The result of concentration test using spiral concentrator is presented in table 5.5 and the graph is presented in Figure 5.5. It was observed that the recoveries decreases with a decreases in the size fraction and the highest recovery was noted to be 99%Mn with a concentrate of maximum grade of 49.34%Mn at this sieve range (-710 + 500)µm. This grade of manganese obtained do not meet the stated literature value of 52.5%Mn required for ferromanganese production

TABLE 5.5: Metallurgical Balance for Spiral Concentrator

Sample	**Feed**			**Concentrate**			**Recovery**
Sieve,Size (µm)	Weight (gm) F	Mn(%) Assay F	Mn Unit (Ff)	Weight (gm) C	Mn(%) Assay C	Mn Unit (Cc)	Recovery Ff/Cc x 100
-710+500	942.12	39.83	37581	753.41	49.34	37225	99.10
-500+355	958.39	40.24	38566	763.72	49.04	37452	92.11
-355+250	951.61	38.97	37162	743.87	48.83	36323	97.74
-250+180	953.05	38.11	36321	730.66	46.75	34158	94.04
-180+125	931.32	36.90	34366	667.15	46.54	31049	90.34
-125+90	936.33	36.13	33830	603.49	47.05	28394	83.93
-90+63	790.40	35.38	34332	623.57	43.71	27256	79.04

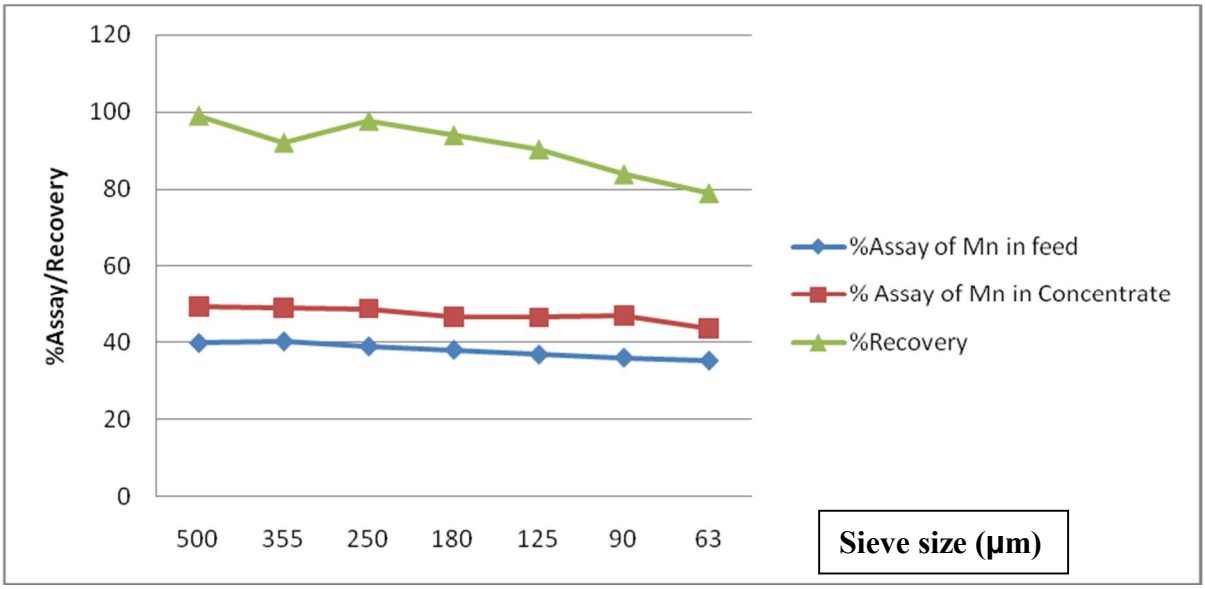


Figure 5.5: The percentages of Mn in the feeds, concentrates and its recoveries for the various size fractions, using the spiral concentrator.

