CHARACTERIZATION AND GRAVITY CONCENTRATION OF KURUNGU IRON ORE, KOGI STATE, NIGERIA

BY

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ZARIA, NIGERIA

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**A DISSERTATION SUBMITTED TO
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**DEPARTMENT OF METALLURGICAL AND MATERIALS ENGINEERING,
AHMADU BELLO UNIVERSITY,
ZARIA, NIGERIA**

MARCH, 2021

DECLARATION

I hereby declare that this dissertation entitled "characterization and gravity concentration of Kurungu iron ore, Kogi state, Nigeria" was carried out by me in the Department of Metallurgical and Materials Engineering. The information used from the literature has been duly acknowledged in the text and a list of references provided. No part of this dissertation has been presented for purpose of award of degree or diploma in any other institution.

_____	_____	_____
Name of Student	Signature	Date

CERTIFICATION

This dissertation entitled “Characterization and gravity concentration of Kurungu iron ore, Kogi state, Nigeria” byIhogbetin, Faderera Funmilola meets the requirements for the award of the degree of Masters in Metallurgical and Materials Engineering of Ahmadu Bello University, and is approved for its contributions to knowledge and literary presentation.

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DEDICATION

This dissertation work is dedicated to the Lord Almighty, Sovereign, the maker and controller of all things. He made this possible.

ABSTRACT

Characterization and concentration of Kurungu Iron ore has been undertaken. Bulk samples were collected from the deposit site located in Kurungu village Ajaokuta Local Government Area of Kogi State, Nigeria. The samples were crushed and pulverized and a representative sample obtained by coning and quartering method. Analysis of the representative sample was done using the XRF for composition analysis, XRD and SEM for the mineralogical analysis and the modified Berry and Bruce method was used to determine the work index of the ore. The XRF reveals that the ore contains 60.86% Fe_2O_3, 0.49% MnO, 0.10% CaO, 36.2% SiO_2, 0.04% CuO, 0.10% ZnO, 0.02%, Rb_2O, 0.36% In_2O_3, 0.1% Sb_2O_3, 0.24% La_2O_3, 0.57% Eu_2O_3 and 0.03% Re_2O_7. Mineralogical analysis by XRD revealed that the iron bearing mineral is Magnetite while Actinolite and Quartz are present as associated minerals. The liberation size was established to be -355+250 µm; having the highest grade value of 65.09%Fe_2O_3. The density of the ore was found to be 3.81 x 10^3kg/m^3. The SEM images show that the minerals were locked together in layers and the work index of 13.96kWh/t was obtained. Beneficiation of the ore using gravity concentration indicated that the iron of the ore can be upgraded from 44.15% to 55.4% Fe with a recovery of 77.80%. Based on the results, Kurungu iron ore can be seen as another potential deposit that can be explored and exploited for use in iron and steel production.

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ABBREVIATIONS, DEFINITIONS, GLOSSARY AND SYMBOLS

XRF	X-Ray Fluorescence
XRD	X-Ray Diffractometer
SEM	Scanning Electron Microscope
EDS	Energy Dispersive Spectrum
µm	Micrometer
%	Percentage
GSN	Geological Survey of Nigeria
RMRDC	Raw Material Research Development Centre
GPS	Global Position System
GDP	Gross Domestic Product
LOI	Loss on Ignition

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

The enormous growth of industrialization from the eighteenth century onward has led to the dramatic increase in the annual output of most mineral commodities, particularly metals. The forms in which metals are found in the crust of the earth and as sea-bed deposits depend on their reactivity with their environment, particularly with Oxygen, Sulphur, and Carbondioxide. Most ores are mixtures of extractable minerals and extraneous rocky material described as gangue. They are frequently classed according to the nature of the valuable mineral (Barry et al, 2016).

Nigeria as a nation is blessed with abundant solid mineral resources distributed in most of the states of the federation. According to reports by the Nigerian Geological Survey Agency, Nigeria has some thirty four known major mineral deposits distributed in locations across the country and offers considerable attraction for investors. There is at present an upsurge of interest in the development of solid mineral resources whose production in the last 30 years has been declining in every case. The privatization, commercialization and general reform exercises currently being undertaken by the government of Nigeria under the Ministry of solid minerals Development are expected to lead to an upsurge in the exploration and development of Nigeria's solid mineral resources(Obaje, 2009).

Three types of metamorphosed iron oxide rich layered metasediments are found in the North West and central parts of the Nigerian basement. The most important economically are those occurring within the Okene migmatite complex in southcentral Nigeria. Nigeria has the potentials of becoming a regional economic hub in the West

African sub-region, but it has been recognized that the growth of Nigeria is slow due to lack of domestic production of iron and steel among others (Elijah, 2003).

Iron and Manganese are two essential ingredients for the production of steel, but Iron is the major component; usually over 90 percent (Ahmad et al, 2017).At present there is no satisfactory substitute for steel even in modern industrialized societies, the supply of iron will therefore remain an important component to industrial development in the twenty-first century. While the developed countries are able to exploit their mineral resources efficiently, the developing countries are faced with inadequate capital and a lack of required technology, such that their dependency on the developed countries is inevitable (Bamalli et al, 2011).

Nigeria is blessed with large reserves of proven and unproven iron ore deposits, only one of the deposits in the proven reserves is currently being exploited and processed for possible use that is the Itakpe iron ore deposit;the deposit has an estimated reserve of about 200 million metric tonnes (Bamalli et al 2011; Elijah, 2013). However, this deposit, based on the design requirement of the Ajaokuta and Aladja plant, will only last for 25 years. This is grossly inadequate for the establishment of a formidable foundation for a well- projected integrated iron and steel plants. Also the Agbaja iron ore deposit, even though the largest iron ore deposit in Nigeria has a very high phosphorous content in addition to its extremely fine grained texture (Alexander et al, 2015).

1.2Statement of Problems of the Research

Most of the minerals found in Nigeria still remain unexploited due to inadequate knowledge on their status, economic viability and requisite mining technologies which has resulted to low investment in the minerals and mining sectorand currently, there is no available information or data on the characterization and possible beneficiation route of Kurungu iron ore deposit.

1.3 Justifications of the Research

Nigeria is blessed with abundant mineral resources and for obvious economic and strategic reasons, there is need to locally develop sustainable sources of raw materials for iron and steel production. Kurungu iron ore deposit covers a land mass area of about 320,000m^2. It has an estimated reserve of over 50 million tonnes (Preliminary estimation). This research therefore, makes a case on the ore for the following reasons;

I. Proper characterization of the deposit will help in exploration and encourage local and foreign investment
II. The deposit can be an additional source of iron ore to complement the existing ones
III. Creation of job opportunities for the native and
IV. Increase of government revenue in the areawhich will in turn encourage the government to provide infrastructural facilities.

1.4 Aim and Objectives

The study is aimed at characterizing and beneficiating Kurungu iron ore deposit located in Ajaokuta Local Government Area of Kogi State, Nigeria.

The objectives are to;

1. determinethe chemical, mineralogical and petrological composition of the ore using XRF, XRD, SEM/EDS and optical microscope.

2. examinesome physical properties such as the density, specific gravity and the electrical conductivities of the ore.

3. determine the mineral assay and the liberation size analyses of the ore sample.
4. determine the work index of the ore sample.
5. beneficiate the ore sample using gravity method.

1.5 Scope of the Study

The scope of this research work involves collecting the sample form the deposit site and characterizing it to know its chemical and mineralogical properties and then determine the liberation size and beneficiating using gravity method.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Introduction

A mineral is a naturally occurring inorganic element or compound having an orderly internal structure and a characteristic chemical composition, crystal form, and physical properties (USGS 2005). Metals rarely occur in their pure“native” form, but are found in nature combined with sulphur as minerals called sulphides or oxygen as minerals called oxides. An exception is gold which occurs in its pure metallic form, which is why it was the first metal discovered and used by humans (Obaje, 2009).Apart from gold, metals only came into use when technology was devised to remove the sulphur and oxygen from their ores (USGS 2005). Mineral deposits are concentrations of metallic or other mineral commodities in the Earth’s crust that result from a variety of complex geologic processes (Plumlee, 2015)

An "ore deposit" is a mineral deposit which has high enough grades of metal that makes it economic to mine, this means that the costs of removing the minerals from the rock and separating the metal from the other minerals are lower than the value of metal per tonne of rock. Rock worth mining is called an ore (Plumlee, 2015).Ore minerals are the minerals of economic interest for which the explorationist is searching;they can be metallic or nonmetallic. Mineralogy is used to understand the relationships between the ore mineral and the uneconomic host rock for their eventual separation. The valuable mineral in one deposit may be a gangue mineral in another, e.g. quartz is valuable in silica sands, but is a gangue mineral in auriferous quartz veins (Obaje 2009).

2.2Ore Mineral Characterization

Mineral characterization is the study of minerals in terms of their size, chemical composition, morphology, texture, association and other attributes. There is an

established and increasingly important need for this type of study to be applied to deposits of industrial minerals due to increasing specification requirements for raw materials and mineral products to compete in the market and the realization that mineral characterization can ensure optimization of mineral processing, thus maximizing profit. Developments in microanalytical technology in recent years have made it possible to characterize minerals in an increasingly comprehensive manner (Cook, 2000).Characterization refers to the broad and general process by which a material's structure and properties are probed and measured. It is a fundamental process in the field of materials science, without which no scientific understanding of engineering materials could be ascertained. Ore characterization involves the qualitative as well as the quantitative analyses of various engineering materials like ores and products like metals, alloys and slag.

The properties of a mineral govern the ease with which existing technology can extract and refine it and this may affect the cut-off grade. Proper exploration techniques require detailed and qualitative beneficiation techniques. Hence, there is need for mineralogical characterization of the ore to obtain clear information on its compositions, texture, morphology and concentrations of respective constituents and to recommend better beneficiation techniques (Muriana, 2015).

The information that is required from a sample includes some, or all, of the following: (i) the grade of the economic minerals; (ii) the bulk chemical composition; (iii) the minerals present; (iv) the proportions of each of these and their chemical compositions; (v) their grain size; (vi) their textures and mineral locking patterns; (vii) any changes in these features from one part of an ore body to another (Joan et al, 2015).

Characterization of iron ore is a very important step required before beneficiation and iron production takes place. In this procedure, the quantity, grade or quality, densities,

shape, and physical characteristics are determined to allow for appropriate application of technical and economic parameters to support production planning and evaluation of the economic viability of deposits (Joan *et al*, 2015).

2.3 Iron Ore

Iron ore is the most abundant rock forming element and composes about 5% of the Earth's Crust. Iron is, however, present in low concentration in most parts of the earth, thus a deposit must have a high percentage of the metal to be considered ore grade for economic purposes. Typically, a deposit must contain at least 25% iron to be considered economically viable. Exploitation of large, low grade iron ore deposits can be achieved through concentration of the iron (Charles,2014).

An iron ore deposit is a mineral body of sufficient size, iron content, and chemical composition with both physical and economic characteristics that will allow it to be a source of iron either immediately or potentially. Iron ore deposits are formed by three geological processes: direct sedimentation - forming bedded sedimentary deposits, igneous activity - forming segregation or replacement deposit and enrichment due to surface and near surface weathering (Charles, 2014).

Iron ore consumption for steelmaking was standing at 850 million tonnes at the end of the twentieth century and was estimated to reach more than 1.3 billion tonnes over the first quarter of the next century. The known world resources of crude iron ores are approximately 800 billion tonnes containing about 230 billion tonnes of Fe(Abraham *et al*, 2012). It is apparent that most of the known deposits contain low-grade ores with iron contents less than 30%. It is thus imperative to find new sources of iron ore to supplement the existing sources, in order to meet the growing demand. Therefore,

revealing and exploiting new deposits of iron ores, particularly of high-grade, is very important (Abraham*et al*, 2012).

One of the most important determining factors for establishing iron and steel plants is the availability of iron ore with good geological, mineralogical and metallurgical properties. Ores containing very high quantities of magnetite or hematite (greater than 60%Fe) are known as “natural ores” or “direct shipping ore”, meaning they can be fed directly into the iron making blast furnaces. The major raw material used to make pig iron is called the iron ore and thus the pig iron is the main raw material to make steel. It has been observed that 98% of the mined iron ore is used to make steel (Agava*et al*, 2016).

Iron, along with its generic products, is currently the most widely utilized metal in the various sectors of the world’s economy. Many factors contribute to this, ranging from the good mechanical properties it possesses to the relative low cost associated with its production. Methods of Iron production include; the blast furnace (BF) route (pig iron) and the direct reduction (DR) route (sponge iron) among others. The iron rich ore can be charged directly in its natural form as a raw material into a blast furnace without any further processing. Iron that contains a lower iron content must be upgraded through beneficiation process before it is charged into the BF or DR furnaces (Abraham *et al*, 2012).

2.4 World Iron Ore Deposits

The world resources of iron ore are estimated to exceed 800 billion tons of crude ore containing more than 230 billion tons of iron (Charles, 2014). The annual world production of iron ore is usually about one billion tonne and, although iron ore is

produced in about fifty countries, the eight largest of these countries produce more than 80% of the world total (Charles, 2014). Table 2.1 presents the iron ore production distribution of the world and Table 2.2 shows the chemical composition of iron ore from some countries.

Table 2.1: Iron Ore Production

Country	Production in metric tonne		
	2009	2010	2011
China	880	1070	1200
Australia	394	433	480
Brazil 300 370	300	370	390
India	245	230	240
Russia	92	101	100
Ukraine	66	78	80
South Africa	55	59	55
USA	27	50	54
Other countries	181	199	201
World total	2240	2590	2800

Source: Charles, 2014

Table 2.2: Chemical Composition of Iron Ores from Some World's Major Producing Nations

Ore Mine	Nation	Chemical composition, mass%				
		Fe	SiO_2	Al_2O_3	S	P
Itabira	Brazil	68.9	.035	0.06	0.010	0.030
MBR	Brazil	67.3	0.79	0.72	0.005	0.037
Carajas	Brazil	65.4	1.00	1.05	0.010	0.038
Nanfen	China	63.4	6.28	1.17	0.110	
Goldsworthy	Australia	63.2	4.90	1.60	0.035	
Hammersley	Australia	62.7	4.20	2.73	0.016	0.059
Irvine Island	Australia	54.4	21.3	0.23	0.040	0.010
Goa	India	57.8	2.50	6.50	0.020	0.040
Donimalai	India	63.5	3.00	3.00	0.050	0.080
Bailadila	India	64.0	2.50	2.50	0.050	0.100
Bakal	Russia	60.7	2.40	2.00	0.030	0.004
Tula	Russia	52.2	10.10	1.25	0.100	0.600
Mesabi	USA	57.5	10.10	0.70	0.010	0.060
Minnesota	USA	54.3	6.80	0.40	0.230	
Reserve Pellet	USA	63.0	8.10	0.40	0.003	0.025
Rushekye	Uganda	68.4	0.96	0.58	<0.001	<0.02
Kamena	Uganda	67.9	0.80	0.65	0.002	0.02
Kyanyanuzinda	Uganda	68.7	0.41	0.35	0.006	0.02
Nyamiyaga	Uganda	69.0	0.62	0.43	0.001	<0.02

*: H, M and L are the high-, medium- and low-grade iron ores, respectively; Source: (Charles, 2014)

2.5Nigerian Iron Ore Deposits

Nigeria is among the African countries with vast iron ore deposits which can be found in some states in the country, Itakpe in Kogi State is believed to have the purest deposits of iron ore and other states where it is deposited includes: Abia, Anambra, Bauchi, Benue, Kwara, Plateau and Nasarawa (Stephen, 2012). Mineral resources contribute about 90% of Nigeria's export by value and aid her industrial development. The location of these minerals depends entirely on the nature of the rocks and on past geological history. Thus we have those associated with basement complex rocks and those that go with sedimentary rocks. In Nigeria, we have two types of rocks, the basement complex rocks which comprise both metamorphic and igneous rocks and secondly the sedimentary rocks (Obaje, 2009).Exploration for iron ore started in Nigeria in 1963 and the effort led to the discovery of commercial quantity of iron ore at Itakpe, Kogi state in 1973. By 1977, iron ore discoveries at Itakpe had reached 200 million tonnes (Ola *et al*, 2009). More exploration moves yielded other discoveries in Agbaja, Ajabanoko, Ochokochoko, Agbade-Okudu and Koton-Karfe. Inventory of proven iron ore deposits in Nigeria is presented in Table 2.3, while iron ore reserves still under investigation are given in Table 2.4 (Ohimain, 2013, Raw Material Research and Development Council 2000).

