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DEPARTMENT OF MINERALS ENGINEERING

A THESIS REPORT ENTITLED

STUDIES INTO THE NATURE OF AKPAFU-TODZI IRON ORE AND ITS RESPONSE TO REDUCTION USING WASTE POLYMERS.

BY

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SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF MASTER OF PHILOSOPHY DEGREE IN MINERALS ENGINERRING

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SEPTEMBER, 2020

DECLARATION

I declare that this thesis work is my own work. It is being submitted for the degree of Master of Philosophy in Minerals Engineering in the University of Mines and Technology (UMaT), Tarkwa. It has not been submitted for any degree or examination in any other University.

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ABSTRACT

This work is to study the nature of Akpafu-Todzi iron ore and how it responds to carbothermal reduction using waste polymers under microwave irradiation and gas heating. Physical analyses such as particle size distribution, tumble and abrasive index, porosity, bulk density and Bond work index were performed on the as-received sample. Pulverised samples of the ore were then characterised by X-ray fluorescence (XRF), X-ray diffraction (XRD) and scanning electron microscopic (SEM) analyses. Reduction studies were conducted on the ore using waste polymers (High density polyethylene (HDPE), low density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET) and their various blends biomass (saw dust (SD), palm nut shells (PNS), coconut shells (CNS)) as reducing agents. The results from the XRF, XRD and SEM analyses of the representative sample showed that the Akpafu-Todzi iron ore is of a low-grade hematite with an average Fe content of about 43.91 wt%, high gangue material (SiO_2+Al_2O_3) and no deleterious elements (sulphur and phosphorus). The values obtained from the bulk density and porosity test showed a strong negative correlation between the two with average values of 3.3 tonnes/m^3 and 12.2% respectively. The mechanical test showed that Akpafu-Todzi iron ore has Tumble Index value > 93.97 wt% and Abrasion Index value < 4.0 wt%. These values indicate that Akpafu-Todzi iron ore will produce little or no fine particles when it goes through the various processing stages. Results from the reduction studies showed that iron ore samples responded very well to the carbothermal reduction using various waste polymers under the various energy sources utilised. The highest extent of reduction recorded was approximately 98%; it occurred after 20 mins with saw dust as reducing agent and microwave irradiation as the mode of heating. Rate of reduction for microwave and “Sika Bukyia” gas heating sources were 0.00948 g.s^{-1} and 0.00427 g.s^{-1} respectively. This implies that the reduction process of Akpafu-Todzi iron ore can record high productivity within a short period of time. Akpafu-Todzi iron ore was found to satisfy the commercial physical requirement but did not satisfy the chemical requirements for the Corex, blast furnace and the major direct reduction processes (Midrex, HYL III and SL/RN). The ore was found to be suitable for composite pellet formation which could be used as feedstock for smelting reduction, microwave reduction and locally design furnaces.

To

Wifey and Daughter

∞

Amanda and Empress

ACKNOWLEDGEMENT

Therefore, by Him, let us continually offer the sacrifice of praise to God, that is, the fruit of our lips, giving thanks to His name (Heb. 13:15). Praise and thanks go to the almighty God for bringing me this far in my academics and giving me strength, protection, good health, wisdom, knowledge and above all understanding during this research work. I couldn’t have done it without His favours and graces He showered on me.

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CHAPTER 1

INTRODUCTION

1.1 Statement of Problem

Iron is primarily used in steel and cast-iron production. About 98% of the world iron ore production is used to make iron in the form of steel and cast iron. Only about 2% are used in cement, pigments, agriculture products and chemical industries (Anon., 2012). Steel and cast iron being the major products have been and still are a vital material in various areas of life. It is utilised in many industrial activities ranging from production of heavy duty machinery to light electrical and electronic appliances, construction materials, and cooking utensils. Before the production of steel and cast iron, the raw material, iron, has to be extracted from its ore.

Rocks and minerals from which iron can be extracted are known as iron ore. When the iron ore can be extracted economically, then it is classified as an iron ore deposit (Misra, 2000). This ore deposit must have a high iron metal concentration to be considered ore grade for economic purposes but, typically, a deposit with at least 25% iron metal concentration can be considered economically recoverable (Amikiya, 2014). There are a lot of ore minerals containing iron metal; however, only a few are used commercially as sources of iron. Ore minerals containing important amounts of iron may be grouped according to their chemical compositions into oxides, carbonates, sulphides and silicates. Oxide minerals are the most important sources of iron, with the carbonates, sulphides and silicates being of minor importance (Poveromo, 1999).

Many countries in the world have large deposits of iron ore at their disposal. These deposits, when exploited, generate income, creates job opportunity and also contributes greatly to the development of their countries. Also, countries with less deposits strive to exploit these natural deposits to gain appreciable revenue from this resource.

Ghana has three main proven iron ore deposits and few unproven deposit. These proven ore deposits of potential industrial or commercial importance in Ghana are Shieni sedimentary iron ore, Opon-Mansi lateritic iron ore and Pudo titaniferous-magnetiferous iron ore (Yendaw, 2012). Akpafu-Todzi iron ore is one of the few unproven deposits in Ghana. This ore deposit lies in the Buem Formation where the type of rocks is mainly thick sequence of shale, sandstone, and volcanic rocks. It also includes bedded cherts and siliceous shales (silexites), limestones, dolomites and, north of Togo, some banded iron formation (BIF) (Graham, 2013).

Akpafu-Todzi is famous in the Hohoe municipality for its iron works and blacksmiths. History has it that, the forefathers of the people of Akpafu-Todzi used to produce their own farming and hunting implement, mainly cutlasses, hoes, guns and hammers. The big question is how were these implements made? These implements were made from iron ore which they dug from the same mountain they leaved on. Signs of the pit from which the iron ore were dug, the furnace used, the slag obtained and implements made, are still extant in the town.

Based on work done on the Akpafu-Todzi iron ore by Kesse and Banson (1975) coupled with plans of rejuvenating iron ore mining in the area, there is the need to establish the physical, chemical and metallurgical properties of this ore. These properties will aid in the establishment of the appropriate route to recover the iron or upgrade the iron content of the ore. These properties generally give an insight to the nature of the iron bearing ore. Characterised on the nature of the ore, the process of iron extraction is mainly the use of coke and natural gas as a reductant. The inaccessible and high cost of these reductants in some parts of the world has caused the emergence of waste polymers being used as a reducing agent. As scraps are the main raw material for steel production in Ghana, utilising waste polymers as reductants, iron extracted from this ore could be used as a supplement raw material to steel companies in the country. Also the ore could be upgraded and exported to earn foreign income.

With the increasing consumption of iron ore in the world and the economic situation of Ghana as a developing country, this work seeks to investigate the nature (type of oxide and its concentration) of the Akpafu-Todzi iron ore and how it responds to reduction using waste polymers in a bid to pave way for its exploitation for economic use in Ghana and beyond.

1.2 Thesis Objectives

This thesis seeks to:

a. Characterise the Akpafu-Todzi iron ore deposit and establish its physical, chemical and metallurgical properties;

b. Study the reducibility of Akpafu-Todzi iron ore with waste polymers; and

c. Provide a suitable route for upgrading the Akpafu-Todzi iron ore and recovering of the metallic iron.

1.3 Methods used

Methods to be used include;

a. Review of relevant literature on the field of study

b. Experimental work

    i. Collection of ore sample;
    ii. Sample preparation;
    iii. Moisture content determination;
    iv. Abrasive index, Tumble index;
    v. Bond ball mill work index test;
    vi. Particle size distribution (PSD);
    vii. Loss on ignition (LOI);
    viii. Specific gravity (s.g)/ Bulk density;
    ix. X-ray fluorescence analysis (XRF);
    x. X-ray diffraction analysis (XRD);
    xi. Scanning electron microscope analysis (SEM); and
    xii. Reduction studies.

c. Analysis of the results

d. Report writing

1.4 Facilities Employed

Facilities used for this project include:

a. University of Mines and Technology library;
b. Geological Engineering Laboratory, University of Mines and Technology;
c. Minerals Engineering Laboratory, University of Mines and Technology; and
d. Ghana Geological Survey Department.

1.5 Organisation of Thesis

This report is divided into five main chapters. Chapter one is the general introduction to research conducted and it includes the problem statement, objective of the research and the methods used in this research. Chapter two of this research reviews the relevant literature in the field of study. The experimental work conducted and the various raw materials and procedures used are detailed in chapter three. Results obtained and the discussion of the results obtained from the experimental work in previous chapter is outlined in chapter four. Finally, after obtaining and discussion of the results, chapter five draws conclusions based on the result and discussions made and suggest recommendations necessary to improve upon the research.

CHAPTER 2

LITERATURE REVIEW

2.1 Concept of Iron as a Metal

The element iron has become a very important element in the lives of every mankind despite the emergence of plastics and rise of humanity to “silicon age”. It has been used directly or indirectly for health purposes and material for manufacturing of various artefacts, with the later the most relevant to this work and will be discussed further. A metal in the first transition series with Fe being its chemical symbol, iron is a brilliant, silvery-white, malleable, ductile and magnetic metal. It has a cubic structure, a melting point of 1 535℃ and boils at 2 750℃ when chemically pure (Kese and Banson, 1975; Bentor, 2014).

Among all the metals that exist in the Earth’s crust, iron constitute about 5%, making it the second most common metallic element in the Earth's crust after aluminium and the fourth most abundant element in the surface of the earth after oxygen, silica and aluminium (Muwanguzi, 2010; Fernández-Real *et al.*, 2002). With its abundance in nature it has become a major element of economic importance, making it arguably the backbone of all industrial development and indispensable to modern civilisation. About 98% of it is used basically for the production of steel, which is an iron alloy with carbon content between 0.2% and 2.1% by weight, depending on the grade of steel (DID, 2010).

Facing stiff competition from aluminium when weight is a major factor (as in aircraft) and plastics when lowest cost is of utmost importance (where strength and durability are not the primary concerns, such as modern American automobiles), iron still is in dominant position in significant relation to human welfare and comfort due the following four main characteristics of varying order of magnitude (Kese and Banson, 1975). These characteristics are as follows:

a. its abundance and low cost;
b. high original strength;
c. alloying properties; and
d. magnetism.

Elemental iron or pure iron is found in nature as the metal only in meteorites and in very rare circumstances where iron minerals have been reduced by environmental factors, they are never mine in it pure form. Like most metals, iron locked inside the Earth exists in the form of oxides, sulphides, silicates, hydroxides and carbonates (Anon., 2014). These various chemical compounds exit as a result of various geological processes which lead to the formation of its ore deposits.

2.2 Iron Ore Deposits

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 carbon dioxide. Gold and platinum metals are found principally in the native or metallic form. Silver, copper, and mercury are found native as well as in the form of sulphides, carbonates, and chlorides. The metals which appear to be more reactive are always in compound form, such as the oxides and sulphides of iron and the oxides and silicates of aluminium and beryllium. Minerals by definition are natural inorganic substances possessing definite chemical compositions and atomic structures (Wills and Napier-Munn, 2006). Rock mass or rock body that contains one or more mineral sufficiently above the crustal abundance to have a potential economic value, is termed as a mineral deposit. When these mineral deposits have passed the test of profitability, they can then be referred to as an ore deposit (Misra, 2000).

In relation with the above definitions, an iron ore deposit can then be referred to as a mineral body of sufficiently high size, iron content and definite chemical composition that can be mined and marketed at a reasonable profit under prevailing conditions of commodity, prices, costs and technology either immediately, or potentially (Arndt and Ganino, 2012). The value of a mineral or rock deposit is determined by economic, environmental, and technological factors (Drzymala, 2007).

2.2.1 Iron Ore-Forming Processes

The processes involved in the formation of ore deposits can be put under five geological processes. These processes are namely; igneous processes, magmatic-hydrothermal processes, hydrothermal processes, surficial and supergene processes and sedimentary processes (Robb, 2005). Among these processes only three of them are mainly associated with iron deposit formation. Direct sedimentation (forming bedded sedimentary deposits), igneous activity (forming segregation or replacement deposit) and enrichment due to surface and near surface weathering (Amikiya, 2014) are the processes involved in the formation of iron ore deposit. Research has shown that the global iron ore production consists of about 90% iron-rich cherty sedimentary rocks and their metamorphic or supergene derivate (Fernández-Real *et al.*, 2002). Table 2.1 below shows the geological processes involved in iron ore deposit formation and their respective type of iron ore formed with their major iron minerals.