5.9 Comparative Analysis of the Methods used in Upgrading of the Wasagu Manganese Ore

Table 5.6 and Figure 5.6 gives the percentages and variations of Mn in the concentrates while Table 5.7 and Figure 5.7 gives the percentages of their corresponding recoveries values and variations for the Spiral, Shaking Table and Magnetic Concentration Methods for the various size fractions. From the results Magnetic concentration method gave the highest value of 52.63% Mn at size fraction (-355+250) μm, followed by Spiral method with 49.34%Mn at size fraction -0.71+0.500μm and Shaking Table method 48.89%Mn at size fraction (-355+250)μm with their corresponding % recoveries of 77.8%, 99.10% and 97.60% respectively. Figure 5.5 comfirmed the variation of manganase in the various size fractions and showed that as size fraction reduces the percentage of manganese increased to some extent and further reduces. This trend agreed with the binomial distribution pattern for most minerals concentrated using the units processing methods. The 52.63%Mn grade concentrate obtained using magnetic method of concentration meet the stated literature value of 52.5%Mn required for the production of ferromanganese alloys. Hence magnetic concentration method is the best adoptable method for the upgrading of the Wasagu manganese ore.

Table 5.6: The percentages of Mn in the concentrates of the Spiral, Shaking Table and Magnetic Concentration Methods for the various size fractions

Sample		Shaking Table	Magnetic method	Spiral Method
Sieve Size(µm)	Mn(%) Assay (Feed)	Mn(%) Assay Conc.	Mn(%) Assay Conc.	Mn(% Assay Conc.
-710+500	39.83	44.53	51.02	49.34
-500+355	40.24	48.64	51.33	49.04
-355+250	38.97	48.89	52.63	48.83
-250+180	38.11	47.50	51.20	46.75
-180+125	36.90	45.89	50.66	46.54
+125+90	36.13	46.48	48.62	47.05
-90+63	35.38	47.33	48.94	43.71

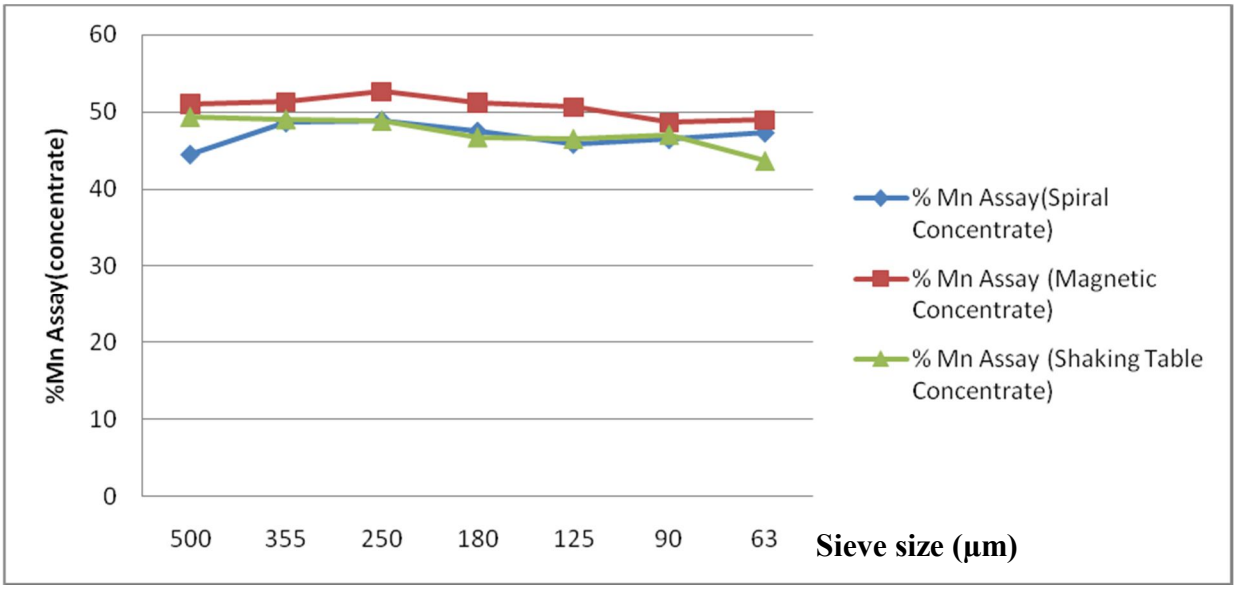


Figure 5.6: The variation of the percentages of Mn in the concentrates of the Spiral, Shaking Table and Magnetic Conctn. Methods for the various size fractions

Table 5.7: The Percentages of Recoveries, for the Diff. Concentration Methods.