Table 2.3: Proven Nigerian iron ore reserves and their chemical composition

Location	**Percentage (%)**									
	Fe	**Fe_2O_3**	**SiO_2**	**Al_2O_3**	**CaO**	**MgO**	**P_2O_5**	**MnO**	**TiO_2**	**Reserved (tonnes)**
Agbaja	45-54	62.64	8.55	9.60	0.72	0.38	2.08	0.14	0.37	2 billion
Itakpe	38-45	53.10	44.80	1.00	0.30	0.20	0.05	0.05	0.10	200-300 million
Ajabanoko	35.61	47.74	0.41	3.39	0.21	0.15	0.11	0.05	0.06	30 million

Choko-choko	37.43	47.65	4.30	9.67	0.15	0.18	0.05	0.52	0.16	70 million
Agbade Okudu	37.43	29.41	0.62	-	0.72	0.38	2.08	0.14	0.37	70 million
Koton-Karfe	48.18	68.83	5.13	6.70	0.45	0.07	2.14	0.56	0.25	850 million

Source:Federal Ministry of Petroieum and Mineral Resources (Bamalli *et al* 2011)

Table 2.4: Nigerian Iron Ore Deposits under Investigation

S/no.	**Locations**	**State**	**Iron Content,%**
1	Muro hills	Nasarawa	25 – 35
2	Dakingari	Kebbi	22 – 52
3	Tajimi	Kogi	22 – 52
4	Ayaba	Kaduna	27.5
5	Rishi	Bauchi	14 – 19
6	Gamawa	Bauchi	40 – 45
7	Karfa	Borno	34 – 45
8	Eginjia(Egenerga)	Benue	34 – 45
9	Oko	Anambra	34.4
10	Gbege		42.7
11	Ajase	Kwara	39.0
12	Gujeni	Kaduna	48.6
13	Chokochoko	Kogi	35.73

Source: Ohimain, 2013, Raw Material Research and Development council(2000)

There is a relationship between iron and steel consumption and industrial and infrastructural development. In realization of this fact the Federal Government of Nigeria in 1979 launched the Country into a new era of Iron and Steel technology by the establishment of the Delta and Ajaokuta steel projects (Ohimain, 2013).The establishment of the project was good and a welcomed idea but the project never got completed because of a number of factors. One of the factors is lack of continuous supply of local raw material. The cost of importing raw materials in terms of foreign exchange and the continuous devaluation of the Naira made it impossible and uneconomical for the plant to be operated. Even with the present arrangement the government had gone into for the Ajaokuta, and Delta Steel plants, the same problem of sourcing and continuous supply of the basic and important raw material (Iron ore concentrate and coking coal) locally will prevent continuous production of steel,

because the Itakpe Iron ore deposit estimated at 200 million tonnes cannot meet the demand of the two plants (Agava, 2016).

The viability of any iron ore and steel plant is dependent on the availability and long-time continuous supply of the basic raw material (iron concentrate). Also because the iron ores are bulky there is the need to source them locally, not only to reduce dependence on the imported source but scarce foreign exchange will also be saved (Agava, 2016).

Nigeria has ample iron ore deposits which are yet to be fully exploited and utilized for the development and economic growth of the nation. There are iron ore deposits in various states which have not been fully exploited and thus there is need toobtain information on the quality of the iron ore deposits and the method for pre- processing as a precursor for use by a steel plant.

Recent studies show that Banded Iron Formation (BIF) occurs in central Nigeria specifically in the Lokoja-Okene-Kabba triangle. The most notable iron ore occurrence in this region are found in Itakpe, Ajabanoko, Ochokochoko, Tajimi, Agbado-Okudu, Ebiya, Ero, Echaraku, Ozenyi and Udiarehu (Elijah, 2013). The percentage iron content of the ores in this region could be classified as rich ores (> 50 % Fe), medium grade ores (30 – 50 % Fe) and lean ores (25 – 30 % Fe) (Ohimain, 2013).Iron ore deposits have not been fully explored and exploited in Nigeria and if fully exploited can serve as a source of foreign exchange for the country (Ahmad*et al*, 2017).

2.6 Types of Iron Ore

a. Hematite (Fe_2O_3) is also known as "natural ore", a name which refers to the early years of mining, when certain hematite ores containing up to 66% iron could be fed directly into iron-making blast furnaces. Hematite deposits are mostly sedimentary in

origin, such as the banded iron formations (BIFs). BIFs consist of alternating layers of chert (a finely grained re-crystallized quartz), hematite and magnetite. Their formation is not fully understood, though it is known that they formed by the chemical precipitation of iron from shallow seas about 1.8-2.6 billion years ago, during the Precambrian period (Mineral Information Institute 2006).

b. Magnetite (Fe_3O_4) is a naturally occurring metallic mineral that is occasionally found in sufficient quantities to be an ore of iron. It contains both iron (II) oxide (FeO) and iron (III) oxide (Fe_2O_3) (Charles, 2014). The mineral magnetite actually has higher iron content than the mineral hematite. However, whilehematite ore generally contains large concentrations of hematite, magnetite ore generally holds low concentrations of magnetite. As a result, this type of iron ore must be concentrated before it can be used to produce steel. Magnetite ore's magnetic properties are helpful during this process(Mineral Information Institute, 2006, Prinsloo, 2010).

c. Martite(Fe_2O_3) is a secondary hematite formed by chemical replacement of magnetite produced at depth and pressure. The replacement proceeds from the outer edges towards the center of the magnetite grains commonly along crystallographic planes (Charles, 2014).

d. Goethite and Limonite(FeO(OH)) are secondary minerals formed by oxidation of Iron-carbonates, hematite, martite and magnetite. Goethite masses are present in quartz where the goethite has replaced hematite. Goethite that replaced hematite does not contain manganese, whereas goethite that replaced carbonates and martite contains significant amounts of Manganese (up to 27% wt. Mn). They are 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 (Prinsloo, 2010, Charles, 2014).

e. Siderite($FeCO_3$) ore 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 to hematite with 70% iron (Charles, 2014).

2.7 Gangue Minerals

Most iron ores contain impurities, which are collectively known as gangue. The presence of small amounts of some elements can have either bad or good effects on the characteristics of an iron ore or on the operation of a steel plant. Flux is normally added to iron ore feed in the blast furnace to increase the furnace efficiency, while other chemicals are added to improve the end product qualities. Ideally, iron ore contains only iron and oxygen, but typically, iron ore contains a lot of elements which are often unwanted in modern steel (Roy, 2008)

There are four main slag forming constituents in iron ores, which include the acidic oxide silica (SiO_2) and the basic oxides lime (CaO) and magnesia (MgO) as well as the neutral alumina (Al_2O_3). Most iron ores have an excess of SiO_2 and Al_2O_3 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 (Charles, 2014). Other oxides such as titanium oxide, chromium oxide e.t.c may also accompany the iron ore depending on the location and formation of the ore.

2.8Deleterious Elements

Common deleterious elements in iron ores are phosphorus and sulphur. Uncommon deleterious elements include vanadium, copper, zinc, chromium, nickel, arsenic, lead, and tin.

Phosphorus - the major effects of phosphorous on iron are increase hardness and strength, lowers solidus temperature, increases fluidity and cold shortness (Srivastava 2001, Mineral Information Institute 2006). Depending on the use intended for the iron, these effects are either good or bad. The strength and hardness of an iron increases with the increasing concentration of phosphorus. At concentrations of phosphorous higher than 0.2%, iron becomes increasingly cold short, or brittle at low temperatures, it lowers the liquidus temperature allowing the iron to remain molten for longer, and increases fluidity (Srivastava, 2001). Remedies for preventing high phosphorus content in iron include avoiding high phosphorus content ores or oxidizing the phosphorus during the refining process (removal of bubbles) by adding iron oxide.

Sulphur usually presents in small quantities in many ores. It dissolves readily in both liquid and solid iron at the temperatures of iron smelting. The effects of even small amounts of sulphur are immediate and serious; it causes iron to be red or hot short. Hot short iron is brittle when hot and the degree of hot shortness is in direct proportion to the amount of sulphur present. Iron with over 0.03% sulphur content is avoided (Mineral Information Institute 2006).

Sulphur can be removed from the ores by roasting and washing, and by the addition of manganese. Roasting of ore oxidizes sulphur to form sulphur dioxide (SO_2), which either escapes into the atmosphere or can be washed out. Addition of manganese removes sulphur in iron ores because manganese forms a high melting sulfide at high

temperatures (1610^{o}C) and therefore, prevents the formation of a liquid iron sulfide at the grain boundaries (Mineral Information Institute 2006, Charles, 2014).

2.9 Sampling

Sampling is the removal from a given lot of material a portion that is representative of the whole yet of convenient size for analysis(Wills, 2006). It is done either by hand or by machine. Sampling is a scientific, selective process applied to a large mass or group (a population, as defined by the investigator) in order to reduce its bulk for interpretation purposes(Wills, 2006). This is achieved by identifying a component part (a sample) which reflects the characteristics of the parent population within acceptable limits of accuracy, precision, and costeffectiveness. In the minerals industry the average grade of a tonnage of mineralized rock (the population) is estimated by taking samples which are either a few kilograms or tonnes in weight. These samples are reduced to a few grams (the assay portion) which are analyzed for elements of interest (Wills and Napier-Munn, 2006)

Mineral Sample Preparation is a vital stage in the process of minerals analytical testing. The purpose of sample preparation is generally the production of a homogeneous sub-sample, representative of the material, correct preparation is critical to obtaining meaningful analytical results.

The size of the laboratory sample is important, too small a sample will not be representative, and too much sample will be unnecessary. Two methods are recommended for sample splitting: riffles, coning and quartering(Wills, 2006).

2.10 Iron ore Characterization Methods

Iron ore characterization is very important in quantitative classification of mineral deposits and all other steps in process flow sheet development. Without proper understanding of the ore characteristics of the deposit, it may be impossible to develop a successful process flow sheet. Iron ore characterization provides information for proper understanding of the mineralogical as well as the chemical nature of the ore (Wehleekema, 2017, Srivastava, 2001, Semukaaya, 2007). Analytical methods employed in metallurgical analysis are classified into classical and instrumental methods. The classical method is slow and is for practical purpose while the instrumental methods are faster and accurate. In the instrumental methods of analyses, measurement is made upon the system as a whole, a particular physical and chemical property of the system is measured to get desired results. Some of the common instrumental analytical techniques usually being used are Atomic Absorption Spectrophotometer (AAS), X-ray Fluorescence (XRF), X-ray Diffractometer (XRD), Scanning Electron Microscopy (SEM) etc.

2.10.1 X-ray fluorescence spectroscopy (XRF)

An x-ray source in the XRF machine is used to irradiate the specimen and to cause the elements in the specimen to emit their characteristic of x-rays, when electrons are ejected from the atom making up the material. A detector system is used to measure the positions of the fluorescent x-ray peaks for qualitative identification of the elements present, and to measure the intensities of the peaks for quantitative determination of the composition. All elements but, low atomic number elements e.g. H, He and Li can be routinely analyzed by XRF. The x-rays have a precisely defined energy and the wavelength (velocity of electron) which are related by the plank's energy equation:(Semukaaya 2007, Salawu, 2015)

$$\boldsymbol{E_1 - E_2 = h}\mathrm{c} \qquad (2.1)$$

Where,

$\boldsymbol{E}_1$ = former energy level of the electron before filling the vacancy

$\boldsymbol{E}_2$ = new energy level of the electron after filling the vacancy

h = plank's constant,

c = velocity of light

As the energies and wavelengths are characteristic of the atoms of the elements emitting the x-rays, they are used for qualitative analysis while the intensity of these characteristic x-rays is related to the concentration of the particular element in the material and is used for qualitative elemental analysis (Wilberforce, 2016).

2.10.2 X-ray diffraction (XRD)

XRD refers to a rapid non-destructive test to determine mineralogical make-up of a crystalline specimen. The basic principle involves impinging an X-ray beam onto a sample and measuring the intensity of the diffracted beam at a range of angles. Depending on the spacing and orientation of the crystal planes, higher intensity peaks will be observed at certain positions.

XRD analysis is a non-destructive method of analysis. It is used for both qualitative and quantitative analysis of materials. This method can be used to determine the actual compounds present in an ore and can also distinguish the different crystal forms of the compounds. XRD can also be used to measure the structural properties (strain state, grain size, phase composition, preferred orientation and defect structure) of these phases and to determine the thickness of thin films and multilayer's, and atomic arrangement in amorphous materials including polymers and at interfaces. XRD is based on the diffraction of x-rays by polycrystalline solids and the reflections are called powder diffractometry. X-rays are deflected by crystals when the condition satisfying the

Bragg's equation is fulfilled. The Bragg's equation is given as Bragg's law by: (Myers, 2002, McQuarrie, 1997)

$$2d \sin \theta = n\lambda \quad (2.2)$$

Where d is the spacing between atomic planes in the crystalline phase and n is an integer called order of reflection. The intensity of the diffracted x-rays is measured as a function of the diffraction angle 2θ and the specimen's orientation.

These characteristic x-rays which are deflected by the crystal are detected by a detector and registered and displayed on paper chart recorder as series of peaks (x-rays patterns). Each has a unique x-ray powder pattern (fingerprints) because the line position depends on the unit cell size and the type of atoms present and their intensities of powder lines are used for qualitative phase analysis, while quantitative phase analysis depends on the accurate determination of the line intensity. XRD offers unparalleled strain states in thin films. XRD is non-contact and nondestructive, which makes it ideal for in situ studies. The limitation of XRD is that, compounds to be measured must be in a crystalline form to give rise to measurable signals and peak overlay may occur and worsens for high angle reflections (Myers 2002, Salawu, 2015, McQuarrie, 1997).

2.10.3 Scanning electron microscopy (SEM)

SEM is often the first analytical instrument used when a "quick look" at a material characteristic is required and the light microscope no longer provides adequate resolution (Kazuhisa, 2002). The method is used to study the properties of material at microscopic level. The most important applications are the investigation of the micro-structure and analysis of in-homogeneity such as defects, dislocations, submicroscopic

precipitates, inclusions, domains, etc. it is used for determining the composition of individual grains of particles and surface properties like topography (Salawu, 2015).

In SEM, a small area of the specimen of a material is irradiated with direct electron beam and characteristic x-ray are produced which are used for the qualitative analysis. As the beam interacts with the sample it creates various signals (secondary electrons, internal currents, photon emission, etc), all of which can be appropriately detected. The most important of the produced electrons (x-rays), called backscattered or primary reflected electrons are detected and amplified. The intensity of the backscattered electron signal is dependent on the atomic number of the specimen and specimen surface of different chemical composition will produce different signal intensities and appear different on the SEM screen. The signal intensities are used for quantitative analysis (Azad, 2018, Salawu, 2015).

2.11 Determination of Ore Physical Properties

The physical properties such as the specific gravity, density, electrical conductivity of the ore is determined to get adequate information of the composition of the mineral. The qualitative and quantitative results from these tests will provide information that is vital to the success of a mining, industrial or construction operation (Simon, 2018,). Data generated from these tests can yield the following data:

I. Precise and accurate identification of the mineral composition of samples, including valuable metals and other elements that may complicate processing
II. Support the most effective processing method for your ore
III. Appropriate sizing of processing equipment
IV. The exact weight of ores which is necessary to calculate shipping and storage costs

2.12 Mineral Processing

The first process most ores undergo after they leave the mine is mineral dressing (processing), also called ore preparation, milling, and ore dressing or ore beneficiation (Balasubramania, 2017). Ore dressing is a process of mechanically separating the grains of ore minerals from the gangue minerals, to produce a concentrate (enriched portion) containing most of the ore minerals and a tailing (discard) containing the bulk of the gangue minerals.

Since most ore minerals are usually finely disseminated and intimately associated with gangue minerals, the various minerals must be broken apart (freed) or "liberated" before they can be collected in separate products. Therefore, the first part in any ore dressing process will involve the crushing and grinding, "comminution" of the ore to a point where each mineral grain is practically free (Balasubramania, 2017).