Table 2.1 Geological Processes of Iron Formation and their Major Iron Minerals

Geological type	Principal iron mineral
Sedimentation	
Banded iron formation (BIF)	Magnetite, Hematite, Siderite, Iron silicate
Iron stones	Chamosite, Limonite, Hematite, Siderite
Igneous Activity	
Magmatic segregations	Titaniferous, Ilmenite, Magnetite, Iron silicates
Pyrometasomatic	Magnetite
Surface or Near-Surface Weathering	
Secondary enrichments of low grade iron deposits	Magnetite, Limonite, Siderite

(Source: Amikiya, 2014)

2.3 Types of Iron-Bearing Minerals and Gangue Minerals

Most naturally occurring minerals contain some amount of iron. Literature has shown that about 300 minerals bear some amount of iron, but only few are rich enough in iron to be classed as iron ores (Amikiya, 2014). This is because majority of the minerals bear just traces of iron and cannot be considered as an iron ore. Some are also in compound with some elements which make it difficult to process. The most commonly used iron-bearing minerals contain iron compounds as magnetite (Fe_3O_4) and hematite (Fe_2O_3) and those with less importance are limonite ($2Fe_2O_3.3H_2O$), siderite ($FeCO_3$) and pyrite (FeS_2) (Kugeria, 2013). The ore under study, Akpafu-Todzi iron ore deposit, consists mainly of hematite iron minerals with silica and aluminium as the main gangue minerals. In table 2.2 is the properties of important iron-bearing minerals.

2.3.1 Magnetite (Fe_3O_4)

This type of iron-bearing mineral consists of about 72.4% of Fe in the pure state with a specific gravity of 5.2 and a Mohs hardness in the range 5.5-6. It is occasionally found sufficiently to be an ore of iron occurring as a metallic mineral in nature. The beneficiation of this ore is very simple compared to other iron bearing minerals. Since the ore consists of metallic minerals, the ore is crushed and the magnetite is separated from the gangue minerals by magnet. This ore contains impurities like silica, alumina and phosphorus (Yellishetty *et. al.*, 2012).

2.3.2 Hematite (Fe_2O_3)

Hematite deposits are mostly sedimentary in origin. Its formation is not fully understood, but literature revels that they are formed by the chemical precipitation of iron from shallow seas about 1.8 to 2.6 billion years ago, during the Precambrian period (Harry *et al.*, 1973; Amikiya, 2014). These deposits are the products of the enrichment of Precambrian BIFs, and they are considered as one of the most vital sources of iron ore today (De Kock *et al.*, 2008). It has a theoretical iron contain of about 70%, specific gravity of 5.1 and Mohs hardness of range 5-6. Its beneficiation is quite cumbersome compared to magnetite.

2.3.3 Limonite ($2Fe_2O_3.3H_2O$)

Limonite is colloidal hydrated ferric oxide, yellow to brown in colour. It is light with a density 3.6-4.0 g/cc. it has about 63% iron in its pure state and Mohs hardness between 5-5.5. They are secondary minerals formed as a result of oxidation of Fe-carbonate, hematite and magnetite (Amikiya, 2014).

2.3.4 Siderite ($FeCO_3$)

Siderite in its pure state contains about 48.3% of iron with a specific gravity of 4 and a Moh hardness of 4. Siderite ores constitute just a fraction of the total world iron ore reserves (Amikiya, 2014).

2.3.5 Pyrite (FeS_2)

Pyrite is a good source of sulphur, but not a good source of iron because of the sulphur, which ruins iron and is hard to separate from it. It contains 47% iron in its pure state. Its specific gravity is 4.9 and its Mohs hardness is between 6-6.5. When heated, sulphur is driven off and the iron is oxidised to magnetite (Amikiya, 2014). Table 2.2 below shows a summary of the properties of iron-ore bearing minerals being discussed.

Table 2.2 Properties of Important Iron Ore-Bearing Minerals

	Hematite	**Magnetite**	**Goethite**	**Siderite**	**Ilmenite**	**Pyrite**
Chemical Name	Ferric oxide	Ferrous–ferric oxide	Hydrous iron oxide	Iron carbonate	Iron-titanium oxide	Iron sulphide
Chemical Formula	Fe_2O_3	Fe_3O_4	$HFeO_2$	$FeCO_3$	$FeTiO_3$	FeS_2
Fe Content (wt %)	69.94	72.36	62.85	48.2	36.8	46.55
Colour	steel grey to red	dark grey to black	yellow or brown to nearly black	white to greenish grey to black	iron-black	pale brass-yellow
Crystals	hexagonal	cubic	orthorhombic	hexagonal	hexagonal	cubic
Specific Gravity	5.24	5.18	3.3–4.3	3.83–3.88	4.72	4.95–5.10
Mohs' Hardens	6.5	6	5–5.5	3.5–4	5–6	6–6.5
Melting Point (°C)	1 565	1 600	-	-	1 370	-

(Source: Yellishetty *et. al.*, 2012)

2.3.6 Gangue Minerals

Like every other ore, iron ore also contains impurities (gangue minerals) which may have good or bad effect on the production of iron and on the operation of a steel plant. The gangue minerals associated with iron ore can be in the form of silica; which is normally removed in the form of slag during smelting operations, metal oxides, alumina and deleterious elements. Deleterious elements are element whose presence in a reduced iron is not desirable. Phosphorus, sulphur, titanium and arsenic are the most common deleterious elements (Amikiya, 2014).

Phosphorus has five major effects on iron; it increases hardness and strength, lowers solidus temperature, increases fluidity and cold shortness. The presence of phosphorus in iron can either be good or bad depending on what the iron will be used for. Sulphur also has a great effect on iron and even a small amount of it in iron has to be taken seriously. It causes the iron to be hot short making the iron brittle when hot (Gordon, 1996). Sulphur can be avoided or removed from iron ores by roasting and addition of manganese which forms a high melting sulphide at high temperatures (1 610 °C) and therefore, prevents the formation of a liquid iron sulphide at the grain boundaries (Verhoeven, 2007).

2.4 World Iron Ore Deposits, Production and Consumption

Ore deposits are not evenly distributed across the globe. Large geological areas are devoid of viable deposits while others constitute what are known as 'metallogenic regions', regions containing an unusually high concentration of deposits of one or several types (Arndt *et. al.*, 2015). Like all other ore deposits, iron ore deposits are not evenly distributed around the world. It is widely distributed in the world and most countries in the world have iron ore deposit. The world has a total iron reserve of about 800 000 million tons of crude iron ore with about 230 000 million tonnes iron content (Jorgenson, 2011). There are about sixty countries in the world which produce iron ore for both domestic use and export markets, with the annual world iron production estimated to be around 1 000 million tons. Australia, Brazil, China, India, Russia, Ukraine, USA and South Africa are the main producers of iron ore, contributing more than 80% of the world total production (Amikiya, 2014). As of the year 2015 the iron ore production has seen increase and decrease in production with China being the highest producer. Table 2.3 shows the iron ore production by main producers from 2010 to 2015.

Table 2.3 Main Producers of Iron Ore in the World from 2010 to 2015

	Production in tonnes (metric)					
Country	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
China	1 077 705 100	1 326 942 000	1 309 637 000	1 451 011 000	1 514 240 000	1 381 288 000
Australia	433 452 000	477 330 291	519 858 812	615 523 352	750 519 855	816 781 763
Brazil	372 001 000	460 400 000	400 600 000	316 800 000	345 800 000	389 146 000
India	207 157 000	168 582 000	136 618 000	152 183 000	129 321 000	155 910 000
Russia	95 500 000	104 000 000	104 000 000	102 100 000	102 100 000	101 000 000
Ukraine	78 541 000	80 900 000	67 149 000	70 389 000	68 337 000	66 902 000
South Africa	58 709 330	58 056 897	67 100 474	71 543 088	80 759 334	73 220 891
USA	49 500 000	54 700 000	54 000 000	53 000 000	55 900 000	42 500 000
Kazakhstan	50 190 000	51 742 000	52 614 000	51 758 500	51 540 800	37 269 700
Iran	35 548 974	38 260 000	32 138 000	57 225 896	69 279 071	58 000 000

(Source: Brown *et al.*, 2016 and 2017)

The world's total consumption of iron ore is not directly determined. The imports of iron ore and production of crude steel, direct reduced iron (DRI) and pig iron all together act as a guide to indicate whether consumption increases or decreases. China contributes about 90% to the increase of iron ore consumption and has become the world's largest consumer of iron (Anon., 2015; Anon., 2012). Despite having three major iron ore deposit of economic importance, Ghana has not exploited any of their ore deposits commercially and currently not among countries who produce iron ore (Yendaw, 2012).

2.5 Iron Ore Deposits in Ghana

Ghana is blessed with lots of mineral deposits such as gold, diamond, bauxite, manganese, iron etc. Exploitation of these mineral deposits is of great importance to the nation as a developing country. As considerations are given to the exploitation of gold, diamond, bauxite and manganese, iron which is in high demand for steel production has to be given the same consideration. There are predominately three main iron ore deposits of potential industrial importance in Ghana. Shieni Hills iron ore deposit, Opon-Mansi iron ore deposit and Pudo iron ore deposit are the main iron ore deposits in Ghana (Yendaw, 2012).

Various investigations on these deposits suggested Shieni and Opon Mansi iron ore deposits have iron content ranging from 35%-50% and 35%-42% respectively. Pudo iron ore deposits had overall average assay for TiO_2 and Fe_2O_3 of 3.9% and 33.5% respectively which could serve as a perfect raw material for ferrous alloy (Iron and Titanium) (Kesse and Banson, 1975). Cardero Resources Corp. in 2013 conducted a Metallurgical testing which depicted that the Shieni iron ore performs well in bench-scale tests reducing directly to metallic iron in one step. Testing completed on Shieni iron ore indicate a head grade of 46.85% iron with a recovery of about 88.65% of iron as DRI concentrate.

Aside these main deposits, the Akpafu iron ore deposit cannot be overlooked. This ore deposit has no much information but just evidence and various accounts of iron making in the community has proven otherwise, so this thesis is aimed at studying this deposit.

2.6 Akpafu-Todzi Iron Ore Deposit

2.6.1 Location and Accessibility of the Study Area

Akpafu-Todzi iron ore deposit is located in a village in the Akpafu Traditional area of the Hohoe Municipality in the mid-east portion of the Volta Region of Ghana. The area can be located between latitudes 7º 10′ 00″ N and 7º 20″ 00″ N longitudes 0º 25′ 00″ E and 0º 30′ 00″ with exact coordinates 7° 15′ 18″ N 0° 29′ 28″ E. It is about four and half-hours' ($4^1/_2$ hr) drive from Accra and about two hours' (2 hr) drive from the regional capital, Ho. The village has its settlement on a mountain with elevation of about 1 223 ft. From the foot of the mountain to the village on top of the mountain is about 2 km. The population of the inhabitants of the village is around 600-700 in total. They call themselves the Mawu and speak Siwu, a Kwa language that is quite distinct from the dominant regional languages Ewe, Twi and Guan. The Siwu name for the village is kaa i kato, or "home up high" (Anon, 2014). Figure 2.1 shows the location of the town on the map of Ghana.

Figure 2.1 Geological map of Ghana showing the study area (Source: Anon, 2014)

2.6.2 Geology of the study area

The mountains of Akpafu-Todzi consist of a valley with minor settlement one mountain and major settlement on the other and few settlements in the valley. The Birimian, the Tarkwaian, the Dahomeyan Systems, the Togo Series and the Buem Formation are the major rock units underlying the country. The rock unit underlying Akpafu is the Buem Formation (Figure 2.3). Earlier researchers such as Kesse (1985) and Dapaah-Siakwan and Gyau-

Boakye (2000) gave the types of rocks that constitute the Buem formation. The west most part of the Buem formation consist of thick, lower sequence of clastic sediments with some carbonate and tillite units succeeded by clastics and volcanics that include mafic flow units and pyroclastic (Kesse, 1985). Figure 2.2 shows the detailed mapping of the study area.