Sample SIEVE SIZE(µm)	**Magnetic Method** Recovery Cc/Ff x 100	**Shaking Table** Recovery Cc/Ff x 100	**Spiral Method** Recovery Cc /Ff x 100
-710+500	44.90	91.59	99.10
-500+355	49.63	97.50	92.11
-355+250	77.78	97.60	97.74
-250+180	58.95	82.70	94.04
-180+125	25.55	80.50	90.34
-125+90	20.38	62.90	83.93
-90+63	41.81	52.70	79.04

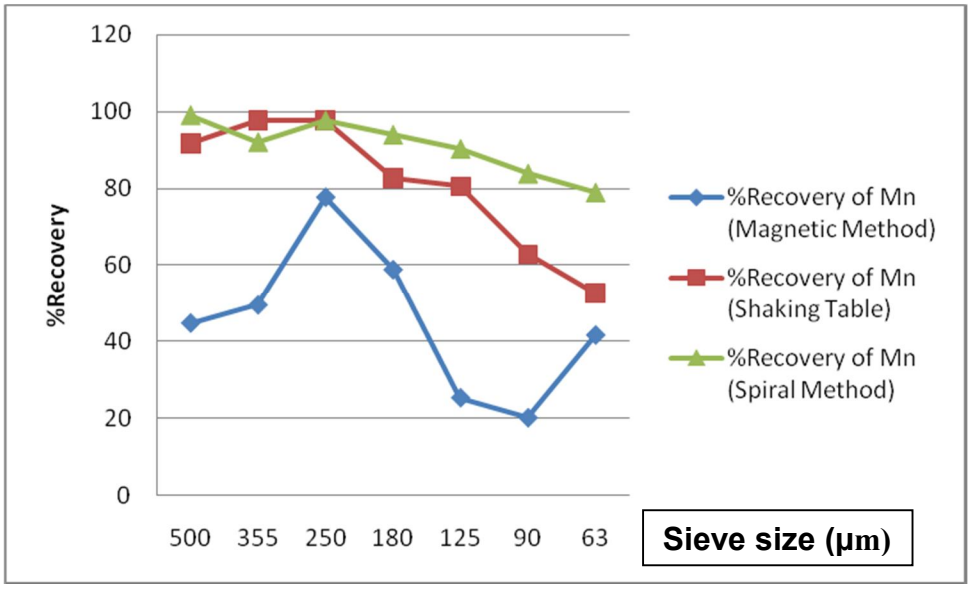


Figure 5.7: The comparism between the percentages of recoveries of Mn using the Spiral, Shaking Table and Magnetic Concentration Methods for the various size fractions.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

The upgrading of Wasagu manganese ore to a metallurgical grade concentrate was investigated. In the process, the chemical analysis of the ore revealed that the head sample of the ore assays 38.76%Mn (50.14%MnO) on the average. The mineralogical characteristics of the ore revealed that it predominantly consist of

spessartine, while quartz and hematite are in minor amount and other minerals associated with the ore are in traces. The work index of the ore was found to be 9.2kwh/tone making the ore a soft ore of grade B (Mathur, 1985).

Separation tests on the ore were carried out using both gravity and magnetic separation techniques. The gravity separation technique involved the use of Wifley shaking table and laboratory scale Mozley spiral concentrator. The shaking table gave an optimum concentrate grade of 48.89%Mn and a recovery of 97.60%, while the Mozley spiral concentrator gave an optimum concentrate grade of 49.34%Mn and a recovery of 99.10%. The magnetic separation test gave an optimum concentrate grade of 52.63%Mn at a recovery of 77.8%. The grade of manganese concentrate obtained from magnetic separation test meet the required literature value of 52.5%Mn for the production of ferromanganese. Based on these results, the magnetic separation technique gave the best grade manganese concentrate and hence is the most recommended method for the upgrading of the ore.