2.12.1 Comminution processes

Comminution is a particle size reduction by breaking, crushing or grinding of ore, rock, coal or other materials.Because most minerals are finely disseminated and intimately associated with the gangue, they must be initially "unlocked" or "liberated" before separation can be undertaken (Usaini, 2014). This is achieved by comminution in which the particle size of the ore is progressively reduced until the clean particles of mineral can be separated by such methods as are available.Comminution is a critical component of most mineral processing flowsheet and serves several purposes, including:(Usaini, 2014)

I. Liberating valuable minerals that are locked within matrix materials in which they are embedded
II. Increasing available surface area for chemical reactions

III. Producing particles within a particular size range to meet product specifications

Crushing and grinding are the two primary comminution processes. Crushing is normally carried out on "run-of-mine" ore, while grinding is normally carried out after crushing. In comminution, the size reduction of particles is done by three types of forces: compression, impact and attrition (Sanislaw, 2019). Compression and impact forces are extensively used in crushing operations while attrition is the dominant force in grinding. The primary used equipment in crushing are jaw, gyratory and cone crushers whereas rod mills and ball mills are generally employed for grinding purposes in a mineral processing plant. Crushing is a dry process whereas grinding is generally performed wet and hence is more energy intensive. Within industrial uses, another purpose of comminution is to reduce the size and to increase the surface area of solids. Factors considered in determining the degree of ore crushing include the concentration of the iron in the ore, its mineralogy, hardness, and moisture content (Charles, 2014)

Comminution consumes the largest part of the energy used in mining operations, from 30 to 70% (Barry et al, 2016). Comminution of ore consumes energy, which is being used to break up the solid ore into smaller pieces. The relationship between the comminution energy and the product size obtained for a given feed size has been a researched extensively over the last century. Theoretical and empirical energy-size reduction equations were proposed by Rittinger (1867), Kick (1885) and Bond (1952), known as the three theories of comminution; and their general formulation by Walker et al. (1937). Finally, Hukki (1962) proposed the revised form of the general form of comminution and suggested that the energy-size relation is a combined form of these three laws (Jankovic, 2010).

Rittinger's law, which assumes that the energy consumed is proportional to the newly generated surface area.

$$E = K\left(\frac{1}{D2} - \frac{1}{D1}\right) \quad (2.3)$$

E = energy input, D1 = initial particle size, D2 = final particle size, K = constant (Wills, 2006)

- Kick's law, which related the energy to the sizes of the feed particles and the product particles.

$$R = \frac{f}{p} \quad (2.4)$$

R = reduction ratio, f = diameter of feed, p = diameter of product (Wills, 2006)

- Bond's law, which assumes that the total work useful in breakage is inversely proportional to the square root of the diameter of the product particles, [implying] theoretically that the work input varies as the length of the new cracks made in breakage.

$$W = \frac{10wi}{\sqrt{P}} - \frac{10wi}{\sqrt{F}} \quad (2.5)$$

W = work input in kilowatt hour per short ton,

P = diameter in microns 80% product passing

F = diameter in microns 80% feed passing

Wi = work index (Wills, 2006)

- Holmes's law, which modifies Bond's law by substituting the square root with an exponent that depends on the material.

2.12.2 Grindability

Ore grindability is the ease with which materials can be comminuted. The data collected from grindability tests are usually used to evaluate crushing and grinding efficiency. Most widely used parameter to measure ore grindability is the Bond work index (wi) (Barry et al, 2016).

2.12.3 Determination of the work index of the ore

The work index expresses the resistance of the material to grinding. Numerically, it is the kilowatt hour per short ton required to reduce the material from theoretically infinite feed size to 80% passing 100μm (Wills, 2006).Grindability is the ease with which the mineral can be comminuted and the data obtained from the grindability tests are used to evaluate the energy requirement and grinding efficiency.

Grindability is used in calculating the energy requirement for the comminution process. Work index is the comminution parameter which expresses the resistance of the material to crushing and grinding. It is a parameter used to measure grindability of an ore and also used in selecting the appropriate comminution equipment for the ore (Obassi *et al*, 2015).

Berry and Bruce (1966) developed a comparative method of determining the grindability of an ore. The method requires the use of a reference ore of known grindability. The reference ore is ground for certain time and the power consumption recorded. An identical weight of the test ore is then ground for a length of time such that the power consumed is identical with that of the reference ore. If r is the reference ore and t the ore under test, then from Bond's Equation,

$$\left(\frac{10\text{wir}}{\sqrt{\text{Pr}}} - \frac{10\text{wir}}{\sqrt{\text{Fr}}}\right) = \left(\frac{10\text{wit}}{\sqrt{\text{Pt}}} - \frac{10\text{wit}}{\sqrt{\text{Ft}}}\right) \quad (2.6)$$

From eqn 2.6, the work index of the test ore is given by

$$Wit = Wir\left(\frac{\frac{10}{\sqrt{Pr}}}{\frac{10}{\sqrt{Pt}}} - \frac{\frac{10}{\sqrt{Fr}}}{\frac{10}{\sqrt{Ft}}}\right) \quad (2.7)$$

Where, Wit = work index of the test ore

Wir = work index of the reference ore

Fr = 80% passing feed of the reference ore

Ft = 80% passing feed of the test ore

Pr = 80% passing of the product of the reference ore

Pt = 80% passing of the product of the test ore

The need to determine the energy required in grinding an ore from the run-off mines to its liberation size prior to process is to prevent over grinding or under grinding and to enhance the selection of appropriate grinding equipment cannot be overemphasized. In short, the textural relationship between minerals within the matrix of an ore and their relation to process selection requires the determination of their liberation sizes(Obassi *et* al, 2015).

The work index of some mineral ore samples is shown on Table 2.5.

Table 2.5: Work Index of some Minerals Ores Samples

Material	**Work index**
Barite	4.28 – 6.24
Bauxite	2.38 – 9.45
Coal	1.63- 11.37
Dolomite	2.82 – 11.27
Emery	3.48 – 58.18
Columbite	3.94 – 10.81
Tantalite	3.6 – 11.90
Soba-Wanka Pyrochlore	4.79 0n the
Fluorspar	2.98 – 9.76
Granite	2.68 – 15.13
Graphite	1.75 – 45.03
Limestone	2.69 – 11.61

Quartzite	2.71 – 12. 18
Titanium ore	4.23 – 11.88
Silica sand	2.65 – 16.46

Sources: Thomas *et al*, (2014); Ministry of Mines and Steel Development (2012); Wills, (2006)

2.12.4 Size/assay analysis

The size/assay analysis is usually performed to establish the distribution of both the valuable and gangue minerals in the various size fractions. Particle size analysis is of great importance in determining the quality of grinding and in establishing the degree of liberation of the valuable mineral from the gangue mineral at various particle size in the separation stage. The choice of particle size analysis technique is a function of the goals of the analysis. Many of the particles encountered in processing are characterized by sieves (classifiers), these are screens with a known opening (mesh) size. Particles smaller than that mesh size will pass through the screen and larger particles are retained. Analysis is performed by building a stack of sieves and shaking the stack, either manually or with a sieve shaker. Material caught on each screen is then weighed and the data combined to extract size distribution. The sieves are then cleaned for reuse (Yaro 1997).

2.10.5 Liberation studies

This is to establish the liberation size of the individual mineral in the ore. Liberation studies are usually concerned with the grain size of the valuable minerals and probably the gangue which may likely affect the subsequent separation process. From the liberation studies economic mesh of the grind will be established. The liberation of the valuable minerals from the gangue is accomplished by comminution and one of the

major objectives of comminution is the liberation or release of the valuable minerals from the associated gangue minerals at the coarsest possible particle size (Salawu, 2015).

The size to which the ore will be ground in order to liberate all the minerals is obtained and also how the different minerals in the ore are going to affect the concentration process, meaning whether there will be interaction between the valuable and other associated minerals. The association of the valuable minerals with other minerals i.e. whether it is finely disseminated or it is an inclusion in the rock or intimately associated. From this also, the feasible method of concentration of the valuable minerals will be conceived depending on the size fractions in which the mineral of interest lies. This will also show whether waste rejection techniques is feasible and how much of the material will be lost with the waste (Salawu, 2015).

2.13 Iron Ore Beneficiation Processes

Depending on the grade of iron ore, they are sometimes beneficiated before smelting. Beneficiation is any process that improves the economic value of the ore by reducing the gangue minerals, which results in a higher grade product and tailings. This is usually done after chemical and mineralogical investigation. The ore is subjected to some concentration processes that can separate the minerals into two or more products. Separation is usually achieved by utilizing some specific differences in physical and chemical properties between the valuable and gangue minerals in the ore (Wehleekema, 2017). Beneficiation methods are usually used singly or different methods can be combined to achieve better results (Wehleekema, 2017). The following are the various beneficiation methods:

2.13.1 Gravity concentration process

Gravity separation is the separation of two or more minerals of different specific gravity by their relative movement in response to the force of gravity and one or more other forces (such as centrifugal forces, magnetic forces, buoyant forces), one of which is resistance to motion (drag force) by a viscous medium such as heavy media, water or, less commonly, air (Balasubramanian, 2017)

Reasons for using Gravity Separation

i. To reject barren waste as an initial pre-concentration step
ii. To recover malleable and/or friable coarse heavy minerals from grinding circuit circulating loads. Such minerals are otherwise hard to recover after regrinding
iii. To pre-concentrate heavy minerals to minimize downstream processing costs
iv. To concentrate heavy minerals
v. To clean low weight yield bulk concentrates
vi. To generate a precious metal concentrate that can go direct to a refinery rather than smelter

The process is widely used alone or in combination with other processing techniques, in particular flotation, magnetic separation and /or chemical treatment. Gravity separation processes are effective, practical and economical in the 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 through knowledge of the mineralogical composition and characteristics of representative sample of the ore (Salawu, 2015). Gravity concentration methods include jigs, sluices, spirals, shaking tables, fine particle separators, and hydrosizers and cyclones. Gravity separation is based on weight only and is directly affected by particle size since volume is proportional to weight. The efficiency, of gravity concentration increases with an increase in particle size. It is necessary to determine the suitability of a gravity concentration process before it is

employed for concentration of an ore. The concentration criterion (CC) is commonly used for this purpose, is given in the equation below (where SG represents specific gravity): (Balasubramanian, 2017).

$$CC = \frac{SG\ (heavy\ \ mineral\ \ ) - SG\ (fluid\ )}{SG\ (light\ \ mineral\ \ ) - \ SG\ (fluid\ )} \quad (2.8)$$

- for CC > 2.5, suitable for separation of particles above 75 micron in size
- for 1.75 < CC < 2.5, suitable for separation of particles above 150 micron in size
- for 1.50 < CC < 1.75, suitable for separation of particles above 1.7 micron in size
- for 1.25 < CC < 1.50, suitable for separation of particles above 6.35 micron in size
- for CC < 1.25, not suitable for any size

Generally, when the quotient is greater than 2.5 (whether positive or negative), then gravity separation is relatively easy. With a decrease in the value of the quotient the efficiency of the separation decreases and below 1.25, gravity concentration is not feasible (Balasubramanian A., 2017)

2.13.2 Magnetic separation

The magnetic separators exploit the difference in magnetic properties between the ore minerals and are used to separate the magnetic minerals from non-magnetic. Magnetic separation can be classified into low and high intensity machines which may be classified into dry or wet feed separation (Wehleekema, 2017). The capacity of a magnet to attract a particular mineral is dependent on the field of intensity and the field gradient and can be shown as in the equation below; (Wills, 2006)

$$\boldsymbol{F} \propto \boldsymbol{H}\frac{\boldsymbol{dH}}{\boldsymbol{dL}} \quad (2.9)$$

Where, F = the force on the particle, H = field intensity and $\frac{dH}{dL}$ = the field gradient

2.13.3 Electrostatic separation

Electrostatic separation is a method of separation based on the differential attraction or repulsion between iron oxide and gangue minerals under the influence of a very high electric field. The separation of one mineral from another will depend upon their motion in response to the dominant force and other competing forces namely gravitational frictional, inertia and centrifugal (Wills, 2006).

2.13.4 Froth flotation

Froth flotation is a selective process used to achieve selective separation (Wills, 2006, Kawatra and Eisele, 2001). It utilizes the differences in physicochemical surface properties of particle of minerals. After treatment with reagent the differences in surface properties between the minerals in the floatation pulp become apparent and floatation takes place, an air bubble attach itself to a particle and lift it to the surface. The particles with attached air bubbles are then removed, while the particles that remain completely wet stay in the liquid phase. Froth flotation can be adapted to a broad range of mineral separations, as it is possible to use chemical treatments to selectively alter mineral surfaces so that they have the necessary properties for the separation (Wills, 2006). The basis of froth flotation is the difference in wettabilities of different minerals. Particles range from those that are easily wettable by water (hydrophilic) to those that are water-repellent (hydrophobic). If a mixture of hydrophobic and hydrophilic particles are suspended in water, and air is bubbled through the suspension, then the hydrophobic particles will tend to attach to the air bubbles and float to the surface. The froth layer that forms on the surface will then be heavily loaded with the hydrophobic mineral, and can be removed as a separated product. The hydrophilic particles will have much less

tendency to attach to air bubbles, and so it will remain in suspension and be flushed (Kawatra, 2001, Charles, 2006).

Often, particle surfaces are selectively modified so that mineral surfaces are hydrophobic while gangue surfaces are hydrophilic. Particle size is important to the process efficiency. Overly fine particles may be entrained in the bubble flow regardless of surface chemistry, reducing the effectiveness of separation efficiency. Overly large particles will tend to sink regardless of bubble attachment (Wehleekema, 2017).

Flotation process can be summarized as follows: Grinding to liberate the mineral particles, reagent conditioning to achieve hydrophobic surface charges on the desired particles, collection and upward transport by bubbles in an intimate contact with air or nitrogen, formation of a stable froth on the surface of the flotation cell, separation of the mineral laden froth from the bath (flotation cell).

Chemicals used for the flotation play an important role in this process, because they have an influence on the different flotation (surface) properties of minerals. They can be divided into these groups:

1) Collectors – used to alter the surface properties of the particles and facilitate the attachment of air bubbles.

2) Frothers – the reagents that must modify the surface tension of the minerals to be floated i.e. permit transportation of valuable mineral to the froth phase.

3) Regulators – control the interaction of collectors between individual minerals, i.e. they can increase or decrease the selective adsorption of collectors on specific minerals for achieving the separation of individual minerals.

a) Modifier - change the pH of the pulp.

b) Depressant – adsorption of modifying reagents on mineral surfaces create a hydrophilic mineral surface that cannot react with collectors.

c) Activators - remove collector coatings from the mineral surface, causing depression of the mineral (Kawatra, 2001).

2.14Previous Studies on some Nigerian Iron Ore Deposits

Asuke, *et al* (2019): The chemical and mineralogical characteristics of Gidan Jaja iron ore located in Zurmi Local Governmental Area of Zamfara State was carried out using X-ray Fluorescence (XRF) spectrometer, X-ray Diffractometer (XRD), Scanning Electron Microscope (SEM) and Optical Microscope. The XRF results obtained revealed that Gidan Jaja Iron ore has an average content of 73.79 % Fe_2O_3, 0.52 % MnO, 17.50 % TiO_2, 0.11 % CaO, 0.50 % Cr_2O_3, 3.84 % SiO_2, 0.43 % Al_2O_3, 0.034 % CuO, 0.02 % NiO, 0.46 % PbO, 2.76 % LOI. Phosphorus and Sulphur were below limit of detection. XRD analysis revealed that the ore contained 56 % Ilmenite, 34 % Magnetite and 10 % Spinel minerals. Petrographic study using polarized light revealed that the iron bearing minerals are predominantly Ilmenite and Magnetite, with minor amount of hematite, spinel and quartz. The results obtained from SEM analysis showed that the iron bearing minerals are separated from other minerals in the ore by smooth grain boundaries.