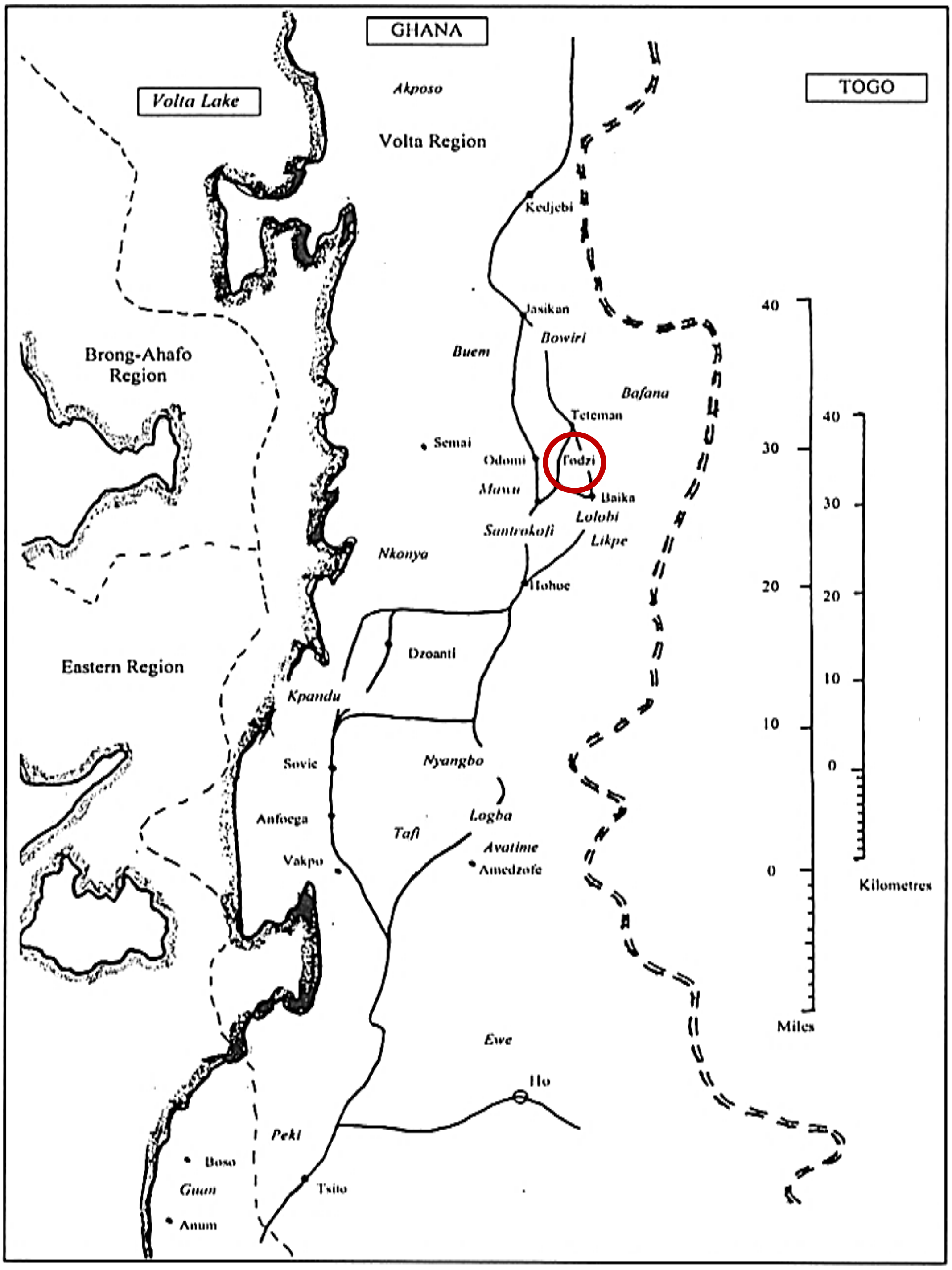

Figure 2.2 Geological Map of Ghana showing Central Part of Volta Region where the study area is located (Source Pole, 2010)

Also, Dapaah-Siakwan and Gyau-Boakye (2000) said that the rocks found in this area are thick sequence of shale, sandstone, and volcanic rocks with subordinate limestone, tillite, grit and conglomerate. It also includes bedded cherts and siliceous shales (silexites), limestones, dolomites and, north of Togo, some banded iron formation (BIF) (Graham, 2013). Figure 2.3 below shows the geological map of Ghana showing rock unit underlying Akpafu study area.

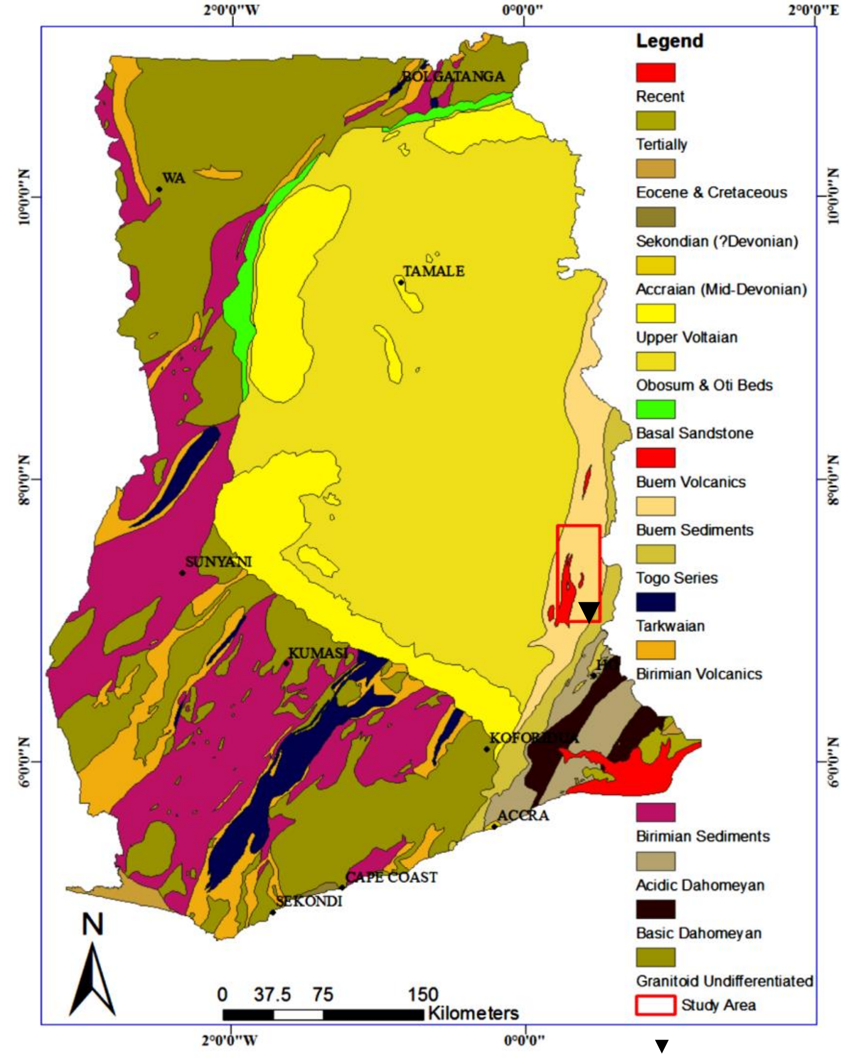

Figure 2.3 Geological Map of Ghana Showing Rock Unit Underlying Akpafu Study Area (modified after Graham, 2013)

There two main rock types of Akpafu-Todzi area. These rock types are buff-weathering shale of phyllitic aspect and hematitic cherty quartzites and sandstone (Kesse, 1975). The two rock types are found to be interbedded. The hematitic cherty quartzites are the main source of the iron ore under study. The main rock type which is the main source of the iron ore was on the average of about 0.3 km broad and run along strike throughout the length of the area. Also within the rock type are joints, fractures and cracks. Due to the underlain by and sometimes interbedded with shale and rocks of phyllite aspect, the iron rich solution was not able to percolate, so the iron in the solution was deposited in the form of sesquioxide (limonite) which is the type of iron ore in the area (Kesse and Banson, 1975).

2.6.3 The iron Industry of Akpafu-Todzi

Akpafu-Todzi was one of the sites of the traditional iron industry for the Akpafu people and they are famous in the municipality for their ironworks and blacksmithing. Due to the iron ore they have their festival which they celebrate, called iron festival.

The Mines

The iron ore used for the iron industry was dug from the same mountain they lived. They actually lived away across the valley to the west, and only came over to work the ore. But as time passed they inhabited the mountain where they worked the ore (Dingemanse, 2011). There are several mine shafts which were dug into the side of the mountain. The mine shafts' entrances looked like that of a cave. This shape was observed to continue throughout the shaft with interiors falling as low as 2-3 ft and rising to 5-6 ft, with a space between the foot of the walls of about 10-15 ft (Rattray, 1916). Due to this orientation when entering the shaft at some point is like entering a slave dungeon and at other points you have to claw your way in. The shaft ran into the mountains in a winding tunnel. The ore was mined using a spear shaft and hammer which is used to chisel out the ore from the walls and root of the mine shaft (Pole, 2010). Some ancient mines can still be visited in the vicinity of the village and Figures 2.3 and 2.4 show photographs of the mine shaft entrance and mode of iron ore mining respectively at Akpafu-Todzi.

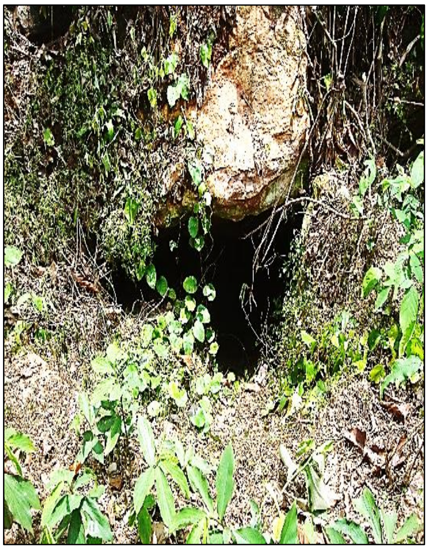

Figure 2.4 Mine Shaft (Cave) Entrance

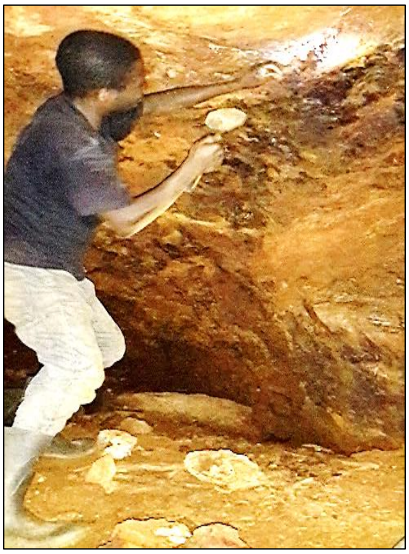

Figure 2.5 Iron Ore Mining

The smelting furnaces

The ore after it has been mined goes for extraction process. It was melted using furnaces built by the iron workers themselves. The furnaces they built look like a rice granary, but the walls are much stronger than that. The height was about 5 ft tall and the diameter was about 3 ft wide. It has a neck of the shape like that of a bottle and open at the top. At the bottom of the furnace was an opening, through which charcoal is fed.

The iron ore is broken into pieces and poured on the charcoal from the opening at the top and again covered with another layer of charcoal. So, the ore is said to be sandwiched between two layers of charcoal. When fire is set to the charcoal, the opening at the bottom is closed with clay until only a small hole left, through which air can enter; also, 5 or 6 small holes are made in the furnace, so that the fire will draw and not go out (Rattray, 1916). The productivity of the smelting furnace was about 4.6 kg per smelt (Pole, 1973). Figures 2.6, 2.7 and 2.8 show the photograph of both past and current state of the smelting furnaces.

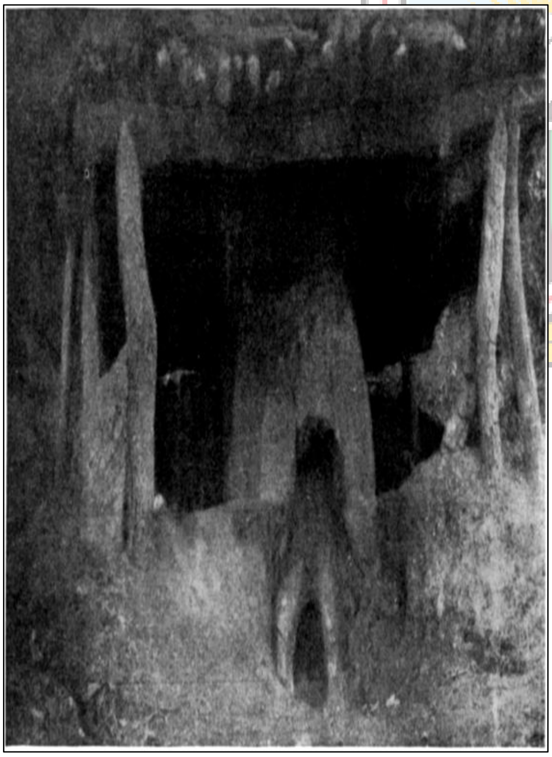

Figure 2.6 Photograph of Furnace Used in the Past (Source: Rattray, 1916)

Figure 2.7 Photograph of Finished Furnace in 1972 (Source: Pole, 2010)

Figure 2.8 Photograph of Current State of Furnace

The forge

After the melting process the iron metal is set to a forge. Here the solid metal is beaten into many shapes. A trench of burning charcoal is blown into white hot flame using bellows (consist of wooden handle and a bag made from the skin of a bush duck) and the iron to be worked is held in this.by the smith. When the metal gets hot it is beaten into the desired shape by the smith using a rock as an anvil. Some of tools made by the blacksmiths at the forge were hammer, tongs, chisel, hoe and cutlass. Evidence of the forge, solid slag and some of the tools made are still in the community (Pole, 2010; Dingemanse, 2011). Figure 2.8, 2.9, 2.10 and 2.11 show some of these evidences.