6.2 Recommendations

Based on the investigation carried out, the manganese ore is a complex ore in which the manganese bearing mineral is sperssartine / almandine. Therefore the manganese is chemically combined with alumina and silica and cannot be effectively separated by physical means alone. Hence, it is recommended that other separation techniques need to be employed that will consider thermal decomposition or froth floatation.

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APPENDICES

APPENDIX 1

SPECIFICATIONS FOR METALLURGICAL GRADE MANGANESE ORE/CONCENTRATE

Constituent (% dry Basis)	Assay
Mn_2O_4 minimum	66.6
Fe, Maximum	6
Al_2O_3 maximum	7
Al_2O_3+SiO_2 maximum	11
Al, maximum	0.18
P, maximum	0.19
Cu+ Pb + Zn, maximum	0.3

(Jacoby, 2003) " Manganese" Industrial Minerals and Rocks.



Plate ii: Photograph of Wasagu Manganese Ore (as-mined)



Plate iii: Photograph of processed Wasagu Manganese Ore

APPENDIX 2

Concentrate From Spiral Concentrator

Sample: Wasagu ore

Analysis: chemical ED-XRF parameter (in%) N.D = Not Detected

	SAMPLE SIZE (μm)	Al_2O_3	SiO_2	SO_3	K_2O	CaO	TiO_2	Cr_2O_3	MnO	AS_2O_3	Fe_2O_3	NiO	CuO	ZnO	SrO	PbO	MoO_3	BaO	V_2O_5	Re_2O_7	Bi_2O_3	P_2O_5	RuO_2	Sc_2O_3
1	-710 + 500	7.8	8.38	ND	0.374	0.793	0.30	0.097	63.13	N.D	13.1	0.099	0.085	0.086	0.006	N.D	0.12	0.2	0.089	0.13	0.089	0.25	ND	N.D
2	.500 .355	8.0	8.29	N.D	0.381	0.790	0.32	0.079	62.74	N.D	13.2	0.10	0.095	0.089	0.063	N.D	0.12	0.19	0.079	0.1	ND	0.25	0.28	N.D
3	.355 + 250	7.9	8.60	N.D	0.424	0.802	0.31	0.77	62.48	0.03	13.4	0.097	0.092	0.082	0.064	0.08	0.13	0.19	0.077	0.1	ND	0.26	0.24	0.01
4	-250 + 180	7.8	9.88	N.D	0.316	0.856	0.36	0.064	59.81	N.D	14.2	0.096	0.088	0.074	0.064	N.D	0.11	0.1	0.072	0.1	N.D	0.3	N.D	ND
5	-180 +125	8.1	11.1	N.D	0.350	1.15	0.35	0.073	59.55	N.D	13.9	0.090	0.087	0.057	0.056	N.D	0.13	0.1	0.078	0.1	0.075	0.29	N.D	ND
6	-125 + 90	7.7	9.93	ND	0.316	1.02	0.36	0.078	60.20	N.D	14.3	0.083	0.079	0.068	0.063	N.D	0.11	0.17	0.083	0.1	0.1	0.26	0.29	'ND
7	-90 + 63	10.0	12.0	0.084	0.340	0.848	0.35	0.069	55.92	N.D	13.6	0.88	0.081	0.060	0.054	N.D	0.10	0.19	0.086	0.10	N.D	N.D	N.D	0.007