Sultan*et al* (2017):studied the mineralogy of Zard Koh and Kulli Koh Iron Ore Deposits of Pakistan. The mineralogical study of the ore deposits was carried out using X-Ray Diffraction,X-Ray Fluorescence, Scanning Electron Microscope attached with Energy Dispersive Spectroscope and Stereomicroscope techniques. Results indicated that the Zard Koh ore is mainly composed of 60.15% maghemite, 23.57% pyrite, 4.07% chlorite, 10.30% grossular and 1.65% admontite minerals. The chemical analysis revealed that Zard Koh iron ore contains an average of 54.27% Fe, 12.73% S, 8.70% Si,

3.07% Al, 4.07% Ca, and 2.16% Mg. Similarly, the mineralogical study of the Kulli Koh iron ore indicated that the ore also contains 51.16% hematite, 29.24% quartz, 8.89% dravite, and 8.76% kaolinite minerals. Elemental analysis of different samples indicated that Kulli Koh iron ore contains an average composition of 40.23% Fe, 20.67% Si, 3.44% Ca, 3.81% Al and 3.25% Mg. Mineralogical study of the Zard Koh and Kulli Koh iron ore deposits suggested that these ore deposits can be beneficiated cost- effectively by using magnetic separation techniques.

Joan*et al* (2015) worked on Characterization of Selected Mineral Ores in the Eastern Zone of Kenya and the results indicated that Katse ore is a rich Magnetite grade with Fe content above 80% with minor amounts of hematite, with quartz and clay as the major gangue (<1% SiO_2 and <1% Al_2O_3) and low contents of the deleterious elements (<1%), which correspond to acceptable levels for commercial iron ores.

Salawu, (2015)CharacterizedGujeni iron ore deposit and reported that the XRF analysis of the ore revealed 48.6%Fe, 0.2%Mn, 12.01%Ti, 2.06%P, 0.2%S, 6.0%Si, 4.4%Al on the average. Mineralogical analysis showed that the ore contained the following minerals in major quantity; haematite, goethite, rutile while, manganese oxide, zincite, zirconium and silicate minerals are present in minor quantities. Particle size/mineral assay analyses revealed that the various mineral phases are evenly distributed in all the various sieve size fractions (+355µm to -50µm). The liberation size of the iron bearing minerals was found to be -250+180µm, containing the highest percentage assay of iron (48.80%Fe). The work index of the ore was found to be 13.96kwh/t

Abraham*et al*, (2012): worked on the characterization of chemical composition and microstructure of natural iron ore from Muko deposits.The study aimed at investigating

the chemical composition and microstructure of raw iron ore from the deposits in Muko area (south-western Uganda). X-ray diffraction and scanning electron microscopy were employed in the investigation and chemical analysis performed to determine the compounds constituting the ore. The quality of this ore was compared to generalized world market standards and ores from other nations. It was found that Muko ore is a rich hematite grade with Fe content above 65%. It has little gangue (<6% SiO_2 and 3-4% Al_2O_3) and low contents of the deleterious elements (P~ 0.02% and S < 0.006 %), which correspond to acceptable levels for commercial iron ores.

Raghukumar *et al*,(2012)studied ways of beneficiatinghigh Alumina iron ore Fines from Noamundi, India for producing sinter/ pellet grade concentrate. The iron ore fine sample has a feed grade of 59.77%Fe, 4.71%SiO_2, and 5.89%Al_2O_3 with 5.53% of LOI (Loss on Ignition). From the study, it was revealed that the sample contains huge quantity of goethite which is partially weathered, interlocked with hematite and gangue minerals like gibbsite, kaolinite and quartz at different proportions. Two conceptual flow sheets were considered for the beneficiation of Indian high alumina iron ore fines. The first option, consisting of hindered settling classifier followed by two stage gravity concentration results in a product quality with 66.82%Fe and 2.1%Al_2O_3 content ensuring 25.15% iron recovery. In the second option, the iron ore fines was treated in a similar approach but the second stage gravity concentration replaced by magnetic separation results in a product quality with 67.77% Fe, 1.53% Al_2O_3 with 28.95% of iron recovery. Mineralogical studies revealed that the concentrate product quality depends on presence of the goethite in the product**.**

Olatunji and Durojaiye (2010) determined the work index of Birnin Gwari iron ore using modified Bond method. Granite was used as a reference ore in the study. The result shows that 80% passing size for the iron ore and granite samples were obtained at 100μm sieve size for the feeds and products. The work index of reference granite was used to calculate the work index of iron ore. The authors reported that the work index of Birnin –Gwari iron ore was determined to be 20.39kWh/t.

Thomas and Yaro (2007) investigated the KotonKarfe iron ore and reported that the ore has iron content of 43.34% with low amount of silica (10.14%). From their findings, they reported that the ore contained magnetite, siderite and goethite as the major constituents while hematite as the minor mineral. The work index of Koton-Karfe iron deposit was determined to be 11.33kWh/t and 17.00kWh/t for both calcined and uncalcined samples while Asuke (2014) characterized the ore and reported that the ore contained mainly magnetite and goethite while siderite, quartz and hematite are present in minor quantities. He also reported that the phosphorus content of the ore is uniformly distributed within the mineral matrix. He concluded that the phosphorous content of KotonKarfe iron ore can be reduced by acidic leaching technique.

Agava, (2006) worked on Agbado Okudu iron ore deposit and reported that the iron ore contained on the average 38.82%Fe, 49.10%SiO_2, 0.05%%P_2O_5 and 0.03%S. Mineralogical analysis revealed that the iron bearing minerals are predominantly magnetite and hematite. The work index of the ore was found to be 4.32kWh/t.

Based on the review of literature available for this research, little or no work has been done to characterize Kurungu iron ore deposit. It is the attempt of this study to provide

useful data on the characterization of the ore in order to ascertain its suitability for iron production.

2.15 Kurungu Iron Ore Deposit

The iron ore deposit is located in Ajaokuta local Government Area of Kogi State. The deposit is bounded by Latitudes 07^0 30' and 13^0 00N' and longitudes 6^0 32'E. The deposit is on an elevation of 233m. The deposit is a Banded Iron Formation (BIF) and sedimentary in nature.Kurungu iron ore deposit covers a land mass area of about 320,000m^2has an estimated reserve of over 50 million tonnes (Preliminary estimation) (Ministry of Mines and Steel Development,2012).

CHAPTER THREE

3.0 MATERIALS AND METHODS

The materials and equipment used in this study are listed below and the various methods involved in the characterization and concentration of the iron ore

3.1 Materials and Equipment Required

Iron ore sample 1000grams

Reference ore sample (Granite) 100grams

Laboratory sledge hammer

Scanning Electron Microscope (SEM)

Global positioning system (Extex GARMIN 10)

Laboratory Jaw crusher (415v,50Hz,4000w & 8.1A)

Pulverizer (220-240V, 50Hz, 370w & 2x3.8A)

Set of sieves (British Standard Test Sieve)

Laboratory sieve shaking machine (220-240V, 50Hz, 80w & 2.3A)

Weighing balance (Metlar MT-2000)

Specific gravity bottle (Pycnometer)

X-ray fluorescence machine (Mini-pal 4 EDXRF by Panalytical)

X-ray diffractometer machine (Empyrean XRD by Panalytical)

Petrological microscope (Xp 300c)

Grinding and polishing machine

Shaking table

3.2 Methodology

3.2.1 Ore Sample Collection

Samples of the iron ore were collected from various points at the deposit site located at Kurungu village, in Ajaokuta Local Government Area of Kogi State. GPS was used to measure the exact location at which samples were taken. Grab method of sampling was adopted in collecting the samples. 60kg of the samples was collected at interval of 150m apart at 3m depth in order to have a representative sample of the ore deposit. Table 3.1 shows the GPS coordinates of where the iron ore samples were sourced.

Table 3.1: Coordinates of the Collection Pits

	PIT			
	Pit 1	**Pit 2**	**Pit 3**	**Pit 4**
Coordinates	N $07^0$30.544’	N $07^0$30.461’	N $07^0$30.536’	N $07^0$30. 543’
	E $06^0$32. 461’	E $06^0$32.350’	E $06^0$32.348’	E $06^0$32.475’

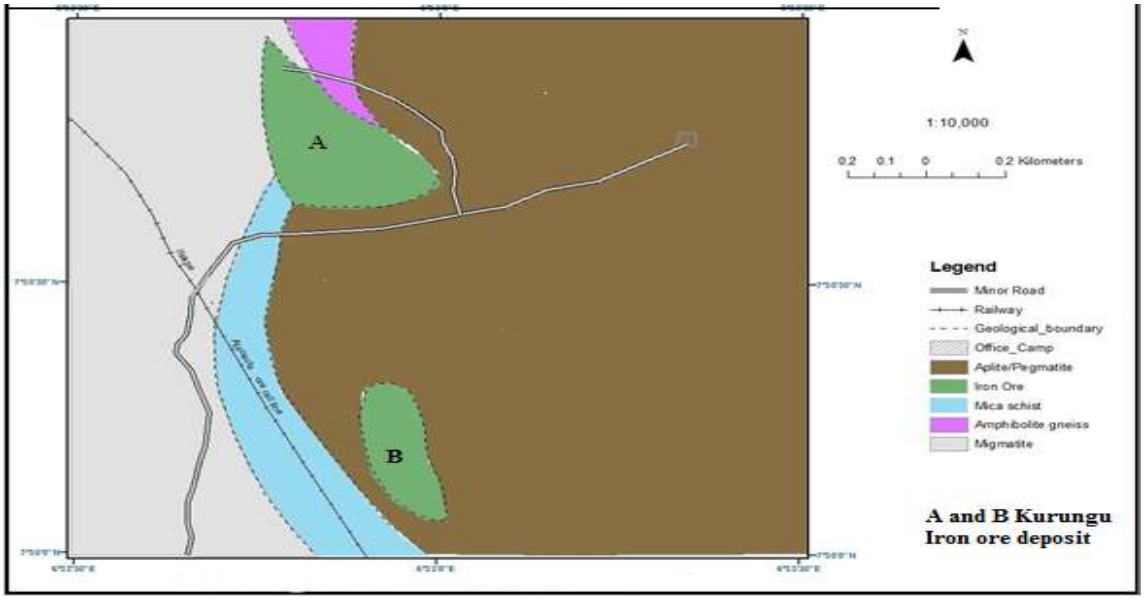


Figure 3.1 Geological Map of Kurungu Iron Ore Deposit

3.2.2 Sample preparation

The sample preparation involved crushing and grinding process done in the material laboratory of material laboratory of the Department of Mineral and Petroleum Resources Engineering Kaduna Polytechnic, Kaduna State. The lump sizes of the ore sample were reduced to the required size (60mm) that was acceptable by the jaw crusher using sledge hammer. The sample was crushed using jaw crusher and the discharge from the crusher were ground to fine particle size using the ball mill then coned and quartered to get a representative sample.

3.2.3 Chemical composition analysis of the iron ore sample

X-ray Fluorescence (XRF) was used to determine the chemical composition; the sample was pulverized (ground to fine powder). Twenty (20) grams of the prepared sample was weighed into a sample cup and then the cup carefully placed in measuring position on the machine. The machine was switched on, set at 14 and 20kV for the determination of major and trace elements respectively.The XRF was conducted at Centre for Minerals Research &Development, Kaduna Polytechnic, Kaduna State.

3.2.4 Mineralogical analyses of the iron ore sample

The mineralogical analysis was carried out using XRD, SEM and petrological analysis was done with the petrological microscope.

The iron ore sample was finely ground, homogenized, then prepared using the sample preparation block and compressed in the flat sample holder to create a flat, smooth surface then mounted on the sample stage in the XRD cabinet. The machine condition was set to 2Θ starting position at different degrees, intensity of diffracted x-ray was continuously recorded as the sample and detector rotates through their respective angles. The d-spacing of each peak was obtained and matched for determination of unknown

materials. This was carried out in Nigerian Geological Survey Agency, Barnawa, Kaduna.For SEM analysis carried out in National Steel Raw Material Exploration Agency, Malali, Kaduna, the ore sample was taken and placed on the sample holder which was then mounted on the machine. An electron beam was then focused over a rectangular area. The sample was irradiated to generate emission from which micrograph of the sample was produced.

For petrological analysis, the iron ore sample was mounted on glass slide using adhesive. The sample was ground and polished using grinding and polishing machine until a thin transparent surface was obtained on the glass slide. The prepared thin surface was then observed under cross and plane polarized light of a metallurgical microscope with an in-built camera and a point-counter machine attached to it. The percentage distribution of the various minerals present in the ore sample was determined using the point counting machine. This was carried out in Nigerian Geological Survey Agency, Barnawa Kaduna.

3.2.5 Determination of the physical properties of the iron ore sample

Determination of the physical properties of the ore was carried out in the material laboratory of the Department of Mineral and Petroleum Resources Engineering Kaduna Polytechnic, Kaduna State, the Specific gravity, density, and electrical conductivity of the ore were conducted as follows:

a. Determination of Specific gravity of the iron ore sample (SG)

The determination of the specific gravity was carried out using the following procedure;

i. The iron ore sample was washed thoroughly, dried and ground.

ii. Empty specific gravity bottle was weighed and recorded as W1.

iii. The ore sample was poured into the bottle to about half full of the bottle; the sample and the bottle were then weighed and recorded as W2.

iv. The remaining space in the bottle was filled with water and weighed together with the bottle and recorded as W3.

v. The content of the bottle was discarded and filled fresh with water. The bottle filled up with water was then weighed and recorded as W4. The specific gravity is then calculated as follows; (Salawu, 2015)

$$\text{Specific gravity (S. G)} = \frac{\text{Weight of test iron ore sample}}{\text{Weight of equal volume of water}}$$

$$\text{Specific gravity (S. G)} = \frac{W2 - W1}{[(W4 - W1) - (W3 - W2)]} \qquad (3.1)$$

b. Determination of Density of the Iron Ore Sample

The specific gravity above is the same with relative density and is given by the formula: (Salawu, 2015)

$$\text{Relative Density} = \frac{\text{Density of Substance}}{\text{Density of Water}} \qquad (3.2)$$

Density of substance = Relative Density x Density of water

Density of the iron ore will be calculated from the above equation. Where the density of water is given by $1 \times 10^3 \text{Kg/m}^3$ (Salawu, 2015)

c) Determination of Electrical Conductivity of the Iron Ore Sample

To determine the electrical conductivity of an ore, the resistivity has to be found since the electrical conductivity of a material is a function of its resistivity. The iron ore sample was cut and shaped into 3 × 1.5 × 3.5cm that could be measured. Inductance Capacitance and Resistance meter (ICR) was used to measure the resistance of the cut

sample which was used to calculate its resistivity and conductivity. Resistance of a material (sample) is directly proportional to its thickness and inversely proportional to its area (Salawu, 2015).

Mathematically:

$$\text{Resistance} \quad R = \frac{L}{A} \tag{3.3}$$

$$\text{Resistivity} \quad \rho = \frac{RA}{L} \tag{3.4}$$

$$\text{Conductivity} \quad \tau = \frac{1}{\rho} \tag{3.5}$$

Where, A is area, L is length or thickness R is resistance of the material, ρ is resistivity, τ is conductivity

3.2.6 Particle size/mineral assay analyses of the iron ore sample

Particle size and mineral assay analyses were carried out to establish the distribution of various minerals especially iron (Fe) in the various size fractions. 600g of the sample was prepared and placed on the set of sieves and the sieves were put on the sieve shaking machine. The sieves were then vibrated for 30 minutes to enhance proper sieving. The minerals on each sieve was weighed, packed and labeled then taken for analyses using XRF.

3.2.7 Liberation size analysis

The liberation size of the valuable mineral was determined by analyzing the minerals in each sieve size fractions. The sieve size fraction that contains the highest percentage assay of Fe content was acknowledged as the liberation size of the iron ore.

3.2.8 Work index determination

Berry and Bruce method, otherwise known as the modified Bond's method was used in determining the work index of the ore. Granite was used as the reference ore. The work index of granite used is 15.13kWh/t and the test conducted in the material laboratory of the Department of Mineral and Petroleum Resources Engineering Kaduna Polytechnic, Kaduna State.