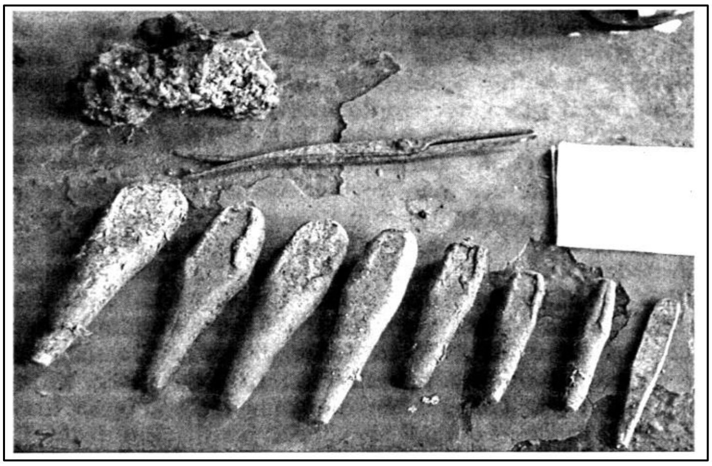

Figure 2.9 A Set of Hammers and Tongs Found by Pole
(Source: Pole, 2010)

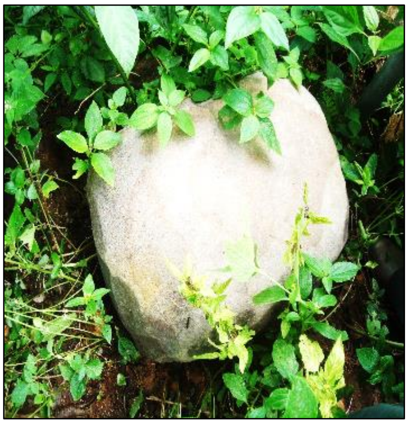

Figure 2.10 Rock Used as Anvil

Figure 2.11 Destroyed Fire Trench

Figure 2.12 Cutlass and Hammer Found at Akpafu-Todzi

2.6.4 Recent Investigations

The first preliminary studies of this deposit were conducted in the year 1975 by Bill. He confirmed the presence of iron ore at the Akpafu area with average of 55% Fe_2O_3, its size and its mode of occurrence. He concluded that due to what is left of the deposit and the way it occurs it would not be suitable for large scale production but could be best for small scale operation.

Dankwah *et al.*, (2016) also investigated the possibility of producing iron nuggets from Akpafu-Todzi using post-consumer plastics and waste biomass. They found out that Akpafu-Todzi iron ore is a low-grade hematite ore with an average grade of about 65 wt % Fe_2O_3 and could be successfully reduced to Fe using carbonaceous materials generated from blends of PNS-PWS.

This study looks at studying the way Akpafu-Todzi iron ore will behave during handling and transportation, the way it can be comminute and its response to carbothermal reduction using waste polymers available in our societies. Also, it will study how best the ore can be processed on a small-scale basis.

2.7 Characterisation of Iron Ore

Every ore has a distinct property and before it is processed to obtain the valuable material from it one must first 'talk to the ore and the ore must talk back' to the person. Only then will one be able to understand the ore, knowing its origin, what it is made up of and how you could get the valuable material you want from it. The process of which we can fully understand an ore under consideration is by characterizing it into its physical, chemical, mineralogical and metallurgical properties. Failure to do proper ore characterization may result in problems as the extraction process proceeds. Iron ore characterization can be said to be the characteristics of iron ore and the parameters that specify the chemical and physical aspects of its composition and structure with how the properties respond to changes in the physical or chemical environment (Muwanguzi, 2010). It is vital to perform characterization on the iron ore before production of iron begins. This will provide the necessary prerequisite to understand its behaviour when employed under various production conditions, its reaction when it comes into contact with reducing agents i.e. coal, metallurgical coke, biomass and plastics, and provides an idea on how the process flow sheet will look like.

2.7.1 Physical Characterisation

The physical method of characterisation is done to ascertain the physical properties of an ore. This method normally damages the ore sample and always needs samples that have not undergone any physical changes. Physical characterisation helps to identify the behaviour of an ore when handling and transporting. It also provides physical properties such as colour, lustre, specific gravity, magnetic properties, etc., which help in physical separation processes. Others also provide the way an ore should undergo comminution. Basically, the physical characteristics or properties of the iron ores are very important because they highlight the ore's behaviour during mining, handling (transportation and screening), charging and descent in the mode of iron making processes (Muwanguzi, 2010). The physical characterisation method employed in these studies are bulk density, abrasive index test, tumbler index test, specific gravity test, porosity test and Bond work index test.

2.7.2 Chemical Characterisation

Identifying the major and minor species or element of an ore sample, there is the need to conduct chemical characterisation. There are two main methods for chemical characterisation, the destructive and the non-destructive methods. The destructive method used in chemical characterisation of ore minerals is the wet chemical methods. Example of this chemical methods include volumetric, gravimetric, and colorimetric analysis. Higher concentrations of various elements are determined using volumetric or gravimetric and for trace element, colorimetric method is used (Amikiya, 2014).

X-ray fluorescence analysis (XRF) and X-ray diffraction analysis (XRD) are normally the non-destructive chemical characterization method. XRF is used to determine major and minor elements of ore minerals and the XRD is for determining the quantity of the chemical species or element present in ore minerals.

2.7.3 Mineralogical Characterisation

Mineralogical characterisation of ore minerals helps to identify the mineralogy of ore minerals. It also helps to identify major minerals, minor minerals or gangue minerals, the crystal structure and their association as well as grain size in different ore phase using macroscopic and microscopic devices like the hand lens and optical microscope respectively (Amikiya, 2014). Also, the morphology of the ore minerals is also determined using scanning electron microscope (SEM).

2.7.4 Metallurgical Characterisation

Metallurgical characterisation of iron ore is basically the study of how an iron ore behave during heating and reduction processes. The method used to achieve the behaviour of the ore during heating is the thermal analysis or thermos-analysis. There are two types of thermos-analysis normally used to study the change in weight of an iron ore sample as a function of time and temperature. These are differential thermal analysis and thermogravimetric analysis (Amikiya, 2014; Muwanguzi, 2010).

2.8 Ironmaking Processes

Iron is produced from its ore through various reduction processes. Currently, the main routes for commercial processes of ironmaking from natural iron ores are in three categories. The use of high grade natural iron ores as a part or a complete charge for blast furnace processes; these types of ores are also used as a part or a complete charge for direct reduction processes and smelting reduction processes (Muwanguzi, 2010; Huitu *et al*., 2013).

2.8.1 Blast Furnace (BF)

A BF is a huge shaft furnace that is top fed with iron ore, coke, and limestone. These materials form alternating layers in the furnace and are supported on a bed of incandescent coke (Peacey and Davenport, 2013). Hot air is blown through an opening into the bottom of the furnace and passes through the porous bed. The coke combusts, producing heat and carbon monoxide (CO) gas (Burgo, 1999). The heat melts the charge (iron ore), and the CO removes the oxygen from the iron ore, producing hot metal (when allowed to solidify in a pig iron casting machine, the resultant solid iron is called pig iron). Hot metal is a solution of molten iron at approximately 1 480 ºC, which contains 4 percent carbon and some silicon. This hot metal flows to the bottom of the furnace, through the coke bed and is periodically "tapped" from the furnace into transfer cars and transported to the basic oxygen furnace (BOF) where it is refined into steel. The BF is the most energy-intensive step in the BF/BOF steelmaking process, generating large quantities of CO_2 (AISI 2010; Hasanbeigi *et al*., 2013).

2.8.2 Direct reduction of iron (DRI)

DRI is defined as a process that produces a solid iron product from iron ore using natural gas or a carbon-based reductant. The process involves reducing iron from its ore below its melting temperature. Direct reduction gives an iron product low in carbon that can be used for direct steelmaking, without requiring prior carbon removal (Muwanguzi, 2010). The iron ore is reduced in solid state at 800 to 1 050 °C either by reducing gas (H_2 + CO) or coal or carbonaceous material. The specific investment and operating costs of direct reduction plants are low compared to integrated steel plants and are more suitable for many developing countries where supplies of coking coal are limited and places where there is abundance of natural gas. The DRI processes can be classified into three major categories:

a. those using gaseous reductants in a granular bed (such as the Midrex and Hylas processes);
b. those using gaseous reductants in a fluidized bed (such as the iron carbide process); and
c. those using solid reductants in a granular bed (such as the SL/RN and Fastmet processes).

The metallisation rate of the end product, called Direct Reduced Iron (DRI) or ‘sponge iron’, ranges from 85% to 95% iron (often even higher). Among the numerous DRI processes, the Midrex and HYL III (by means of gas) and the SL/RN (rotary Kiln; by means of coal reduction) have had the most successful industrial implementation. The Midrex process contributes the biggest share of the DRI produced, which corresponds to about 60% of the world production (Muwanguzi, 2010; Hasanbeigi *et al*., 2013). The MIDREX process typically consists of four stages: reduction, reforming, heat recovery, and briquette making. A mixture of pellets or lump ore, possibly including up to 10 percent fine ore, enters the furnace shaft. As the ore descends, oxygen is removed by counter-flowing reduction gas, which is enriched with hydrogen and CO (IEA 2010; Hasanbeigi *et al*., 2013). The iron is then formed into briquettes, and heat from the process is recovered.

2.8.3 Smelting Reduction

Smelting reduction iron (SRI) is an alternative to the BF, as it also produces liquid iron. Smelting reduction was developed to overcome the need for the energy-intensive products (coke and sinter), instead it is aimed to use coal and iron fines. Iron ore first undergoes a solid-state reduction in a pre-reduction unit. The resulting product at this stage, similar to DRI, is then smelted and further reduced in the smelting reduction vessel where coal is gasified, producing heat and CO-rich hot gas that can be further oxidised to generate additional heat to smelt the iron. The heat produced from the coal gasification is used to smelt iron and the hot gas is transported to the pre-reduction unit to reduce the iron oxides that enter the process. Several smelting reduction processes are under development; some have been commercially proven (COREX, FINEX, and ITmk3), others are still under demonstration, example Hismelt (IEA, 2010; Hasanbeigi *et al*., 2013).

2.9 Applications

Iron is primarily used in steel and cast-iron production (about 98%). Only a marginal part is used in cement, pigments, agriculture products or chemical industry. The biggest markets for steel are construction, transportation (e.g. automotive industry, ship building, railways), mechanical engineering, metal products, pipes, packaging as well as electrical and household appliances (Anon., 2012).

2.10 Reducibility of Iron Ore

The reducibility of an ore can be defined as the ability of an ore to undergo reduction, with little or no hindrances. Most iron ores with higher iron content are in the form of oxides and these make them suitable for reduction. The reducing agent used for the reduction of iron ore is mainly metallurgical coke, which has a high carbon content and natural gas (which is predominantly methane gas), hydrogen gas, carbon monoxide (Longbottom and Kolbeinsen, 2008).

Research has been conducted to find alternative replacement for metallurgical coke as a reducing agent for iron ore reduction. Since reduction is mainly by carbon, carbonaceous materials which are abundant in the environment are now used for reduction. Examples of these carbonaceous materials that are used for reduction are plastics, coconut shells (CNS), palm nut shells (PNS), saw dust (SD) etc. These materials are abundant in the environment and they become useful as reductants when they are no longer important for their originally intended purpose.