APPENDIX 3

Tailings From Spiral Concentrator

Sample: Wasagu– Manganese – Ore

Analysis: Chemical ED-XRF **Parameter (in %) N.D = Not Detected**

	Sample Size (µm)	Al_2O_3	SiO_2	SO_3	K_2O	CaO	TiO_2	Cr_2O_3	MnO	AS_2O_3	Fe_2O_3	NiO	CuO	ZnO	SrO	PbO	MoO_3	BaO	V_2O_5	Re_2O_7	Bi_2O_3	P_2O_5	RuO_2	Sc_2O_3	Yb	Zr	Y_2O_3
1	-710 +500	12.9	12.0	0.075	0.311	0.528	0.38	0.059	50.75	ND	15.4	0.090	0.081	0.788	0.048	N.D	0.01	0.21	0.09	N.D	N.D	N.D	ND	N.D	N.D	0.061	N.D
2	-500 + 355	12.0	11.4	0.093	0.334	0.534	0.40	0.060	52.15	N.D	15.8	0.093	0.089	0.527	0.054	N.D	0.095	0.26	0.076	ND	N.D	0.12	ND	N.D	N.D	0.076	N.D
3	-355+ 250	8.8	8.83	N.D	0.309	0.586	0.37	0.072	58.84	003	16.8	0.11	0.10	0.31	0.056	0.21	0.24	N.D	0.085	0.1	N.D	0.25	0.32	N.D	N.D	0.04	N.D
4	-250 + 180	8.7	8.97	N.D	0.315	0.582	0.36	N.D	58.23	N.D	16.4	0.10	0.096	0.24	0.066	N.D	0.12	0.20	0.11	0-1	N.D	0.26	0.29	N.D	N.D	N.D	N.D
5	-180 +125	8.5	9.36	N.D	' 0.297	0.617	0.36	0.069	58.69	0.02	16.7	0.11	0.20	0.13	0.062	0.11	0.13	0.22	0.080	0.1	N.D	0.29	ND	0.009	N.D	N.D	0.042
6	-125 +90	8.60	10.0	N.D	0.368	0.756	0.33	0.069	58.05	N.D	15.5	0.098	0.090	0.10	0.061	N.D	0.12	0.20	0.089	0.1	0.083	0.25	0.31	0.01	N.D	N.D	N.D
7	-90 + 63	8.1	9.41	N.D	0.319	0.601	0.36	0.073	58.48	N.D	16.3	0.099	0.093	012	0.061	0.14	ND	0.21	0.081	0.1	N.D	0.24	0.29	0.02	N.D	0.04	N.D

APPENDIX 4

Concentrate From Wifley Shaking Table

Sample: Wasagu ore – Manganese – Ore

Analysis: Chemical ED-XRF **WF – Concentrate. Parameter (in %) N.D = Not Detected**

	Sample Size (μm)	Al_2O_3	SiO_2	SO_3	K_2O	CaO	TiO_2	Cr_2O_3	MnO	AS_2O_3	Fe_2O_3	NiO	CuO	ZnO	SrO	PbO	MoO_3	BaO	V_2O_5	Re_2O_7	Bi_2O_3	P_2O_5	RuO_2	Sc_2O_3	Yb	Zr	Y_2O_3	Nb
1	-710 + 500	1..05	1.09	0.047	0.430	0.731	0.37	0.074	56.98	ND	12.5	0.086	0.075	0.067	0.055	ND	0.088	0.2	0.087	0.11	ND	ND	0.24	ND	0.25	ND	ND	0.092
2	-500+355	7..8	8.42	ND	0.396	0.798	0.33	0.078	62.23	ND	12.6	0.092	0.087	0.070	0.064	ND	0.11	0.19	0.089	0.13	ND	0.27	0.26	0.007	.054	ND	ND	ND
3	-355+250	7..5	8.38	ND	0.387	0.818	0.33	0.069	62.55	ND	13.5	0.098	0.094	0.078	0.055	ND	0.11	0.18	0.078	0.13	ND	0.26	0.28	ND	0.17	ND	ND	ND
4	-250 +180	7.2	9.79	ND	0.322	1.19	0.35	0.074	60.77	ND	13.9	0.084	0.085	0.065	0.055	ND	0.11	02	0.082	01	ND	0.28	0.29	0.01	ND	ND	ND	ND
5	-180+125	7.6	9.96	ND	02.81	139	0.37	0.072	58.71	ND	14.1	0.074	0.094	0.053	0.046	ND	011	0.1	0.088	0.1	ND	0.29	0.30	ND	0.16	ND	0.04	ND
6	- 125+90	7..6	11.2	ND	0.277	1.26	0.38	0.070	59.47	ND	14.0	0.079	0.083	0.056	0.050	ND	011	0.1	0.076	0.1	.083	0.25	ND	0.01	0.12	ND	ND	ND
7	-90+63	7..3	9.72	0.04	0.336	1.10	0.39	0.072	60.56	ND	14.3	0.091	0.085	0.073	0.060	ND	0.10	0.2	0.085	0.1	ND	0.26	0.31	ND	0.74	ND	ND	ND