100g of both the test ore and the reference ore were crushed and pulverized in the laboratory ball milling machine. The same quantity of both the test ore and reference ore were then taken and sieved into various fractions using the automatic sieve shaker for 15 minutes. The selection of the sieves was based on scale of root two ($\sqrt{2}$) and arranged from the coarsest to the finest as follows: +355, -355+250, -250+180, -180+125, -125+90, -90+63, -63. The sample was placed at the topmost sieve and a pan placed at the bottom. The weighed amount of the test and reference ores retained on each sieve was then feed into the ball mill. The retained sieve size fractions were further subjected to grinding so as to obtain a product that is 80% passing 100μm. This was used to calculate the work index of the test ore using the Berry and Bruce formula in equation (3.6);

$$\mathrm{Wit} = \mathrm{Wir}\frac{\left[\frac{10}{\sqrt{\mathrm{Pr}}}-\frac{10}{\sqrt{\mathrm{Fr}}}\right]}{\left[\frac{10}{\sqrt{\mathrm{Pt}}}-\frac{10}{\sqrt{\mathrm{Ft}}}\right]} \tag{3.6}$$

Where,

Wit = work index of the ore under test

Wir = work index of the reference ore

Fr = 80% passing feed of the reference ore

Ft = 80% passing feed of the ore under test

Pr= 80% passing product of the reference ore

Pt = 80% passing product of the ore under test

3.2.9 Concentration criteria

The concentration criterion (CC) for the ore was calculated using the equation (3.7);

$$CC = \frac{SG\ (heavy\ \ mineral\ \ ) - SG\ (fluid\ )}{SG\ (light\ \ mineral\ \ ) - \ \ SG\ \ (fluid\ )} \quad (3.7)$$

Where, SG (heavy mineral) = specific gravity of Kurungu iron ore

SG (light mineral) = specific gravity of silica

SG (fluid) = specific gravity of water

3.2.10Gravity concentration

A Shaking table in the material laboratory of the Department of Mineral and Petroleum Resources Engineering Kaduna Polytechnic, Kaduna State, was used to concentrate the ore and the best parameters for achieving best grade and recovery were determined. Five hundred grams (500g) of the 250µm size fraction form the feed and was fed through the hopper at a rate of about 100g/minute. The feed water was supplied at a rate of about 200ml/minute. The inclination of the table was set at an angle of 180^{o}. Collection of concentrates, midlings and tailings was continuous throughout the process. The mildling was recycled, and two products obtained as concentrate and tailing were dried, weighed and recorded. Samples of concentrate and tailing were taken for XRF analysis to determine their composition.

CHAPTER FOUR

4.0RESULTS AND DISCUSSIONS

4.1 Chemical Analysis Result of Kurungu Iron Ore Sample

The chemical analysis of the representative sample from the ore is presented in Tables 4.1.

Table 4.1: Percentage distribution of the various oxides in the head sample of Kurungu Iron ore

Oxide name	% Composition
SiO_2	36.20
CaO	0.956
MnO	0.490
Fe_2O_3	60.86
CuO	0.041
ZnO	0.098
Rb_2O	0.020
In_2O_3	0.360
Sb_2O_3	0.10
La_2O_3	0.240
Eu_2O_3	0.570
Re_2O_7	0.03
LOI	0.035

The XRF analysis in Table 4.1 shows that the ore contains 60.86% Fe_2O_3 (42.57%Fe) and 36.2% SiO_2 which is the major gangue material of the ore, it also contains 0.10% CaO, 0.49% MnO, 0.10% ZnO, 0.36% In_2O_3, 0.24% La_2O_3 and 0.57% Eu_2O_3. Other oxides present in trace quantity are 0.04% CuO, 0.02% Rb_2O, 0.1% Sb_2O_3 and 0.03% Re_2O_7,the percentage of iron reported can be compared to those of other iron deposit in Nigeria as shown on Table 2.4(Bamalli *et al* 2011).

4.2Mineralogy Results of Kurungu Iron Ore

The XRD spectrums of the representative sample of Kurungu iron ore is shown in Figure4.1

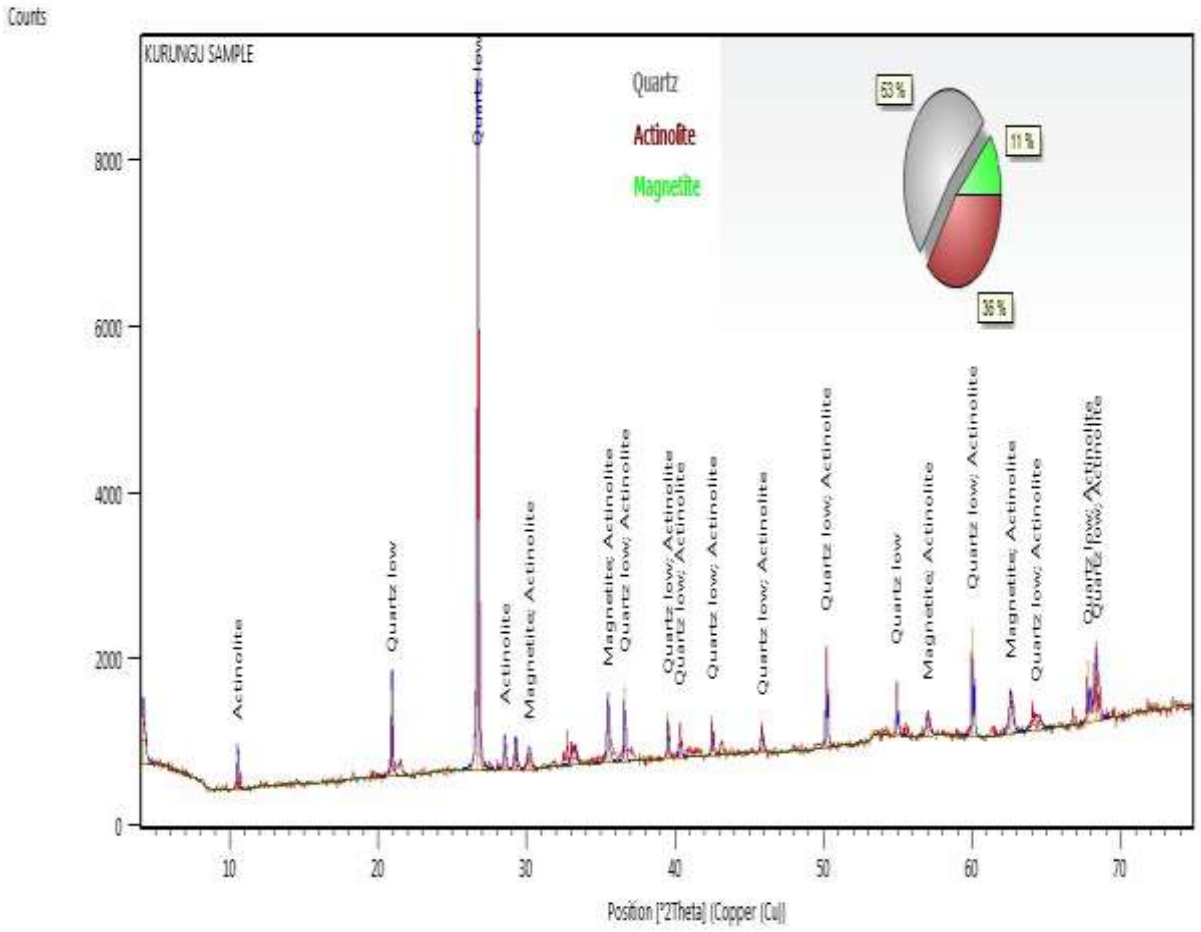


Figure 4.1: XRD Spectrum of the Representative Sample of Kurungu Iron Ore

Table 4.2: Mineralogical Composition of the Kurungu Iron Ore as Determined from XRD

Mineral name	Compound name	Chemical formula
Magnetite	Magnetite	$Fe_{24.00}O_{32.00}$
Actinolite	Actinolite	$Fe_{6.22}Mn_{0.18}Mg_{3.91}Al_{0.05}Ti_{0.00}Ca_{3.63}Na_{0.04}Si_{15.98}H_{3.72}$

Quartz	Silica mineral	$Si_{3.00}O_6$

The X-ray diffraction results as shown in Figure 4.1 and Table 4.2 revealed the presence of three mineral phases; Magnetite (40%), as the valuable mineral, while quartz (50%) and Actinolite (10%) are the associated minerals. The presence of these mineral phases can be attributed to the differential mineralization of the deposit.However, two of the minerals are single phases which indicate that they can be separated from each other easily after Comminution, while the one in complex phase must be comminuted to a point that will enhance its liberation for possible physical separation.The mineralogical composition of the ore is similar to earlier work reported by report by Thomas and Yaro, 2007.

4.2.2 SEM / EDS of the head sample

The SEM images and EDS of the head sample are presentedas Fig. 4.2 a - d

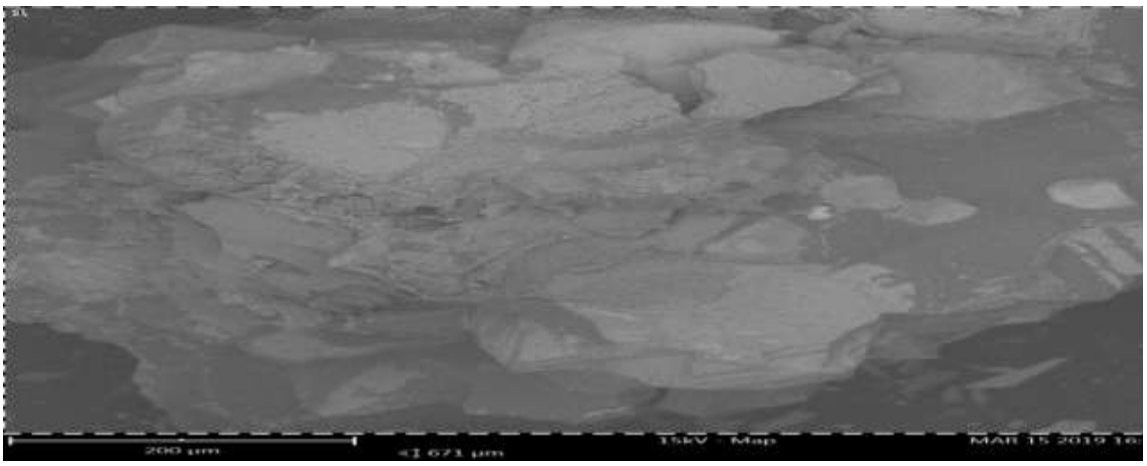


Figure 4.2 (a): SEM Micrograph of Composite Sample (x671µm)

Table 4.3: EDS of Composite Sample

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
26	Fe	Iron	39.36	55.89

14	Si	Silicon	60.31	43.06
53	I	Iodine	0.33	1.05

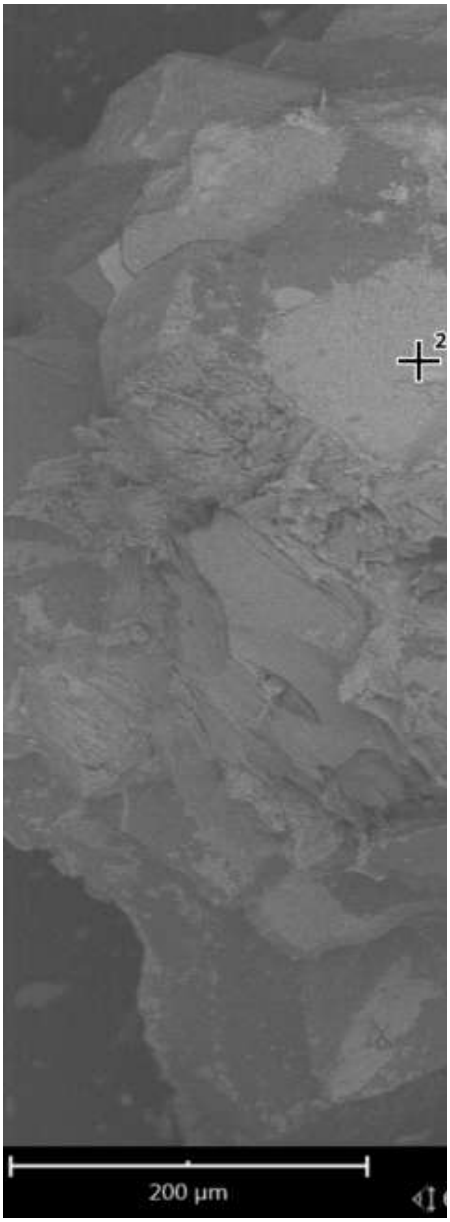


Figure 4.3 (b) SEM Micrograph of Representative Sample Highlighting the Portion of Iron (x671µm)

Table 4.4: EDS of Representative Sample Highlighting the Portion of Iron

Element Number	**Element Symbol**	**Element Name**	**Atomic Conc.**	**Weight Conc.**
26	Fe	Iron	100.00	100.00

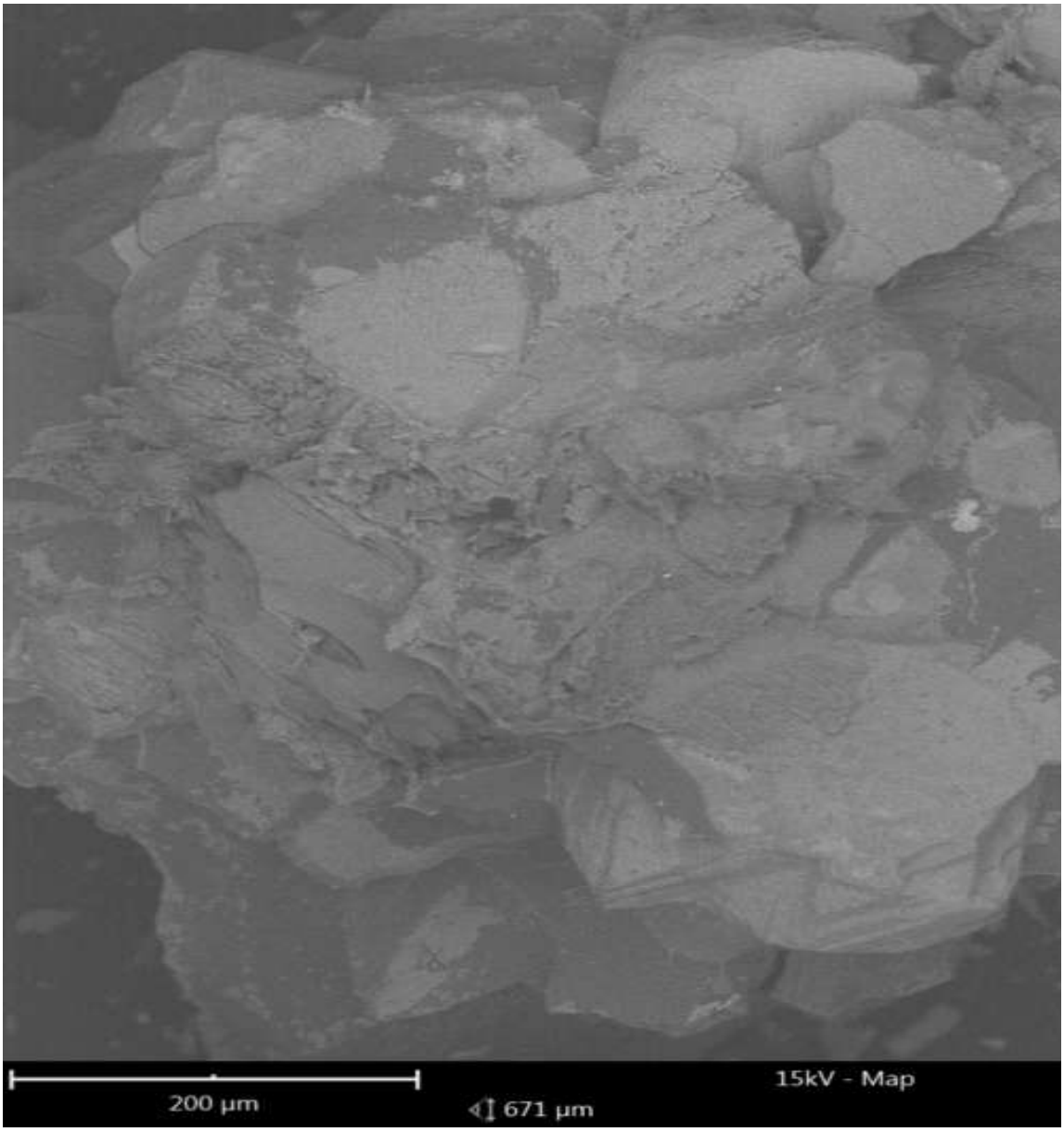


Figure 4.2 (c) SEM Micrograph of Representative Sample Highlighting the Portion of Silica (x671µm)