Dankwah (2014a) used blends of HDPE and coconut shells (CNS) as reducing agent for the production of metallic iron from iron oxide (Fe_2O_3). Several small droplets of metallic iron were seen distributed across the entire volume of the crucible after the reduction processes and he concluded that blends of postconsumer HDPE with waste CNS could be used effectively as reducing agents in iron making. Also, he conducted another experiment on ‘Reduction of FeO in EAF Steelmaking Slag by End-of-Life Polystyrene (PS) and its Blend with Metallurgical Coke’. The reduction done with the blend of polymer improved with the extent of reduction increasing from 51.9% for coke to 92.6% and 93.9% for the blends and he concluded that PS and blends of PS with coke could be used to partly or wholly replace the conventional coke used in iron and steelmaking as reductants (Dankwah, 2014b). Dankwah *et al*. (2015) used mixed plastics waste as reductant in ironmaking. These mixed plastic waste composed of 50 wt.% high density polyethylene (HDPE), 30 wt.% polypropylene (PP), 10 wt.% low density polyethylene and (LDPE) and 10 wt.% polyethylene terephthalate (PET) were employed. Results from this research showed that iron oxide can be effectively reduced to produce metallic iron using mixed plastic waste as reductant. An improvement in extent of reduction was observed over metallurgical coke and the individual polymers when mixed plastics waste was used as reductant. This eliminates the need to sort out individual plastics from municipal solid waste for their effective utilisation as reductants in ironmaking.

Also, research involving the use of PET (Polyethylene terephthalate) which is the remarkable percent of plastic wastes, was used due to its high carbon content as an alternative reductant in iron and steel industry. Composite pellets containing PET wastes and magnetite iron ore were reduced at relatively high temperatures during various reduction times in order to investigate its behaviour during reduction melting process. The results of experiments showed that reduction rate of iron ore increased as a function of time (Polatolat *et. al.*, 2013). Yunos *et al.*, (2016) used polypropylene (PP) to reduce iron oxide composite pellet for steelmaking processes. In their study, carbon from polymeric material such as the recycled PP was utilised as a reducing agent, which has not been extensively investigated especially in steelmaking processes. It was observed that hematite was the main phase present in the sample while a phase transformation from iron oxide to metallic iron occurred at high temperatures. They then concluded that reduction of iron oxide with recycled PP could be effectively used as an alternative carbon source and reducing agent in steelmaking.

Utilisation of biomass in ironmaking was investigated by Mašlejová in 2013. Her investigation showed that biomass such as saw dust, crushed corn, bark and charcoal could be used effectively in ironmaking and the replacement of fine coke by these biomass is advantageous. It was concluded that the addition of charcoal produced the best result among the tested biomass but there is the possibility of utilising the other biomass seasonally.

Man *et. al.*, 2014 looked at the effect of particle size on reduction behaviour in iron ore-coal composite pellets. They used three samples of different particle sizes, 25-48 µm, 75 -106 µm and 150 -180 µm in the studies. Their results showed that the particle size 25-48 µm was more sufficient to complete the reduction. Report from their XRD analysis showed that the reduced material was predominantly metallic iron (Fe) compared to the other particles sizes whose residues were basically wustite (FeO) and metallic iron (Fe). They concluded that size particle of 25-48µm had a faster reduction which was attributed to more developed surface.

Many investigations have also been conducted by many other researchers (Matsuda *et al.*, 2006; Nishioka *et al.*, 2007; Matsuda *et al.*, 2008; Ueki *et al.*, 2008; Dankwah *et al.*, 2011;

Kongkarat *et al.*, 2011; Murakami *et al.*, 2009; Murakami and Kasai, 2011; Dankwah *et al.*, 2012; Dankwah, 2013; Dankwah and Koshy, 2014; Dhunna *et al.*, 2014; Mansuri *et al.*, 2013; Dwumah *et al.*, 2016; Dankwah and Buah, 2017) trying to use different carbonaceous materials to effect reduction. These investigations have not only provided an alternative for metallurgical coke as a reductant but have also provided means of waste recycling since most of these carbonaceous materials are waste. Accordingly, this work seeks to investigate how the Akpafu-Todzi iron ore will respond to reduction by some of these carbonaceous materials and the effect of their composite on reduction of Akpafu-Todzi iron ore.

2.11 Microwave Utilisation in Iron Oxide Reduction

There has being lots of issues related to the use of convectional ironmaking process, some of which is the environmental impact (high amount of CO_2 emission) and high energy requirements. The emergence of microwave irradiation in carbothermal reduction of iron ore has gained much attention because of the high potential for an essential reduction of carbon dioxide emission and its tendency to heat powders because of the possible volumetric heating (Takayama *et. al.*, 2008; Hayashi *et. al.*, 2013)

Carbon materials are, in general, very good absorbents of microwaves, i.e., they are easily heated by microwave radiation. This characteristic allows them to be transformed by microwave heating, giving rise to new carbons with tailored properties, to be used as microwave receptors, in order to heat other materials indirectly, or to act as a catalyst and microwave receptor in different heterogeneous reactions (Menéndez *et. al.*, 2010).

In recent years, the number of processes that combine the use of carbons and microwave heating instead of other methods based on conventional heating has increased. Koleini and Barani (2012) highlighted the use of microwave in treatment of minerals and Table 2.4 shows the time in minutes and the maximum temperature in degree Celsius that the minerals attained during the treatment process.

Also, they stated that the earliest work on the microwaving of minerals began with a study of the high temperature processing of certain oxides and sulphides using a resonant cavity operating at 2.45 GHz and variable power up to 1.6 kW. Aguilar and Gomez (1997) researched on microwaves applied to carbothermal reduction of iron ore pellets. The results obtained from their research indicated that iron oxide absorbs microwave, therefore it is possible to supply energy or be used in reduction processes.

Table 2.4 Microwave heating of some oxides and sulphide compounds

Compound	Heating time (min)	Max. Temperature (^{o}C)
Al_2O_3	24	1900
C	0.2	1000
CaO	40	200
Co_2O_3	3	900
CuO	4	800
CuS	5	600
Fe_2O_3	6	1000
Fe_3O_4	0.5	500
FeS	6	800
MgO	40	1300
MoO_3	0.46	750
MoS_2	0.1	900
Ni_2O_3	3	1300
PbO	13	900
UO_2	0.1	1100

(Source: Koleini and Barani, 2012)

Also Kirschvink (1996) conducted an experiment involving microwave absorption by magnetite. Various research has evolved with the use of microwave in iron ore reduction (Mourão *et. al.*, 2001, Ishizaki *et. al.*, 2006, Nishioka *et. al.*, 2006) and this work also will employ the use of microwave in the reduction of Akpafu-Todzi iron ore and also compare it to reduction using the conventional heating method.

Applying 915 MHz microwave to iron production from Fe_3O_4 and graphite was investigated by Kashimura *et. al.* (2012). The study was carried out in electric and magnetic fields of microwaves in order to study their individual effect and their combined effect on chemical behaviour of iron ore reduction. It was found that the combined effect of thermal energy and a portion of the microwave magnetic field enhanced deoxidation in carbothermal reduction. Research done by Junaidi *et al.*, 2014 used microwave irradiation to reduce 60 g composite of high purity iron ore, charcoal as a reducing agent and calcium oxide as a flux in the ratio 1:4:8. The homogeneous mixture was put in crucible and treated by microwave heating with several of power supply 2000, 3000 watt and irradiation time 40, 50, 60 min. Results from these studies showed that microwave irradiation increases the temperature behaviour in reduction of iron ore. They concluded that power supply and irradiation time were the main parameters in the reduction process. The optimum reduction process was observed at 3000 W power supply and 60 min irradiation time. This state can increase Fe content up to 81.67%.

This investigation will look at reduction of iron ore using waste polymers under microwave irradiation with time intervals of 10 min for 60 min and the result will be compared to that under conventional heating process.

2.12 'Sika Bukyia' Utilisation in Iron Oxide Reduction

'Sika Bukyia' is a locally made gas furnace which was originally designed for mercury-free gold ore smelting processes. It has been utilised in smelting of gold ore concentrates and also reduction of iron oxide present in bauxite ores. Iron oxide present in the bauxite ore was successfully reduced using the 'Sika Bukyia' as a source of energy. This reduced material was magnetic and it was separated from the non-magnetic portion using a magnet. XRD of the magnetic portion showed predominately magnetic peaks which confirmed the presence of magnetite (Fosu *et al.*, 2016). Darmey *et al.* (2016) also indicated that it is possible to use the locally made gas furnace in reducing the iron oxide impurities present in bauxite ores. Following the success of previous works, which were basically the conversion of hematite to magnetite, this present investigation will look at using the locally made gas furnace, 'Sika Bukyia', in reducing iron oxide to metallic iron under the time interval of 20 min for 60 min.

CHAPTER 3

EXPERIMENTAL WORK

3.1 Raw Materials

Lump samples of iron ore and slag (after crude method of producing iron by local artisans and blacksmiths) were obtained from Akpafu-Todzi in the Hohoe Municipal Assembly (HMA) in the Volta Region of Ghana. The sample methods utilised in sampling the iron ore and slag for these studies were random stratified and random sampling, respectively. A composite sample of about 70 kg was obtained for the iron ore lump samples and about 25 kg for the slag samples. Figures 3.1 and 3.2 show samples of iron ore and slag lump respectively.

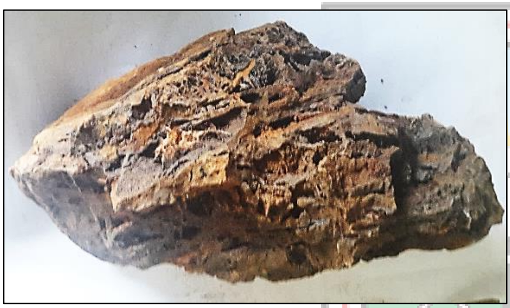

Figure 3.1 Iron Ore Lump

Figure 3.2 Iron Slag Material

Waste plastics and waste biomass were used as source of carbonaceous material for this study. The waste plastics was collected from the vicinity of University of Mines and Technology, Tarkwa (UMaT) and the waste biomass such as palm nut shells (*Elaes guineanses*), coconut shells (*Cocos nucifera*) and saw dust which hereafter will be referred to as PNS, CNS and SD respectively, was obtained from Tarkwa and its environment. The full list of the various waste plastics employed in this study is detailed in Table 3.1. It should be noted that plain flour was used as a binding agent.

Table 3.1 Detailed Waste Plastics Polymer Used

Name	Abbreviation	Type Used
High-Density Polyethylene	HDPE	Pure water sachet
Low-Density Polyethylene	LDPE	Shopping bags
Polystyrene	PS	Packaging
Polypropylene	PP	Buckets
Polyethylene Terephthalate	PET	Voltic bottles

3.2 Apparatus Used

A greater portion of this study was carried out in the Minerals Engineering Laboratory of the University of Mines and Technology, Tarkwa with a minor aspect carried out in Rock and Soil Mechanics Laboratory of the University of Mines and Technology, Tarkwa and external laboratory in Australia. The equipment used in the laboratory to carry out the experimental work were:

a. Crushers- Hammer, Morse Jaw Crusher and Marcy GY-Roll Crusher;
b. Ball Mill of diameter 30 cm and length 23 cm;
c. Tumbling Mill;
d. Riffle Sampler;
e. ASTM-E11 Screens;
f. Electronic Measuring Scale;
g. MWM200 Kenwood Microwave Oven;
h. Gas Furnace also known as ‘Sika Bukyia’;
i. Ring of Magnate;
j. Gas Stove/Coal Pot; and
k. Electric Furnace.

3.3 Methods Used

The methods used to carry out this investigation to obtain its objectives are as follows:

a. Sample preparations;
b. XRD, XRF and SEM Analysis;
c. Particle size distribution (PSD);
d. Bulk density determination;
e. Porosity determination;
f. Specific gravity determination (s.g.);
g. Abrasive and Tumble index determination;
h. Bond ball mill index determination; and
i. Reducibility Studies.
    i. Estimating the masses and blends of the various raw materials
    ii. Pelletising
    iii. Curing and Drying and
    iv. Firing Process

3.4 Sample Preparations

3.4.1 Iron Ore

Samples of the Akpafu-Todzi iron ore and the slag were broken into various lumps using a hammer and samples were taken for bulk density test, porosity test, abrasive and tumble index test. The remaining samples were crushed using a Morse Jaw Crusher to reduce the size. The particle size of the ore and the slag were further reduced using a secondary crusher known as Marcy GY-Roll Crusher. The secondary crusher product of the iron ore was screened with a 4 mm sieve size and the oversize was sent for tertiary crushing and this was done till all the material passed the 4 mm sieve. A representative sample was taken for Bond ball mill index test using the riffle sampler. The crushed slag and the rest of the crushed iron ore were then milled for 15 mins each to produce finer particle size using a ball mill. A product of -250 µm was obtained for the slag material and the iron ore materials after milling were screened using different sieve sizes to obtain three (3) main size fractions (-250 µm +180 µm, -180 µm +106 µm and -106 µm +0). The various screen size products were then bagged using sample bags and the sample bags were labelled accordingly. Figure 3.3, 3.4 and 3.5 shows pictures of the crushed iron and slag test samples.