APPENDIX 5

Tailings From Wifley Shaking Table

Sample: Wasagu – Manganese – Ore

Analysis: Chemical EDX-XRF **WF – Tailings. Parameter (in%) N.D = Not Detected**

Sample Size (μm)	Al_2O_3	SiO_2	SO_3	K_2O	CaO	TiO_2	Cr_2O_3	MnO	AS_2O_3	Fe_2O_3	NiO	CuO	ZnO	SrO	PbO	MoO_3	BaO	V_2O_5	Re_2O_7	Bi_2O_3	P_2O_5	RuO_2	Sc_2O_3	Yb	Zr	Y_2O_3	Nb	Th
1 -710 + 500	12.6	12.9	0.073	0.404	0.601	0.444	0.062	ND	49.06	15.5	0.08	0.08	0.29	0.05	ND	0.093	0.2	0.78	0.10	ND	ND	ND	ND	0.19	0.10	.040	0.098	0.02
2 -500 + 355	8.5	9.12	ND	0.328	0.609	0.33	0.062	ND	58.80	16.0	0.095	0.08	0.98	0.059	ND	0.10	0.17	0.10	0.14	0.1	0.28	0.33	ND	0.23	ND	.042	ND	ND
3 -355 + .250	8.9	9.69	ND	0.343	0.625	0.463	0.064	ND	57.43	15.3	0.10	0.09	0.20	0.058	ND	0.11	0.19	0.09	0.1	ND	0.29	0.29	ND	.073	ND	ND	ND	ND
4 -250 + 180	8.5	9.71	0.04	0.326	0.697	0.31	0.067	ND	58.64	15.1	0.10	0.09	0.11	0.063	ND	0.12	0.19	0.08	0.1	ND	0.27	ND	ND	ND	ND	ND	ND	ND
5 -180 + 125	8.5	10.4	ND	0.339	0.754	0.34	0.066	ND	57.86	14.9	0.096	0.09	0.13	0.061	ND	0.11	0.17	0.78	0.14	0.84	0.26	0.29	ND	0.08	ND	ND	ND	ND
6 -125 +90	8.4	10.1	ND	0.366	0.736	0.34	0.065	ND	57.35	14.9	0.092	0.09	0.089	0.059	ND	0.12	0.17	0.84	0.1	ND	0.26	0.28	ND	0.05	ND	ND	ND	ND
7 -90 + 63	8.0	9.68	ND	0.348	0.664	0.35	ND	ND	58.86	15.0	0.097	0.09	0.095	0.060	ND	0.12	0.2	0.88	0.1	ND	0.25	ND	ND	0.43	ND	ND	ND	ND

APPENDIX 6

Sample: Wasagu – Manganese – Ore

Analysis: Chemical EDX-XRF **Magnetic Separation. Parameter (in %) N.D = Not Detected**

	Sample Size (μm)	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	V_2O_5	Cr_2O	MnO	Fe_2O_3	NiO	CuO	ZnO	BaO	Re_2O	Ag_2O	
1	-71 0+500 Magnetic	8.15	9.85	0.34	1.01	0.39	0.08	0.07	61.54	16.55	0.09	0.08	0.07	0.19	0.15	1.32	
2	-710 +500 Paramagnetic	7.87	8.00	0.44	0.56	0.52	0.12	0.09	65.28	14.25	0.11	0.08	0.09	0.10	1.19	1.32	A
3	-710 +500 Non magnetic	10.03	18.00	0.39	0.84	0.56	0.08	0.07	49.99	17.80	0.09	0.09	0.05	0.18	0.16	1.45	
4	-500+355 Magnetic	8.50	9.60	0.31	1.16	0.38	0.09	0.09	62.68	15.40	0.08	0.09	0.06	0.18	0.15	1.20	
5	-500+355 Para magnetic	8.05	8.00	0.40	0.74	0.41	0.09	0.07	65.68	14.80	0.11	0.07	0.08	0.15	0.17	1.15	B
6	-500+355 Non- magnetic	ND	11.87	0.41	0.58	0.43	0.08	0.07	59.85	15.25	0.11	0.08	0.08	0.15	0.17	1.21	