Table 4.5:EDS of representative Sample Highlighting the Portion of Silica

Element Number	**Element Symbol**	**Element Name**	**Atomic Conc.**	**Weight Conc.**
14	Si	Silicon	100.00	100.00

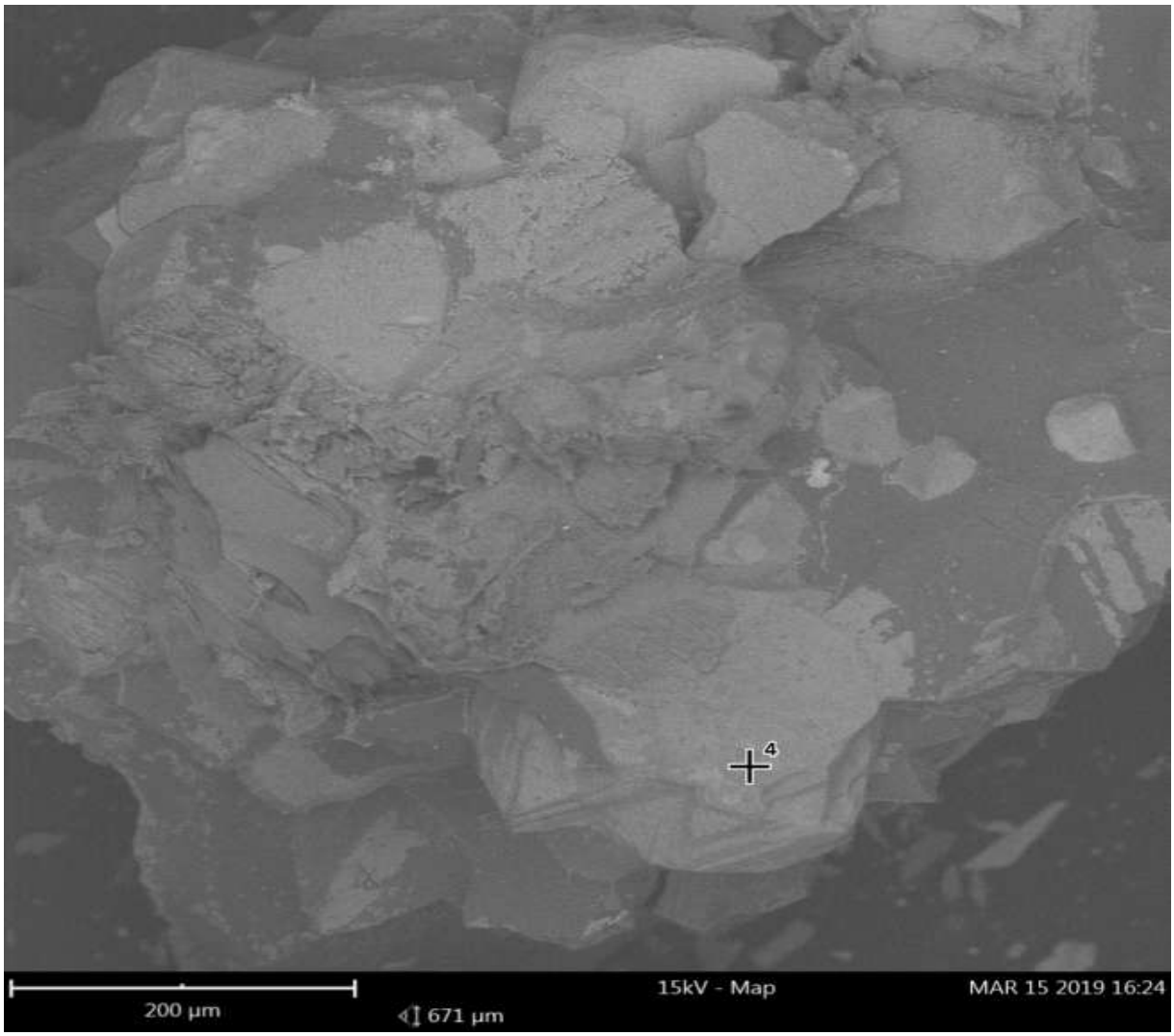


Figure 4.2 (d) SEM Micrograph of Representative Sample Highlighting the Portion of Iron and Silica (x671µm)

Table 4.6: EDS of Representative Sample Highlighting the Portion of Iron and Siliaca

Element Number	**Element Symbol**	**Element Name**	**Atomic Conc.**	**Weight Conc.**
26	Fe	Iron	87.33	93.20
14	Si	Silicon	12.67	6.80

From the micrographs it can be seen that the minerals are locked together in layers showing that it has to be well comminuted for proper liberation to take place. The EDS confirms the presence of Fe and Si. Figure 4.2(b) shows the highlighted portion containing iron. Figure 4.2(c) shows the highlighted portion containing silicon in dark colour. Figure 4.2(d) shows a mixture of dark and light colour patches of both iron and silicon. This is in line with earlier results obtained from the XRF and XRD that the ore contains iron oxide and quartz.

4.3 Petrological Analysis

The sample of the iron ore was viewed under cross and plane polarized light. The micrographs of the thin sections of the representative sample are shown in Plates I & II.

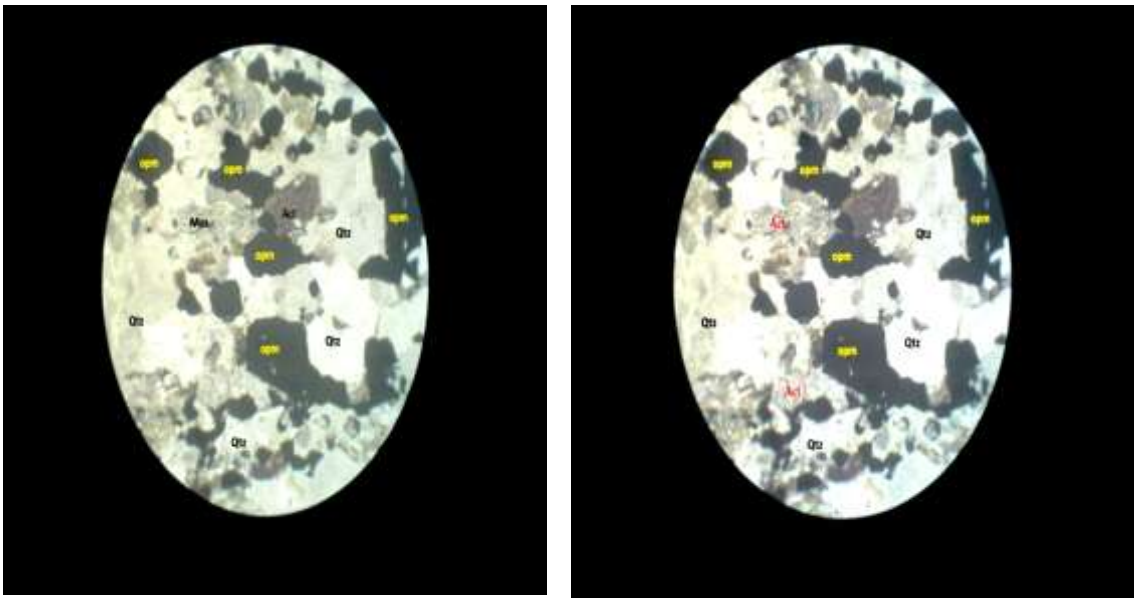


Plate Ia and b: Kurungu Iron Stone viewed under Cross-polarized Light (x200)

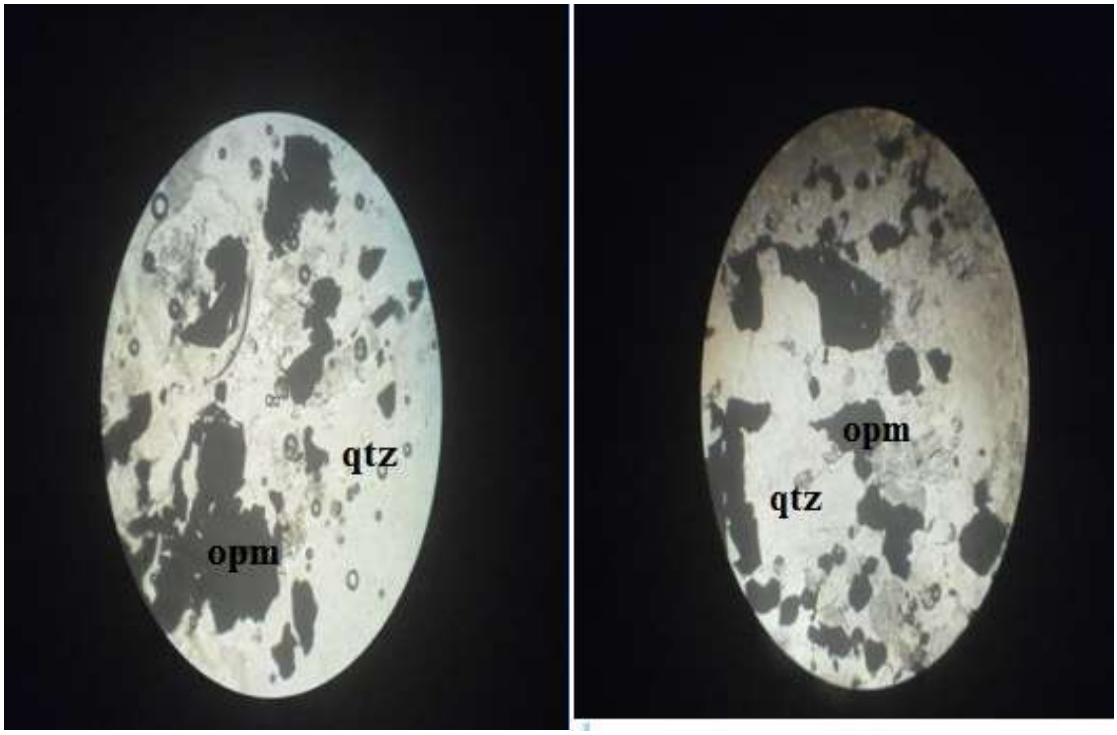


Plate IIa and b: Kurungu Iron Stone viewed under Plane-polarized Light (x200)

Plate I and II shows the thin sections of the ore under transmitted light microscope, it reveals that the ore matrix consists of quartz (white) and iron mineral (dark) and Actinolite (grey).

The quartz under plane polarized light presented as colorless, anhedral in shape, not fractured nor altered and it has sharp contact with other grains and under cross polarized light it shows as grey to white in colour.

The iron mineralsare the dark colored grains under plane and cross polarize light. Possibly iron oxide seems to have a preferred orientation.

Actinolite, under plane polarized light is slightly pink in color to colorless, pleochroic to light green, moderate relief, euhedral in shape, perfect cleavage, have a preferred orientation. And under cross polarized light, interference color: light pink to light green on rotation of the stage. The minerals grains are separated by grain boundaries and

indications that the minerals can be fragmented during the process of comminution and be liberated (Thomas et al, 2019).

4.4Physical Properties Results of Kurungu Iron Ore

The results of the various laboratory analyses carried out to get the physical properties of the ore are presented and analyzed as follows:

4.4.1 Specific gravity

Table 4.7: Result of Specific Gravity determined of Kurungu Iron Ore

	Test 1 (g)	**Test 11 (g)**	**Average**
Wt of empty density bottle W_1	23.3	23.3	23.3
Wt of empty density bottle + sample W_2	28.3	28.3	28.3
Wt of empty density bottle + sample + water W_3	74.3	74.25	74.28
Wt of density bottle + water W_4	70.6	70.6	70.6

The specific gravity of the ore was calculated using equation 3.1 and the value was 3.811

4.4.2 Density

Equation 3.2 was used to find the value of the density of the ore to be equal to 3.811 x $10^3 kg/m^3$

4.4.3 Electrical conductivity

The results obtained for calculating the electrical conductivity of the ore is as follows:

Length of the sample (L) = 3cm

Diameter = 3.5cm r = 3.5/ 2 = 1.75cm

The equations 3.3, 3.4 and 3.5 were used to calculate the resistance, resistivity and finally the conductivity of the ore respectively

Table 4.8: Physical Properties of Kurungu Iron Ore

Property	**Value**
Specific gravity	3.811
Density	$3.811 \times 10^{3} kg/m^{3}$
Electrical conductivity	$1.17 \times 10^{-3} \Omega^{-1} m^{-1}$

Table 4.8 presents the summary of the results of physical properties of the head sample. From the results the specific gravity of the ore was found to be 3.811 and the density to be $3.811 \times 10^{3} kg/m^{3}$. The electrical conductivity of the ore was found to be $1.17 \times 10^{-3} \Omega^{-1} m^{-1}$. The result shows that the ore can be beneficiated using gravity since the specific gravity of the major gangue material is less than 3.811 and from principle particles of high specific gravity will move more slowly than lighter particles, and so a lateral displacement of the material will be produced (Balasubramanian, 2017). The electrical conductivity is low so electrostatic separation might not be viable for beneficiation.

4.5Particle Size Analysis

The result of the particle size analysis of the representative sample of the ore is presented on **Table 4.9** Particle Size Analysis of Kurungu Iron Ore

Sieves Range (µm)	**Weight retained (g)**	**Weight retained (%)**	**Nominal Aperture size (µm)**	**Cummulative weight retained (%)**	**Cummulative weight passing (%)**
+355	60.0	06.00	355	06.00	94.00
-355+250	100.1	10.01	250	16.01	83.99
-250+180	187.4	18.74	180	35.75	64.25
-180+125	273.0	27.30	125	62.05	37.95
-125+90	250.4	25.04	90	87.09	12.91
-90+63	95.9	9.59	63	96.68	3.32
Pan	33.2	3.32		100	0.00
Total	1000	99.96			

Table 4.9 reveals that +355µm retains 60g, -355+250µm retains 100.1g, -250+180µm retains 187.4g, -180+125µm retains 273g,-125+90µm retains 250.4g, -90+63µm retains 95.9g of the minerals.

4.6Determination of the Liberation Size of Kurungu Iron Ore

Table 4.10 presents the XRF analysis of the various sieve sizes of the ore after sieving. From the Table 4.10 below the chemical analysis of the various sieve fractions show that, the 250µm fraction has the highest quantity of Fe_2O_3.The results also shows that the liberation size of the ore is 250µm because it contains 65.09% iron oxide representing 45.53%Fe. The sieve size that contained the highest percentage assay of iron is the liberation size of the iron ore (Olatunji 2010).

Table 4.10: Result of the Chemical Analysis of the various Sieve Fraction of the Ore Sample after Sieving using XRF

Oxide	**Aperture size µm / %Composition**					
	355	**-355+250**	**-250+180**	**-180+125**	**-125+90**	**-90+63**
CaO	1.536	1.754	0.547	1.003	0.433	0.881
SiO_2	30.752	25.110	28.317	34.591	40.826	40.107
Al_2O_3	1.650	1.921	0.453	1.211	0.870	1.321
Cr_2O_3	ND	0.006	ND	ND	0.012	0.041
MnO	1.032	1.683	0.501	0.396	1.104	ND
Fe_2O_3	**57.025**	**65.092**	**63.120**	**58.346**	**50.541**	**53.174**
TiO_2	ND	0.012	0.410	0.018	ND	ND
ZnO	0.172	0.055	0.054	0.102	ND	0.021
MgO	ND	0.031	0.002	ND	ND	ND
Le	7.825	4.335	6.595	4.332	6.213	4.454

4.7Work Index Determination

Tables 4.11 and 4.12 present the sieve analyses of the feed and product of the ball mill of the reference sample (granite ore) while Table 4.13 and Table 4.14 present the sieve analysis of the feed and product of the test ore.