Figure 3.3 Iron Ore Lump

Figure 3.4 Crushed Lump

Figure 3.5 Crushed Slag

3.4.2 Carbonaceous Material Prepared from Waste Plastic Polymers

The various waste plastic polymers employed in this study were melted individually in a metallic container on a gas stove. When each waste plastic polymer got completely molten, each was poured out to cool and solidify. After cooling and solidification, they were broken into smaller particles and pulverised separately in a ball mill for 5 mins. The mill product was screened using screen size of 180 µm and the undersize was collected and bagged.

3.4.3 Carbonaceous Material Prepared from Waste Biomass Polymers

Waste biomass polymers were charred separately using an electric furnace. The charring process was accompanied by the emission of smoke. The charring process got to completion at the point where no further smoke was detected from the furnace. The charred waste biomass polymers were pulverised individually for about 5 mins using a ball mill. The milled product was screened using a screen size of 180 µm and the under size obtained. It should be noted that all the reducing agents utilised in this studies has been priory characterised in parallel studies within the group. Figures 3.6, 3.7 and 3.8 show the raw, charred and pulverised carbonaceous materials generated from PNS, CNS and SD, respectively.

Figure 3.6 (a) Raw PNS (b) Charred PNS (c) Pulverised PNS

Figure 3.7 (a) Raw CNS (b) Charred CSN (c) Pulverized CNS

Figure 3.8 (a) Raw SD (b) Charred SD (c) Pulverised SD

3.5 XRF, XRD and SEM Analysis of the Iron Ore

10 g of iron ore and slag of particle size -106 µm was taken, bagged and labelled A1 and AS1. The various particle size ranges were mixed and 10 g of both iron ore and slag were taken respectively, bagged and labelled A2 and AS2 respectively. Sample A1, A2, AS1 and

AS2 were all sent for XRF (to determine oxides available and their respective amounts), XRD (to determine peaks of major species) and SEM (to determine the morphology) analyses at an external laboratory in Australia.

3.6 Particle Size Distribution (PSD)

PSD is of great importance in determining the quality of grinding and in establishing the degree of liberation of the values from the gangue at various particle sizes (Will and Napier-Munn, 2006). About 2 kg of iron ore sample was stage crushed and the particle size distribution determined using series of screens from 4000 microns to 150 microns. Graphs of log of cumulative percent weight passing against log of sieve size for both samples were drawn and the P80 estimated.

3.7 Bulk Density Determination

This research investigated the bulk density of lumps of iron ore using the wax-immersion method. This method was adopted since it was confirmed by Crawford (2013) to be the most accurate and recommended method for the bulk density determination. This was as result of the ability of liquid waxes to closely mould into the surface pore of the sample which gives the most accurate estimate of the volume of the sample.

The apparatus used for this test were; a pot containing wax, a measuring cylinder, thread, electronic measuring scale with sensitivity of 0.1 g, wash bottle and a retort stand. Two (2) sets of samples, each consisting of five (5) lumps of iron ore were prepared for bulk density test. The pot containing wax was plugged to heat it to about 57℃ since it was in the solid form. The density of the wax was determined to be 0.911 g/cm^3. The weight of the sample was then measured and recorded as M_S. The sample was then dipped into the wax pot to coat the sample. Slowly the sample was removed from the liquid wax and the wax allowed to harden on the sample. Any air bubbles which were trapped in the wax were carefully push out and extra coating of wax applied to cover any holes in the wax. The weight of the wax coated sample was then determined and recorded as M_{SW}. The mass of wax coated on the sample (M_W) was obtained from M_{SW} - M_S. The wax coated sample was then tied with a thread and dipped into a measuring cylinder with a known volume to determine the volume displaced by the wax coated sample. The volume displaced was determined to 1 cm^3 then recorded as V_{SW}. The volume of the wax coated (V_W) was determined by dividing the mass of the wax coated by the density of wax. Volume of sample (V_S) was then evaluated from

V_{SW} - V_W. The bulk density of the sample was then calculated by dividing the mass of sample, M_S by volume of sample, V_S.

$$\text{Bulk Density} = \frac{M_S}{V_S} \tag{3.1}$$

where, M_S = mass of sample;

V_S = volume of sample.

3.8 Porosity Determination

Porosity is said to be the total voids present in a rock sample to the total volume of the rock sample expressed as a percentage. With the above definition serving as a guide, the porosity of the ore sample was determined. Two (2) set of sample A and B with each consisting of five lumps of iron ore, glass bowl, hot plate and electronic balance having a sensitivity of 0.1 g were used in the test. The lump samples were weighed and labelled accordingly and arranged in the glass bowl filled with water to the brim and left for 24 hrs. After the twenty-fourth hour the samples were removed from the glass bowl, wiped off water with a towel and was weighed and recorded as M_{SS}. The sample each was dried on a hot plate to drive away any entrapped water and weighed and recorded as M_{DS}. The volume of the dry samples was then evaluated by using the water displacement method and recorded as V_{DS}. The volume of void of each of the samples was calculated from the difference M_{SS}-M_{DS} to get mass of water entrapped which is also the mass of void in the lump sample, M_S. Since the density of water is 1g/cm^3 the volume of water entrapped will be equal to the mass of water entrapped. Accordingly, the volume of void, V_V is equal to the mass of void, M_V. The porosity was then determined by using the formula below:

$$\text{Porosity,P} = \frac{V_V}{V_{DS}} \tag{3.2}$$

where, V_V = volume of voids; and

V_{DS} = volume of dry sample.

3.9 Specific Gravity Determination

Specific gravity of an iron ore lump is defined as the ratio of mass of lump sample to that of an equal volume of water at a specific temperature (Akande *et al*, 2013). Five (5) iron ore lump samples were used for this test with each going through the method described hereafter. An empty 250 ml measuring cylinder was weighed on the electronic weighing balance having a sensitivity of 0.1 g and the weight was recorded as M_1. The measuring cylinder was then filled with water up to the 50 ml mark, weighed and then recorded as M_2. The iron ore sample was put into the measuring cylinder which was filled with water to the 50 ml mark and weighed again and recorded as M_3. The specific gravity, (s.g.) of the specimen was derived by using the mathematical expression in equation 3.3.

$$\text{Specific gravity, s.g.} = \frac{M_3 - M_2}{M_2 - M_1} \tag{3.3}$$

where, M_1 = mass of empty measuring cylinder

M_2 = mass of empty cylinder + water

M_3 = mass of empty cylinder + rock sample +water

3.10 Abrasive Index (AI) and Tumbler Index (TI) Determination

The abrasion index and tumbler index with respect to this study are said to be the relative measure of the resistance of an iron ore lump material to breakage or degradation by abrasion and impact respectively (Muwanguzi, 2012). The method used was adopted from the Bureau of India Standard (IS 6495 (1984): Method of Tumbler Test for Iron Oxides: Lump Ores, Sinter and Pellets). 3 kg of -40 mm +35 mm iron ore lump samples was used for the test. The test sample was gently placed into a 300 mm × 300 mm × 5 mm tumbling drum and placed on a roller which was rotating at 30 rpm for 200 revs (approximately 6 mins 40 sec). The material was removed gently from the drum and subjected to screening using 5.6 mm sieve (instead of 6.3 mm) and 500 µm sieve. The mass of the fractions retained on 5.6 mm sieve and that retained on and passing through 500 µm sieve was determined and recorded to 0.1 g. The abrasive and tumbler index were determined using equations 3.4 and 3.5, respectively:

$$TI = \frac{m_1}{m} \times 100 \tag{3.4}$$

$$AI = \frac{m - (m_1 + m_2)}{m} \times 100 \tag{3.5}$$

where, m = mass of the sample before test;

m_1 = mass of the sample retained on 5.6 mm sieve after the test; and

m_2 = mass of the sample passing through 5.6 mm and retained on 500 µm sieves after the test.

3.11 Work Index (W_i) Determination

In this study the standard Bond Ball Mill Work Index (BBMWI) test procedure was used to determine the work index of the iron ore sample. BBMWI is known as the measure of a material’s or an ore’s resistance to crushing and grinding. With reference to this study BBMWI will be defined as the kilowatt-hours per short ton needed to break an iron ore from an infinite size to a product size of 80% passing 106 μm (Haffez, 2012). The test was carried out in a closed circuit with a 106 μm laboratory sieve. Firstly, the iron ore sample (feed) was stage crushed to -4 mm +106 μm and a representative sample taken for particle size distribution to estimate the F_{80}. A standard ball mill of size 0.30 m × 0.23 m with rounded corners and running at 72 rpm was charged with feed weight equivalent to 700 cm^3 and steel balls of weight 19 kg and ground initially at 100 revolutions. The ground sample was screened with 106 μm sieve and the undersize sample was weighed and fresh feed was added to the oversize to bring its weight back to that of original charge. The revolution required was then determined from the previous period. This procedure was repeated at least five (5) times until the weight of undersize produced per mill revolution reached equilibrium. The average of net grams per revolution from the last three cycles is taken as the ball mill grindability (Gbp) in g/rev. A representative sample of product is sized to determine the P_{80}. Finally, the BBMWI is calculated using the Bond equation (1961) shown in equation 3.6.

$$W_i = \frac{44.5}{(Gbp^{0.82} \times P^{0.23}\left[\left(\frac{10}{\sqrt{P_{80}}}\right)-\left(\frac{10}{\sqrt{F_{80}}}\right)\right]} \tag{3.6}$$

where, $Gbp =$ ball mill grindability in g/rev;

$P =$ opening in (μm), of the sieve size tested;

$P_{80} =$ 80% passing size of the product in microns; and

$F_{80} =$ 80% passing size of the feed in microns.

3.12 Reducibility Studies

3.12.1 Estimating the masses and blends of the various raw materials

The mass of each pellet prepared was 30 g with the ratio 70 wt.% iron ore to 30 wt.% carbonaceous materials. This ratio was selected for testing based on it being identified as the optimum in previous reduction studies. The various blend ratio of the carbonaceous materials used are detailed in Table 3.2. The detailed calculations and masses used for iron ore-carbon mixture pellet formation are shown in appendix A.

Table 3.2 Blend Ratio of Carbonaceous Material Used for Iron Ore-Carbon Mixture Pellet Formation

Carbonaceous Material	**Blend Ratio of Carbonaceous Materials**
1	100% HDPE
2	100% LDPE
3	100% PS
4	100% PP
5	100% PET
6	100% PNS
7	100% CNS
8	100% SD
9	40% HDPE+ 20% LDPE+30%PP+10%PS
10	40% HDPE+ 20% LDPE+30%PP+10%PET
11	40% HDPE+ 20% LDPE+30%PP+10%PNS
12	40% HDPE+ 20% LDPE+30%PP+10%CNS
13	40% HDPE+ 20% LDPE+30%PP+10%SD

3.12.2 Pelletising

After the calculation of the various weights the pellets were formed. 21 g of iron slag sample of screened product -250 µm was weighed and poured into a laboratory bowl. 9 g of carbonaceous material was also weighed and added to the iron slag sample in the laboratory bowl. The iron slag-carbon mixtures were homogenised and moulded into a spherical pellet with the help of a 5% binder (flour) and droplet of water. By varying the weight of the carbonaceous material and its blend, the above steps were repeated in forming the rest of the composite pellets and were labelled as MS1 to MS13. The same procedure was used in forming the iron ore pellet but the screened products used were -250 µm +180 µm, -180 µm +106 µm and -106 µm +0 and the average size were 215 µm, 143 µm, 53 µm, respectively. Each size fraction had two sets of iron ore-carbon composite pellets. The 215 µm size had its set of composite pellets labelled as MOA1 to MOA13 and the other as COA1 to COA13. For the 143 µm size it was labelled as MOB1 to MOB13 and the second set as COB1 to COB13. Finally, the size 53 µm were labelled as MOC1 to MOC13 and the other set of pellets as COC1 to COC13. The first letters of the pellet labels stand for the mode of heating i.e. Microwave heating (M) and Convectional heating (C). A picture of some of the green pellets formed is shown in Figure 3.9.