APPENDIX 7

Sample: Wasagu – Manganese – Ore

Analysis: Chemical EDX-XRF **Result of Magnetic Separation. Parameter (in %) N.D = Not Detected**

	Sample Size (μm)	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	Fe_2O_3	NiO	CuO	ZnO	BaO	Re_2O	Ag_2O	
1	-355 + 250 Magnetic	8.37	10.54	0.31	1.85	0.33	0.37	0.09	60.25	14.70	0.06	0.08	0.04	0.10	0.15	1.25	
2	-355 +250 Paramagnetic	7.85	7.75	0.52	0.69	0.40	0.09	0.071	67.34	13.45	0.10	0.07	0.08	0.10	0.18	1.20	C
3	-355 + 250 Non-Magnetic	8.55	11.87	0.41	0.58	0.43	0.08	0.07	59.85	15.25	0.11	0.08	0.08	0.15	0.17	1.21	
4	-250 + 180 Magnetic	8.6	9.90	0.32	1.30	0.42	0.09	0.079	62.28	15.20	0.09	0.072	0.04	0.19	0.19	1.15	
5	-250+180 Paramagnetic	8.35	8.40	0.40	0.85	0.32	0.09	0.09	65.50	14.00	0.11	0.07	0.07	0.19	0.16	1.12	D
6	-250 +180 Non - magnetic	8.50	14.48	0.49	0.55	0.48	0.09	0.07	57.82	14.90	0.11	0.09	0.072	0.183	0.15	1.20	

APPENDIX 8

CHEMICAL EDX-XRF OF MAGNETIC SEPARATION

Sample: Wasagu – Manganese – Ore

Analysis: Chemical EDX-XRF **Result of Magnetic Separation. Parameter (in%) N.D = Not Detected**

	Sample Size (μm)	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	V_2O_5	Cr_2O	MnO	Fe_2O_3	NiO	CuO	ZnO	BaO	Re_2O	Ag_2O	
1	-180 + 125 Magnetic	9.00	10.17	0.39	1.08	0.40	0.09	0.08	61.67	15.30	0.09	0.07	0.05	0.20	0.16	1.09	
2	-180 + 125 Paramagnetic	8,13	9.45	0.40	1.04	0.41	0.093	0.07	64.82	13.85	0.09	0.07	0.05	0.15	0.14	1.11	E
3	-180+125 Non- magnetic	8.47	19.00	0.39	0.61	0.40	0.07	0.064	54.63	14.10	0.10	0.08	0.56	0.15	0.16	12.5	
4	-125 + 90 Magnetic	8.55	10.35	0.37	1.01	0.38	0.09	0.08	60.74	16.45	0.09	0.07	0.05	0.21	0.10	1.06	
5	-125 + 90 Paramagnetic	8.15	9.53	0.40	1.00	0.41	0.10	0.09	64.21	14.40	0.10	0.08	0.06	0.17	0.16	0.99	F
6	-125 + 90 Non - magnetic	8.30	19.73	0.36	0.61	0.41	0.09	0.06	53.78	14.05	0.10	0.09	0.06	0.22	0.15	1.20	

APPENDIX 9

CHEMICL EDX-XRF OF MAGNETIC SEPARATION

Sample: Wasagu ore – manganese – ore

Analysis: chemical EDX-XRF **RESULTS MAGNETIC SEPARATION parameter (in%)**

N.D = Not Detected

	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	V_2O_5	Cr_2O	MnO	Fe_2O_3	NiO	CuO	ZnO	BaO	Re_2O	Ag_2O	
	8.90	9.80	0.38	0.80	0.39	0.09	0.07	61.48	15.90	0.10	0.07	0.06	0.15	0.15	1.00	
c	8.70	10.20	0.44	0.87	0.39	0.09	0.07	62.62	15.00	0.10	0.08	0.06	0.18	0.15	0.94	G
tic	8.55	10.03	0.41	0.79	0.47	0.09	0.08	61.73	15.15	0.11	0.08	0.07	0.19	0.15	0.100	