Table 4.11: Result of Sieve Size Analysis of the Feed Reference Material (Granite)

Sieve size Range (µm)	**Weight retained (g)**	**Weight retained %**	**Nominal aperture**	**Cummulative Weight retained %**	**Cummulative Weight passing %**
+355	8.36	8.36	355	8.36	91.64
-355+250	19.36	19.36	250	27.72	72.28
-250+180	17.87	17.87	180	45.59	54.41
-180+125	11.91	11.91	125	57.50	42.50
-125+90	13.89	13.89	90	71.39	28.61
-90+63	13.81	13.81	63	85.20	14.80
-63	14.80	14.80	-	100	0.00

Using Gaudin Schumann expression

$$80\%\ \text{Cum Passing Size} = \left(\frac{80\%}{\%\ \text{passing size 1}}\right)^2 \text{x size1}$$

If 250µm = 72.28

$$= \left(\frac{80}{72.28}\right)^2 \text{ x } 250 = 306.26\mu\text{m @ } 80\%$$

Table 4.12: Result of Sieve Size Analysis of the "Product"Reference Material (Granite)

Sieve size Range (µm)	**Weight retained (g)**	**Weight retained %**	**Nominal aperture**	**Cummulative Weight retained %**	**Cummulative Weight passing %**
+355	2.20	2.20	355	2.20	97.80
-355+250	17.93	17.93	250	20.13	79.87
-250+180	2.47	2.47	180	22.60	77.40
-180+125	3.68	3.68	125	26.28	73.72
-125+90	27.86	27.86	90	54.14	45.72
-90+63	14.61	14.61	63	68.75	31.25
-63	31.25	31.25	-	100	0.00

Using Gaudin Schumann expression

$$80\% \text{ Cum Passing Size} = \left(\frac{80\%}{\%\text{ passing size 1}}\right)^2 \text{ x size1}$$

If 250µm = 79.87

$$= \left(\frac{0.8}{0.798}\right)^2 \text{ x } 250 = 250.81\mu\text{m @ } 80\%$$

Table 4.13: Result of Sieve Size Analysis of the "Feed" Test Material (Kurungu Iron Ore)

Sieve size Range (µm)	Weight retained (g)	Weight retained %	Nominal aperture	Cummulative Weight retained %	Cummulative Weight passing %
+355	6.20	6.20	355	6.20	93.80
-355+250	10.79	10.79	250	16.99	83.01
-250+180	10.85	10.85	180	27.84	72.16
-180+125	29.83	29.83	125	57.67	42.33
-125+90	17.67	17.67	90	75.34	24.66
-90+63	12.87	12.87	63	88.21	11.79
-63	11.79	11.79	-	100	0.00

Using Gaudin Schumann expression

$$80\%\ \text{Cum Passing Size} = \left(\frac{80\%}{\%\ \text{passing size 1}}\right)^2 \text{x size1}$$

If 180µm = 72.16

$$= \left(\frac{0.8}{0.7216}\right)^2 \text{x} 180 = 221.2\mu\text{m@}80\%$$

Table 4.14: Result of Sieve Size Analysis of the "Product" Test Material (Kurungu Iron Ore)

Sieve size Range (µm)	Weight retained (g)	Weight retained %	Nominal aperture	Cummulative Weight retained %	Cummulative Weight passing %
+355	0.48	0.48	355	0.48	99.52
-355+250	11.90	11.90	250	12.38	87.62
-250+180	8.52	8.52	180	20.90	79.10
-180+125	12.14	12.14	125	33.04	66.96
-125+90	30.20	30.20	90	63.24	36.76
-90+63	8.11	8.11	63	71.35	28.65
-63	28.65	28.65	-	100	0.00

Using Gaudin Schumann expression

$$80\%\ \text{Cum Passing Size} = \left(\frac{80\%}{\%\ \text{passing size 1}}\right)^2 \text{x size1}$$

If 180µm = 79.10

$$= \left(\frac{0.8}{0.791}\right)^2 \text{x } 180 = 184.1\mu\text{m @ } 80\%$$

The modified Bond work index method (equation 3.6) was used to calculate the work index of the ore and the value was found to be 13.96kWh/t.This implies that about 13.96 kilowatts hour per shot tonne of energy is required to grind the ore from theoretical infinite feed size to 80 percent passing 100µm in line with Bond's work index and this means that it will cost ₦532.02 to comminute one tone of Kurungu iron ore to 80% passing 100 µm if one kilowatt of electricity cost ₦38.11 in Nigeria. This is very significant because energy is very expensive and grinding is the most energy intensive operation in mineral processing (Wills, 2006).

4.8Result of Gravity Concentration Test on Kurungu Iron Ore

The result of the gravity concentration test using the shaking table performed onKurungu iron ore sampleusing ore of 250µm which is the liberation size of the ore is presented in Table 4.15. Table 4.16 presents the metallurgical balance sheet of the process

Table 4.15: Chemical Composition of processed Samples of Kurungu iron ore using X-Ray Fluorescence (XRF)

Oxide	**Heavy (Concentrate)**	**Light (Tailings)**
Al_2O_3	0.761	3.470
SiO_2	5.169	68.180
CaO	0.537	2.003
TiO_2	3.019	< LOD
Cr_2O_3	0.037	0.852
MnO	1.312	< LOD
Fe_2O_3	84.572	14.870
CuO	< LOD	0.776
ZnO	0.054	0.017
MgO	< LOD	< LOD
Sb_2O_3	< LOD	< LOD
Bal	4.538	9.831
TOTAL	99.999	99.999

LOD: limit of detection

Table 4.16: Metallurgical Balance of Kurungu Iron Ore after gravity concentration

Material	Weight (g)	Assay %	Unit	Recovery %

		Fe_2O_3	SiO_2	F	SiO_2	Fe_2O_3	SiO_2
Feed	500.00	63.120	28.317	31560.00	14158.50	100	100
Concentrate	310.00	84.57	5.169	24555.10	1271.93	77.80	8.98
Tailings	190.00	14.87	68.18	5024.26	9755.36	15.92	68.90
Midllings		0.56	26.65	1980.74	3131.21	6.28	22.12

From Table 4.15, the chemical analysis shows that the concentrate produced contained 84.57% Fe_2O_3 (59.15%Fe) and 5.17% SiO_2, while the tailing gave 14.87% Fe_2O_3 (10.40%Fe) and 68.18% SiO_2.This means that more of the iron content reported at the concentrate and more of the SiO_2 reported at the tailing as compared to the feed. This separation and upgrade of the concentrate is achieved as a result of the variation in properties of the Fe_2O_3 and SiO_2 that report in the concentrate and tailing respectively (Agava, 2006).

The metallurgical balance of the processed Kurungu iron ore shows that the concentrate produced contained 84.57% Fe_2O_3 (59.15% Fe) and 5.169% SiO_2 with recoveries of 77.80% for Fe, while the tailing produced contained 14.87% Fe_2O_3 (10.40% Fe) and 68.18% SiO_2 with recoveries of respectively, showing that there is an upgrade in the iron content from 60.86% Fe_2O_3 (42.57%Fe) in the feed to 84.57% Fe_2O_3 (59.15% Fe) in the concentrate. There is also a decrease in SiO_2 from 36.20% SiO_2 in the feed to 5.17% SiO_2 in the concentrate. The shaking table can be said to be a good means of separating the ore to produce high quality concentrate (Ugwuegbu et al, 2013).

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The works on Characterization and gravity concentration of Kurungu iron ore was carried out and the following conclusions are drawn:

I. The chemical analysis revealed that the iron ore contains 60.86% Fe_2O_3, 0.49% MnO, 0.10% CaO, 36.2% SiO_2, 0.04% CuO, 0.10% ZnO, 0.02%, Rb_2O, 0.36% In_2O_3, 0.1% Sb_2O_3, 0.24% La_2O_3, 0.57% Eu_2O_3 and 0.03% Re_2O_7. The result indicates that the ore contains 42.57% Fe and thus can be regarded as medium-grade iron ore with high amount of silica.

II. The physical properties of the iron ore are as follows: specific gravity of 3.81, density of $3.81\times10^3 kg/m^3$ and electrical conductivity of $1.17 \times 10^{-3}\Omega^{-1}m^{-1}$.

III. The mineralogical analysis of the ore revealed that the iron bearing mineral is Magnetite while Actinolite and quartz are present as associated minerals

IV. The iron bearing minerals and other associated minerals were found to have distributed themselves in various proportions in the sieve size fractions (+355μm to -63μm). However, the liberation size of the valuable mineral (Fe_2O_3) was achieved at -355+250μm sieve size fraction, and the work index of the ore was found to be 13.96kWh/t.

V. Beneficiation of the iron ore indicated that the iron (Fe) of the ore can be upgraded from 42.57% to 59.15% Fe with a recovery of 77.80% using gravity concentration. The result obtained shows that Kurungu iron ore can be upgraded using gravity separation method.

VI. Based on the results, Kurungu iron ore can be seen as another potential deposit that can be explored and exploited for usage in iron and steel production.

5.2 Recommendations

i. The result of the concentration test can be optimized by changing some parameters to achieve a better recovery of iron from the tailings

ii. Other means of beneficiation such as froth flotation is hereby recommended to be looked into for the production of super concentrate of the iron ore that will be suitable for sinter and pellet production.

iii. More sensitive characterization technique should be applied to the Kurungu Iron ore to ascertain the actual content of some deleterious component like Phosphorus and sulphur

5.3 Contribution to Knowledge

i. The findings in this research have shown that Kurungu iron ore contains 60.86%Fe_2O_3 (42.57%Fe) and 36.2% SiO_2 chemically, mineralogical characteristics reveals that the ore contains Magnetite, Quartz and Actinolite.

ii. The research have revealed the liberation size to be 250μm, work index of 13.96kWh/t.

iii. Beneficiation of the iron ore indicated that the iron (Fe) of the ore can be upgraded from 42.57% to 59.15%Fe with a recovery of 77.80% using gravity concentration.

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APPENDIX 1

Specific gravity

	Test 1 (g)	**Test 11 (g)**	**Average**
Wt of empty density bottle W_1	23.3	23.3	23.3
Wt of empty density bottle + sample W_2	28.3	28.3	28.3
Wt of empty density bottle + sample + water W_3	74.3	74.25	74.28
Wt of density bottle + water W_4	70.6	70.6	70.6

From equation 3.1,

$$SG = \frac{Weight\ of\ sample\ in\ air}{Weight\ of\ equal\ volume\ of\ water}$$

$$\text{Specific gravity (S. G)} = \frac{\text{W2 – W1}}{[(\text{W4 – W1}) - (\text{W3 – W2})]}$$

Substituting from values on Table 4.4,

$$SG(1) = \frac{(28.3 - 23.3)}{[(70.6 - 23.3) - (74.3 - 28.3)]} = 3.846$$

$$SG(1) = \frac{(28.3 - 23.3)}{[(70.6 - 23.3) - (74.25 - 28.3)]} = 3.775$$

$$Average\ S.G = \frac{SG(1) + SG(2)}{2} = \frac{3.846 + 3.775}{2} = 3.811$$

The specific gravity of the ore is 3.811

$$\text{Relative Density} = \frac{\text{Density of Substance}}{\text{Density of Water}}$$

$$\text{Density of water} = 1000\text{kg/m}^3$$

Since the relative density is equal to specific gravity

Therefore,

$$\text{Density of substance} = \text{Relative density x density of water}$$

$$\text{Density of substance} = 3.811 \text{ x } 1000 = 3.811 \text{ x } 10^3\text{kg/m}^3$$

Electrical conductivity

The results obtained for calculating the electrical conductivity of the ore is as follows:

Length of the sample (L) = 3cm

Diameter = 3.5cm r = 3.5/ 2 = 1.75cm

Resistance = 0.961 x $10^6\Omega$

Using equation 3.4 and 3.5

Resistivity $\rho = \frac{RA}{L}$

$$A = \pi r^2 = \frac{22}{7} \times 1.75^2 = 9.625cm^2$$

$\rho = \frac{0.961 \text{ x } 106 \times 9.625}{3} = 3.08 \times 10^6$

Conductivity $\tau = \frac{1}{\rho}$

$\tau = \frac{1}{3.08 \times 10^6} = 1.17 \times 10^{-3}\Omega^{-1}m^{-1}$

Work index calculation using Bond Ball work index equation

$\text{Wit} = \text{Wir} \ \frac{\{\frac{10}{\sqrt{\text{Pr}}} - \frac{10}{\sqrt{\text{Fr}}}\}}{\{\frac{10}{\sqrt{\text{Pt}}} - \frac{10}{\sqrt{\text{Ft}}}\}}$

Where,

Wir = 15.13kwh/t, Pr = 250.81 µm, Fr = 306.26 µm, Pt = 184.10 µm, Ft = 221.20 µm

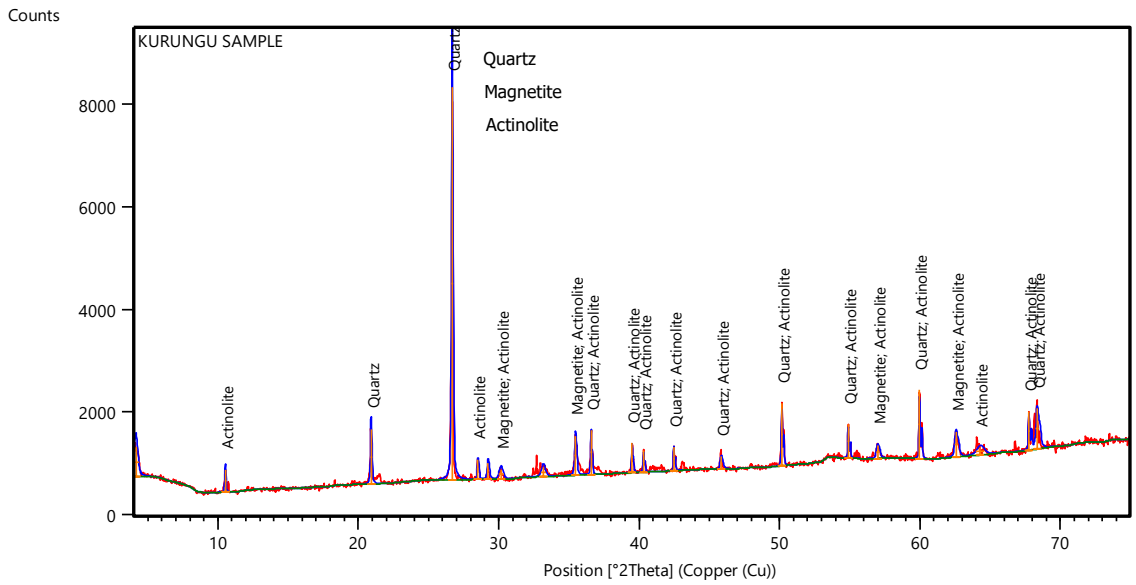
$$Wit = 15.13 \times \frac{\left\{\frac{10}{\sqrt{250.81}} - \frac{10}{\sqrt{306.26}}\right\}}{\left\{\frac{10}{\sqrt{184.10}} - \frac{10}{\sqrt{221.2}}\right\}} = 15.13 \text{ x } 0.923 = 13.96 \text{ kWh/t}$$

Measurement Conditions: (Bookmark 1)

Dataset Name	KURUNGU SAMPLE
File name	F:\New Folder\KURUNGU SAMPLE.udf
Sample Identification	KURUNGU SAMPLE
Comment	Configuration=Reflection-transmission Spinner Stage, Owner=User-1, Creation date=7/27/2010 10:30:07 AM Goniometer=Theta/Theta; Minimum step size 2Theta:0.0001; Minimum step size Omega:0.0001
Measurement Date / Time	30/05/2018 11:01:00
Raw Data Origin	PHILIPS-ASCII (.UDF)
Scan Axis	Gonio
Start Position [°2Th.]	4.0045
End Position [°2Th.]	74.9845
Step Size [°2Th.]	0.0260
Scan Step Time [s]	18.8700
Scan Type	Continuous
Offset [°2Th.]	0.0000
Divergence Slit Type	Automatic
Irradiated Length [mm]	10.00
Specimen Length [mm]	10.00
Receiving Slit Size [mm]	0.1000
Measurement Temperature [°C]	25.00
Anode Material	Cu
K-Alpha1 [Å]	1.54060
K-Alpha2 [Å]	1.54443
K-Beta [Å]	1.39225

K-A2 / K-A1 Ratio	0.50000
Generator Settings	40 mA, 45 kV
Diffractometer Type	XPERT
Diffractometer Number	1
Goniometer Radius [mm]	240.00
Dist. Focus-Diverg. Slit [mm]	91.00
Incident Beam Monochromator	No
Spinning	No