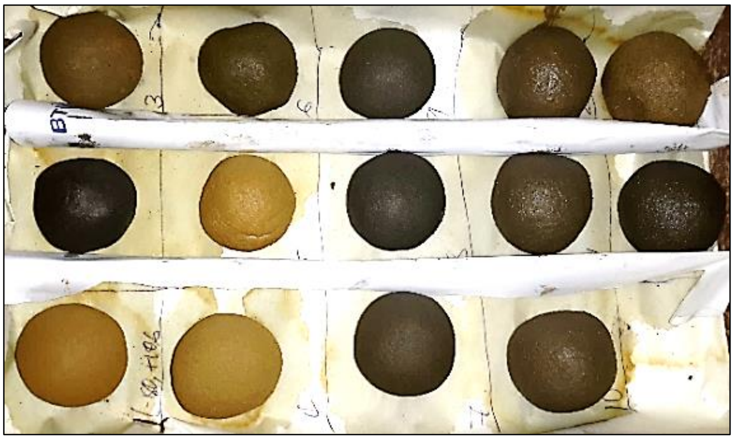

Figure 3.9 Green Composite Pellets

3.12.3 Curing and Drying

The composite pellets were allowed to cure for 3 days (72 hours) to gain the requisite compressive strength needed for firing process. It was further allowed to dry in open air for 4 days to eliminate completely the moisture content. Allowing the pellets to dry in open air was to ensure that the chemical composition of the composite pellets was not tempered with.

3.12.4 Firing Process

Microwave Heating

The dry composite pellets were subjected to microwave heating using the 2400 MW, 50 Hz, SHARP® microwave. Using the method of finding the best spot for the highest energy input of a microwave described by Aguilar and Gomez (1997) the best spot was located to be 0.08 m from the entrance opening and 0.135 m from the aperture side of the microwave. The weight of a dry composite pellet was noted and recorded as mass of pellet (M_P). It was then placed in an alumina fireclay crucible of weight (M_C). The initial mass of the crucible containing the pellet was noted and recorded as M_1. It was then placed at the best spot determined earlier in the microwave and heated for time interval of 10 mins for 60 mins. At every interval the weight of the crucible and its content is noted and recorded as M_{10}, M_{20}, M_{30}, M_{40}, M_{50} and M_{60} and the weight differences calculated and the weight lost also estimated. The temperature was also checked at the interval from time to time using a thermocouple. Since the crucible with its content has to be removed from the microwave the temperature reading was not that effective because temperature changes very rapidly (Figure 3.10). The above procedure was used for the other composite pellets formed.

Figure 3.10 Thermocouple Temperature Reading

Conventional Heating

The conventional reduction study was carried out using a gas furnace which is affectionately called ‘sika bukyia’. The weight of a dry composite pellet was noted and recorded as mass of pellet (M_P). It was then placed in an alumina fireclay crucible of weight (M_C). The initial mass of the crucible containing the pellet was noted and recorded as M_1. The ‘sika bukyia’ was then pre-heated to a temperature of about 500 ^{o}C and the crucible with its content was placed inside. It was fired for 60 mins and the weight of the crucible with its content was noted at every 20 mins and the mass recorded as M_{20}, M_{40} and M_{60}. This was repeated for all other composite pellets formed and their weight differences calculated and subsequently using it to calculate the weight lost and extent of reduction. Figures 3.11 and 3.12 below show the ‘sika bukyia’ firing process.

Figure 3.11 ‘Sika Bukyia’ Gas Firing

Figure 3.12 Crucible Being Fired

CHAPTER 4

RESULTS AND DISCUSSION

4.1 The Nature of Akpafu-Todzi Iron Ore

After Akpafu-Todzi iron ore was subjected to chemical analysis such as XRD, XRF and SEM/EDS analysis it was found that the ore exhibits a lower hematite content about 64.471 wt% and with high percentage content of impurities like SiO_2 (19.606 wt%) and Al_2O_3 (2.288 wt%). The absence of sulphur which is a deleterious element in iron and steel making was of a great importance because a small amount can cause the iron to be brittle when hot. Table 4.1 below shows the chemical composition (XRF) of Akpafu-Todzi iron ore.

Table 4.1 Chemical Composition (XRF) of Akpafu-Todzi Iron Ore

Component	Composition (wt%)
Fe_2O_3	64.471
SiO_2	19.606
CaO	0.042
Mn_3O_4	0.042
Al_2O_3	2.288
TiO_2	0.085
Na_2O	0.128
K_2O	0.049
MgO	0.151
P_2O_5	0.289
Cr_2O_3	1.191
NiO	0.272
LOI	10.930
TOTAL	100

The absence of deleterious element which is a major boost for Akpafu-Todzi iron ore to be used in ironmaking without any prior beneficiation but the presence of high amount of silica poses great concerns because silica requires higher temperature during reduction process, so the higher the silica content the higher the temperature required for reduction and has a negative impact on reduction of hematite. The loss on ignition value (approximately 11 wt%) indicated the presence of high volatile materials (organic matter) in the ore. Both the silica content and the volatile materials can be removed or reduced to its barest minimum by pre-treating (washing and preheating) the ore before ironmaking process to minimize the energy required for iron reduction.

Further confirming the Akpafu-Todzi iron ore is of hematite grade, the ore was also characterised by XRD analysis. The diffraction patterns correspond to those of Fe_2O_3. Figure 4.1 below shows the diffraction patterns.

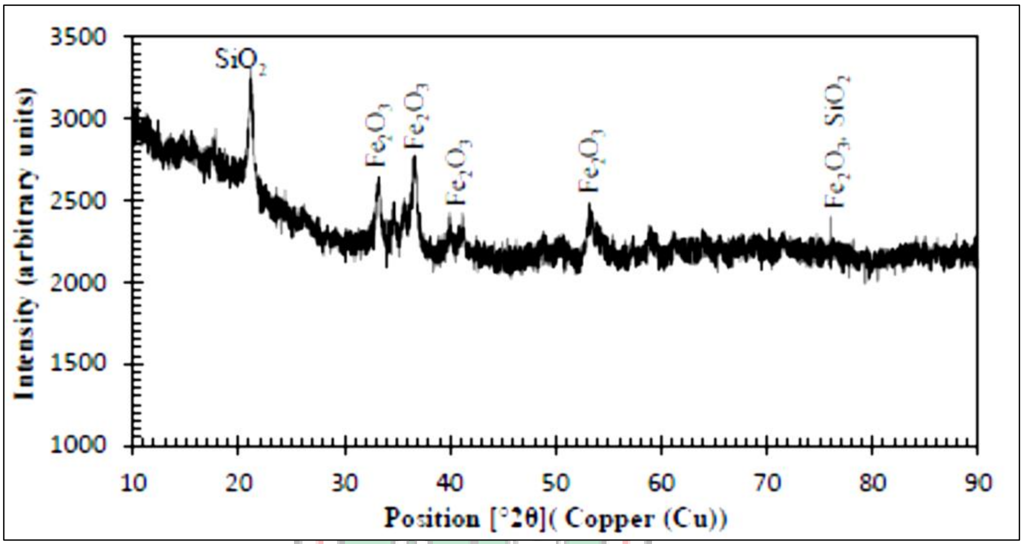

Figure 4.1 XRD of Akpafu-Todzi Iron Ore

The grade of iron ores in the world are classified according to their Fe content. An iron ore is said to be low grade when Fe content is less than 58 wt%, medium grade when Fe content is between 58 wt% and 64 wt% and high grade when Fe content is more than 65 wt% (Anon., 2017). SEM/EDS analysis of the Akpafu-Todzi iron ore as showed in the Figures (4.2, 4.3 and 4.4) and Table (4.2, 4.3 and 4.4) for three regions indicated Fe content of 44.07 wt%, 42.88 wt% and 44.78 wt%, respectively for regions 1 to 3. Its potential for worldwide commercial exploitation is low but it is possible to exploit on small scale bases. Comparing these values to the world's iron ore classification, the Akpafu-Todzi iron ore corresponds to the low-grade iron ore (about 43.91 wt% which is less than 58 wt%). These findings agree with that of Kesse and Banson (1975) that the Akpafu-Todzi iron ore is of a low grade. Its potential for worldwide commercial exploitation is not high but it is possible to exploit on small scale bases.

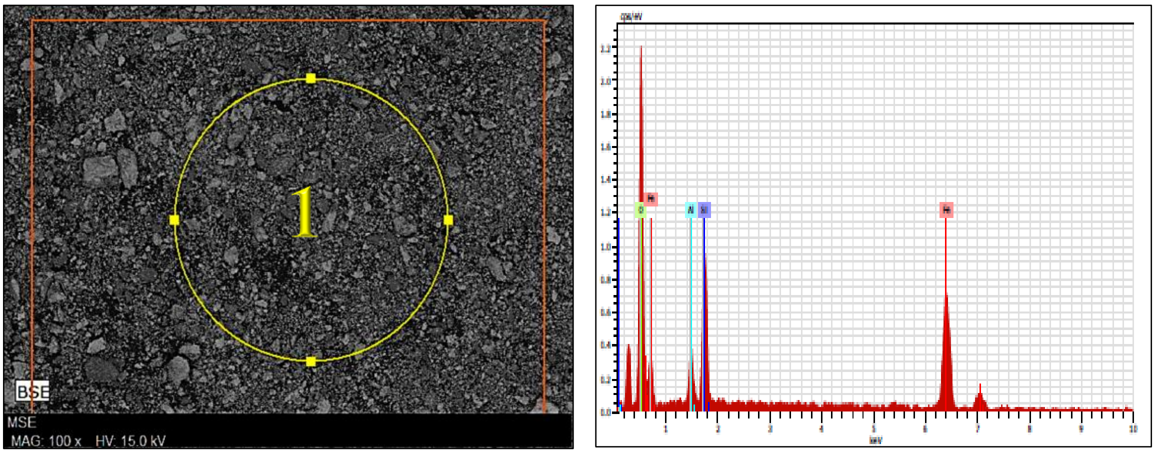

Figure 4.2 SEM/EDs Analysis for Akpafu-Todzi Iron Ore (Region 1)

Table 4.2 Values of SEM/EDs Analysis for Akpafu-Todzi Iron Ore (Region 1)

Element (K-series)	Weight %	Atomic %
F	44.07	20.45
O	39.83	64.52
Si	11.93	11.01
Al	4.18	4.01
SUM	100	100

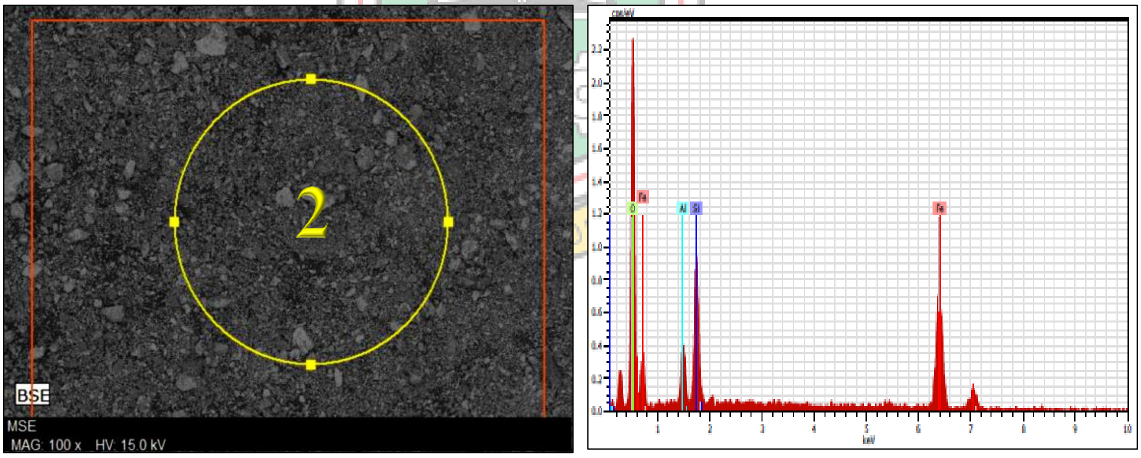

Figure 4.3 SEM/EDs Analysis for Akpafu-Todzi Iron Ore (Region 2)

Table 4.3 Values of SEM/EDs Analysis for Akpafu-Todzi Iron Ore (Region 2)

Element (K-series)	Weight %	Atomic %
F	42.88	19.78
O	39.88	64.22
Si	12.25	11.24
Al	4.98	4.76
SUM	100	100