Main Graphics, Analyze View: (Bookmark 2)



Peak List: (Bookmark 3)

Pos. [°2Th.]	Height [cts]	FWHM Left [°2Th.]	d-spacing [Å]	Rel. Int. [%]
4.1609	579.24	0.3070	21.23648	7.57
10.5256	426.81	0.0768	8.40497	5.58
20.9101	1071.12	0.1023	4.24842	13.99
26.6877	7654.24	0.1023	3.34037	100.00

28.5236	381.23	0.1023	3.12941	4.98
29.2482	319.34	0.1535	3.05350	4.17
30.1546	187.76	0.3070	2.96376	2.45
33.1655	179.70	0.3070	2.70126	2.35
35.4696	765.02	0.1279	2.53089	9.99
36.5837	873.50	0.0768	2.45633	11.41
39.4990	577.63	0.0768	2.28149	7.55
40.3154	425.41	0.0768	2.23716	5.56
42.4808	461.05	0.0768	2.12800	6.02
45.8488	247.21	0.1535	1.97922	3.23
50.1684	1225.66	0.0768	1.81846	16.01
54.9090	651.69	0.0768	1.67216	8.51
56.9912	262.99	0.2047	1.61591	3.44
59.9896	1341.49	0.0768	1.54212	17.53
62.5790	494.62	0.2047	1.48439	6.46
64.2663	133.12	0.6140	1.44943	1.74
67.7743	757.33	0.0936	1.38156	9.89
68.3615	794.23	0.2047	1.37225	10.38

Pattern List: (Bookmark 4)

Visible	Ref. Code	Score	Compound Name	Displacement [°2Th.]	Scale Factor	Chemical Formula
*	96-901-2601	69	Quartz	0.025	0.641	Si3.00 O6.00
*	96-900-5813	39	Magnetite	-0.094	0.072	Fe24.00 O32.00
*	96-900-1937	10	Actinolite	0.149	0.069	Fe6.22 Mn0.18 Mg3.91 Al0.05 Ti0.00 Ca3.63 Na0.04

	Si15.98 H3.72 O47.92 F0.02 Cl0.06

Document History: (Bookmark 5)

Insert Measurement:

- File name = KURUNGU SAMPLE.udf
- Modification time = "31/05/2018 16:32:03"
- Modification editor = "NOOR"

Interpolate Step Size:

- Derived = "Yes"
- Step Size = "0.01"
- Modification time = "31/05/2018 16:32:03"
- Modification editor = "PANalytical"

Search Peaks:

- Minimum significance = "4"
- Minimum tip width = "0.01"
- Maximum tip width = "1"
- Peak base width = "2"
- Method = "Minimum 2nd derivative"
- Modification time = "23/05/2018 23:23:52"
- Modification editor = "NOOR"

Search & Match:

- Allow pattern shift = "Yes"
- Auto residue = "No"
- Data source = "Profile and peak list"

- Demote unmatched strong = "Yes"
- Multi phase = "Yes"
- Restriction set = "Minerals"
- Restriction = "Restriction set"
- Subset name = ""
- Match intensity = "Yes"
- Two theta shift = "0"
- Identify = "No"
- Max. no. of accepted patterns = "5"
- Minimum score = "50"
- Min. new lines / total lines = "60"
- Search depth = "10"
- Minimum new lines = "5"
- Minimum scale factor = "0.1"
- Intensity threshold = "0"
- Use line clustering = "Yes"
- Line cluster range = "1.5"
- Search sensitivity = "1.8"
- Use adaptive smoothing = "Yes"
- Smoothing range = "1.5"
- Threshold factor = "3"
- Modification time = "23/05/2018 23:01:12"
- Modification editor = "NOOR"

Convert Ref. Pattern to Phase:

- Modification time = "31/05/2018 16:35:40"
- Modification editor = "NOOR"

Move Lettering:

- Modification time = "31/05/2018 16:37:45"
- Modification editor = "NOOR"

Move Lettering:

- Modification time = "31/05/2018 16:37:48"
- Modification editor = "NOOR"

Move Lettering:

- Modification time = "31/05/2018 16:37:53"
- Modification editor = "NOOR"

Kurungu Iron Ore

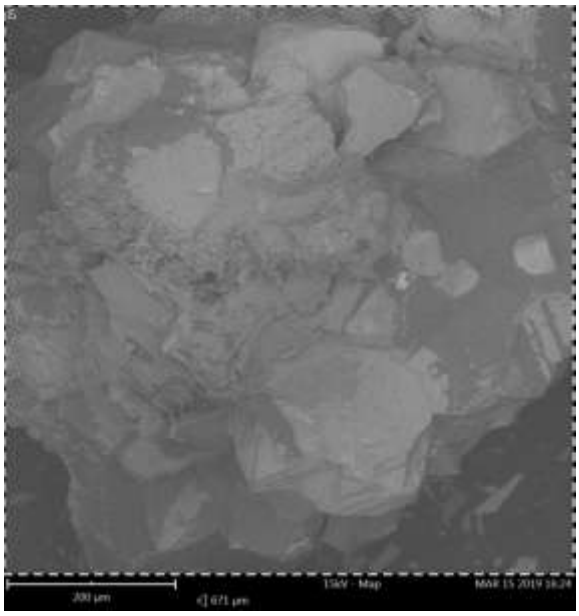
Contains 1 image with a total of 4 analyses

01. Image 21

4 analyses: 1x region, 3x spot

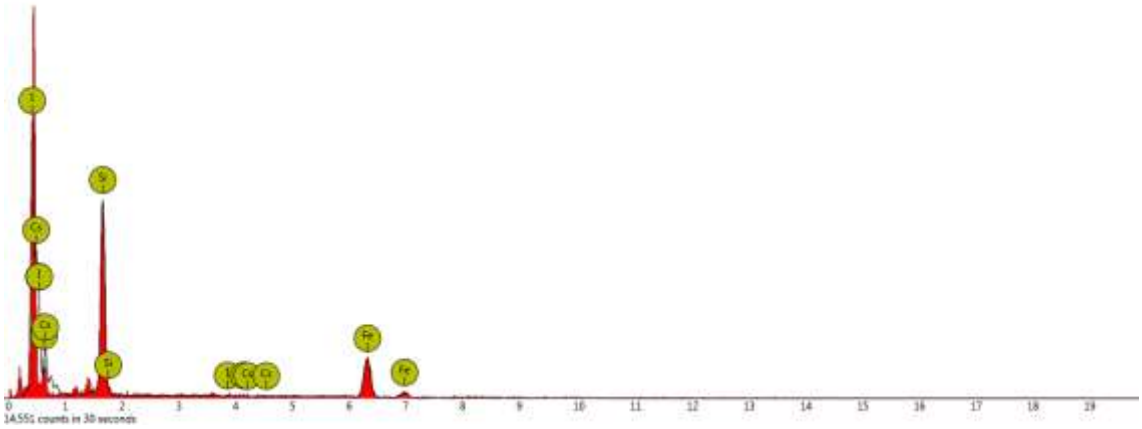
Image 21

1. region



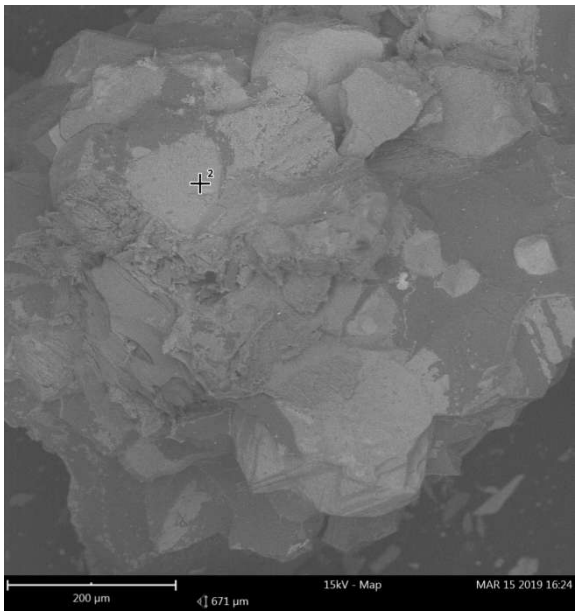
	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
26	Fe	Iron	39.36	55.89
14	Si	Silicon	60.31	43.06
53	I	Iodine	0.33	1.05

FOV: 671 µm, Mode: 15kV - Map, Detector: BSD Full, Time: MAR 15 2019 16:24



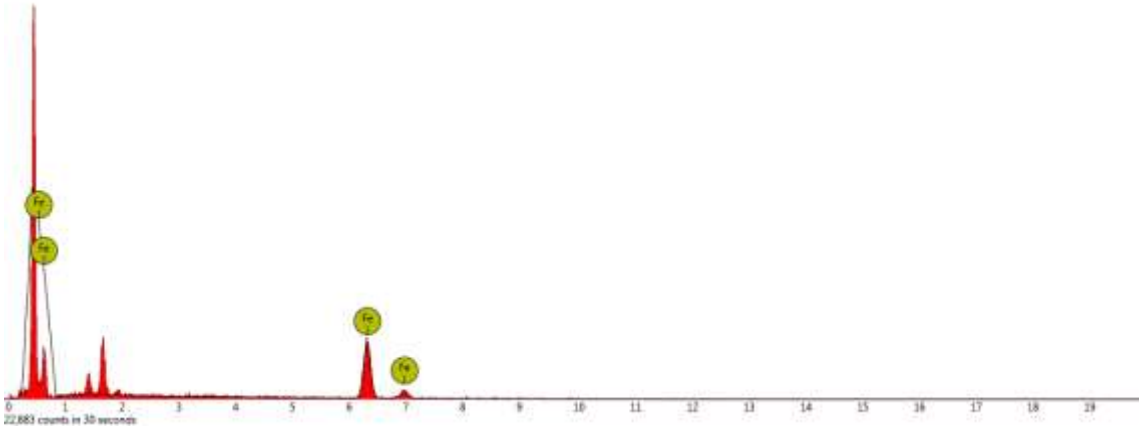
Disabled elements: B, C, O

2. spot



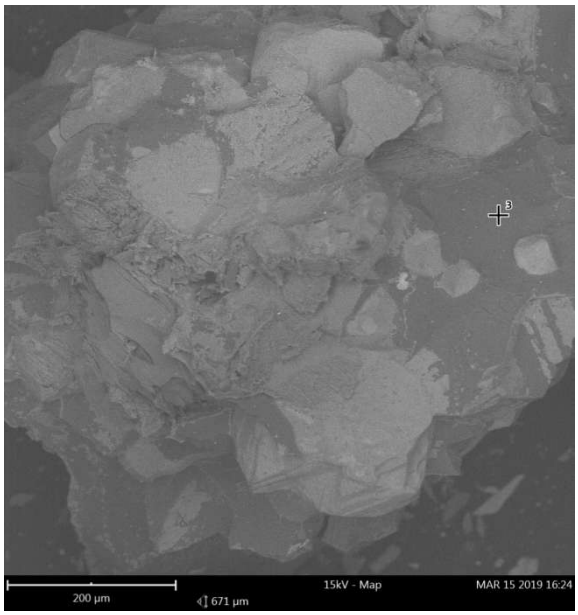
Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
26	Fe	Iron	100.00	100.00

FOV: 671 µm, Mode: 15kV - Map, Detector: BSD Full, Time: MAR 15 2019 16:24



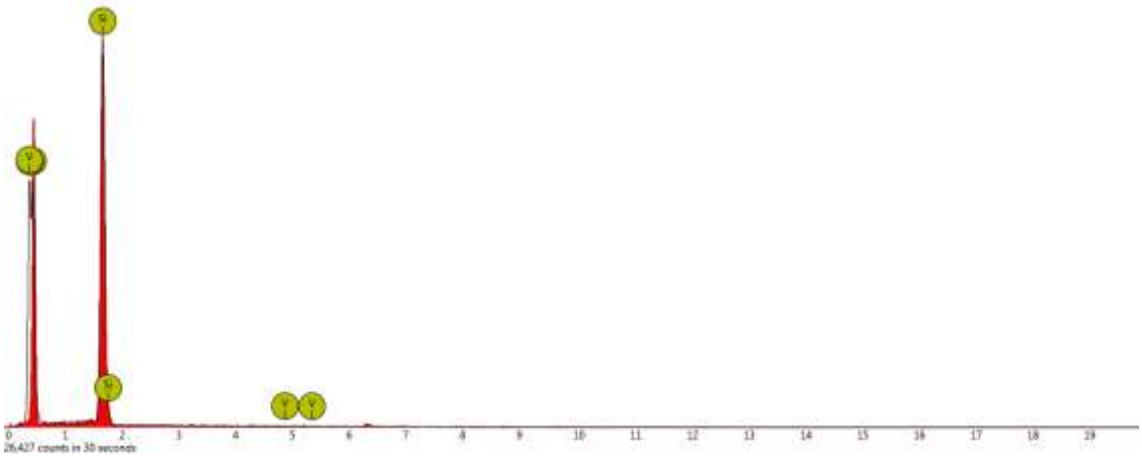
Disabled elements: B, C, O

3. spot



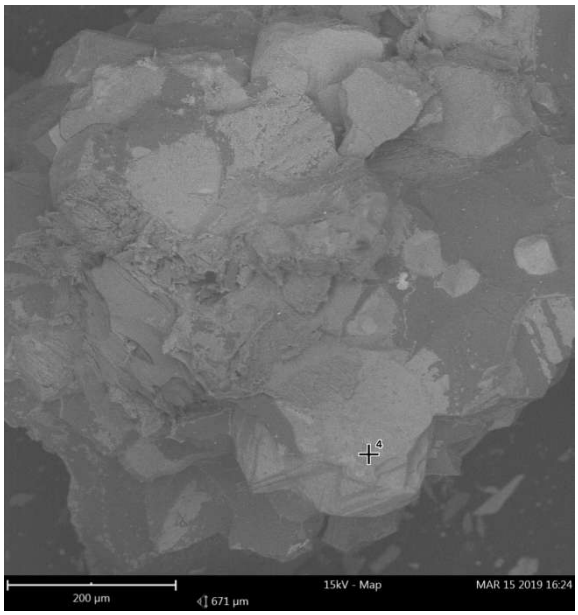
Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
14	Si	Silicon	100.00	100.00

FOV: 671 µm, Mode: 15kV - Map, Detector: BSD Full, Time: MAR 15 2019 16:24



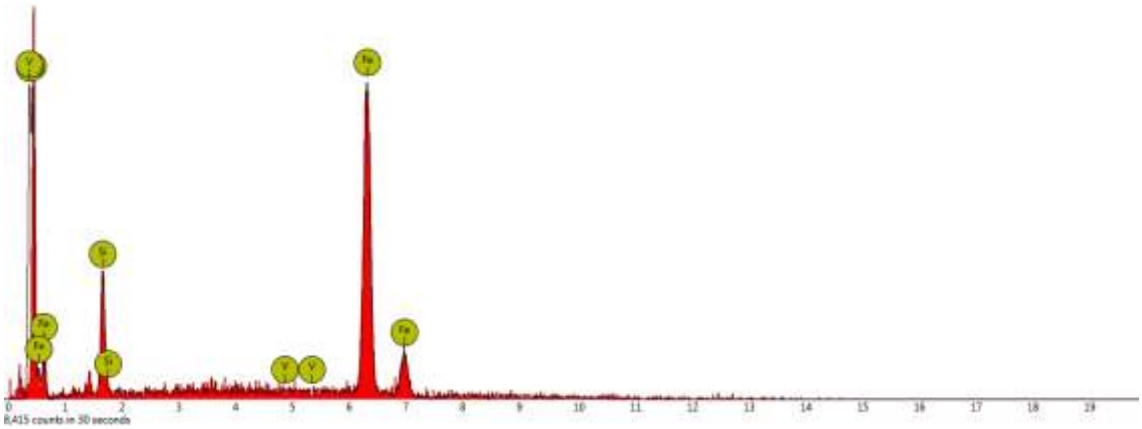
Disabled elements: B, C, O

4. spot



Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
26	Fe	Iron	87.33	93.20
14	Si	Silicon	12.67	6.80

FOV: 671 µm, Mode: 15kV - Map, Detector: BSD Full, Time: MAR 15 2019 16:24



Disabled elements: B, C, O