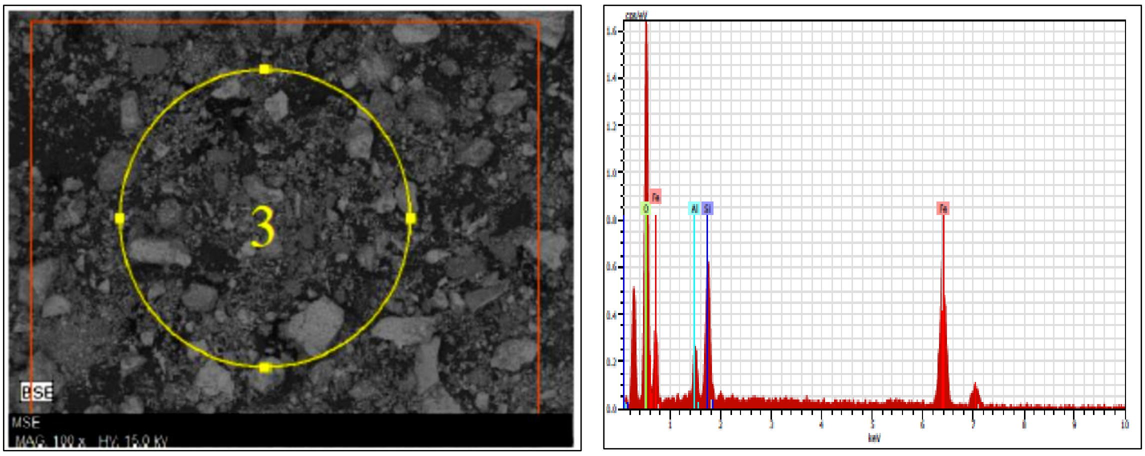

Figure 4.4 SEM/EDs Analysis for Akpafu-Todzi Iron Ore (Region 3)

Table 4.4 Values of SEM/EDs Analysis for Akpafu-Todzi Iron Ore (Region 3)

Element (K-series)	Weight %	Atomic %
F	44.78	20.86
O	39.77	64.67
Si	11.19	10.37
Al	4.25	4.10
SUM	100	100

Comparing the chemical composition of Akpafu-Todzi iron ore to the commercial chemical composition requirement of various ironmaking process routes in Table 4.5, it could be seen that the Akpafu-Todzi iron ore falls short in all the various process routes. Taking the Fe content of the Akpafu-Todzi iron ore (Region 1 to 3), 44.07 wt%, 42.88 wt% and 44.78 wt%, they all are below the value of Fe content for Corex (65.0%), BF (62-65%), Midrex (67.0%), HYL (65.5%) and Rotary Kiln (64.0%).

Table 4.5 Commercial Requirement for Various Ironmaking Process Routes

Process	**Fe Content (%)**	**Gangue (SiO_2+Al_2O_3) (%)**	**LOI (%)**
Corex	65.0 min	4.0 max	-
BF	62-65 min	6.0 max	2.0 max
DRI-Midrex	67.0 min	3.2 max	1.5 max
DRI-HYL	65.5 min	2.2 max	1.5 max
DRI- Rotary Kiln	64.0 min	4.0 max	-

(Source: DID, 2010)

The gauge and LOI also fell short of the commercial requirement. This information indicates that Akpafu-Todzi iron ore is not suitable for any of the process routes stated above. The solution to this will be finding or developing alternative process route or modifying existing process route or possibly upgrade the Akpafu-Todzi iron ore to suit the process routes stated previously.

4.2 Particle Size Distribution (PSD)

The PSD of Akpafu-Todzi Iron ore and slag materials indicated that the ore and slag materials after stage crushing produced a small quantity of fine products which was evident from the result of the cumulative percent weight passing through the smaller test sieve size. This implies that the ore does not produce much fines when it undergoes disintegration. The smallest test sieve size used for the size analysis was 150 µm and the cumulative percent weight passing were 4.71% and 4.97% for the ore and slag, respectively. The table containing all other values of the size analysis is shown in appendix B.

Particle size distribution curve was constructed and the 80% passing (P80) and 50% passing (P50) were estimated. The P80 and P50 of the ore is 3 317 µm and 1.887 µm sieve sizes respectively and that of the slag material is 3 140 µm and 1 769 µm respectively. The P80 of the iron ore after stage crushing indicates that the ore does not produce much fines. This information plays an important role since it gives the size distribution of the crushed products that will undergo milling. Figure 4.5 and 4.6 show the particle size distribution curve for the ore and slag materials respectively.

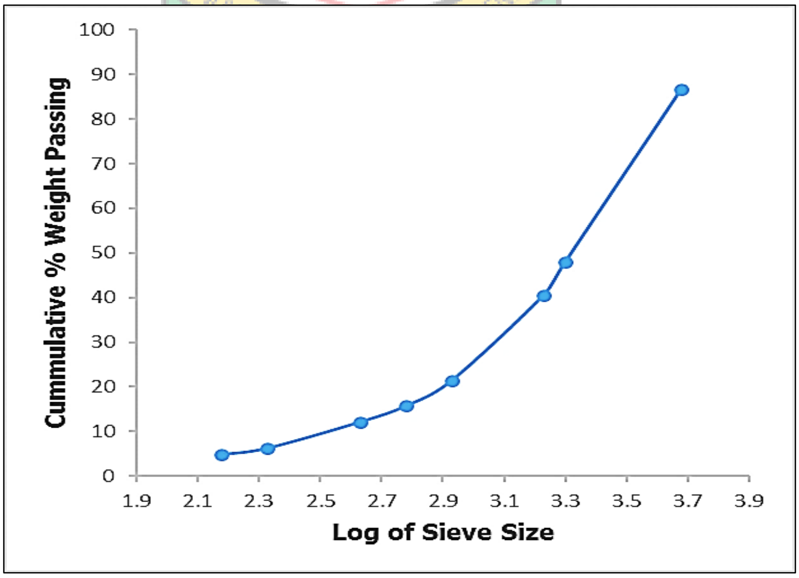

Figure 4.5 Graph of Log of Sieve Size Against Cumulative % Weight Passing for Ore Sample

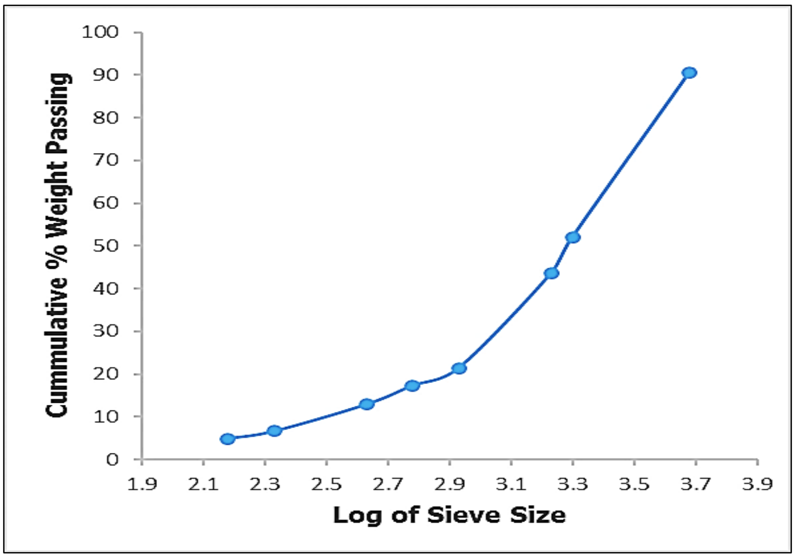

Figure 4.6 Graph of Log of Sieve Size against Cumulative % Weight Passing for Slag Sample

4.3 Bulk Density versus Porosity

The physical property that deals with voids (i.e. bulk density and porosity) was determined. Bulk density of Akpafu-Todzi iron ore was found to be between 2.9 tonnes/m^3 and 4.1 tonnes/m^3 with an average of 3.3 tonnes/m^3 and standard deviation of 0.4195. The porosity was also found to have the lowest value of 8.5% and highest value of 15.3% with an average of 12.2% and standard deviation of 2.2284. The full results of the bulk density and porosity are detailed in appendix C.

Bulk density and porosity have a relationship since both deal with total void present in a sample. So, a graph of bulk density against porosity gave a scatter plot and with a line of best fit drawn. The graph exhibited a strong negative correlation (R= -0.8903) between the two parameters. This implies that if bulk density increases porosity decreases and vice versa, so bulk density and porosity are inversely proportional to each other. Figure 4.7 shows the correlation graph between bulk density and porosity.

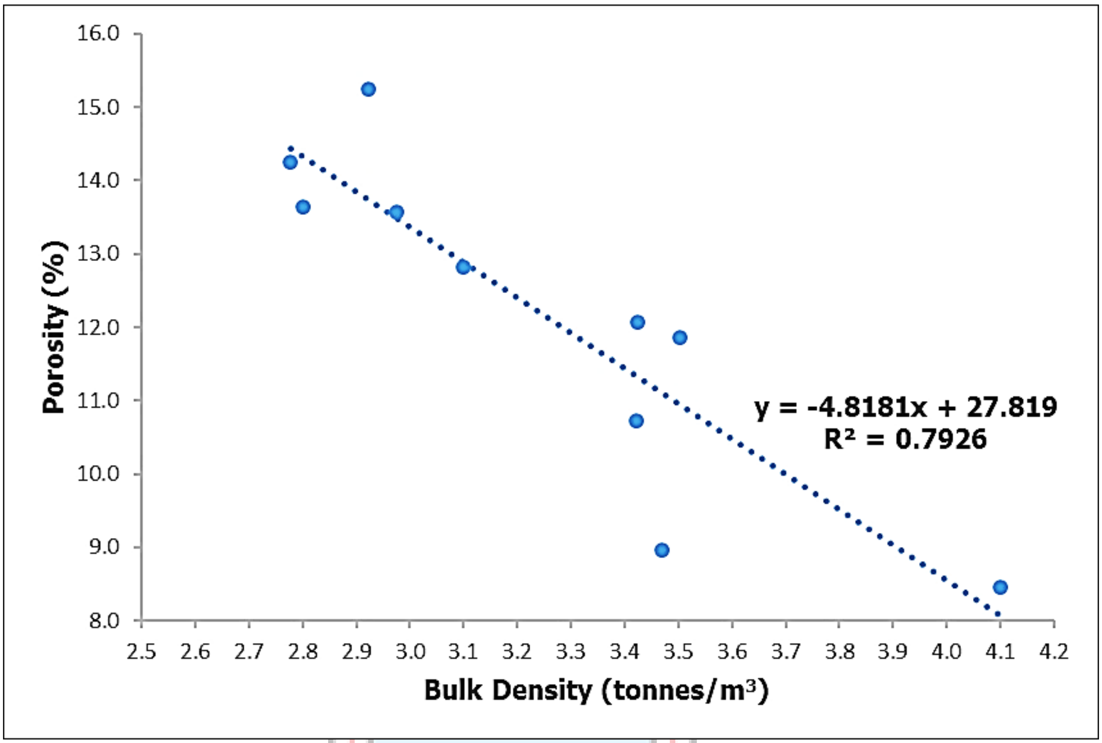

Figure 4.7 Scatter Diagram with Regression Line Correlating Porosity with Bulk Density for the Iron Ore lumps

Equation linking the bulk density with porosity is given by the relation below and knowing one parameter the other could be estimated using this relation;

$$y = -4.8181x + 27.819 \qquad (4.1)$$

where y = porosity; and

x = bulk density.

4.4 Tumble Index (TI) and Abrasive Index (AI)

The TI and AI are refered to as the cold strength test because the test does not require high temperature or heat. The TI of Akpafu-Todzi iron ore was found to lie betwween 93.97 wt% and 95.33 wt% and the AI between 2.5 wt% and 3.5 wt%. Table 4.6 shows the results obtained from the TI (wt% of +5.6 mm) and AI (wt% of -0.5 mm).

The physical specification for iron ore lump used for various ironmaking processes are given in Table 4.7. The values of the TI and AI obtained for Akpafu-Todzi iron ore lump were compared to that of stardard commercial physical requirements for various process routes.

It was found out that the TI and AI values of Akpafu-Todzi iron ore lumps fall within the allowable limits.

Table 4.6 TI and AI Values of Akpafu-Todzi Iron Ore Lumps

Sample	TI (weight % of +5.6 mm)	AI (weight % of -0.5 mm)
AKA	95.06	2.73
AKB	95.33	2.60
AKC	93.97	3.40
Average	94.79	2.91

Table 4.7 Commercial Physical Requirement for TI and AI of Iron Lump Ores

Process	TI (weight % of +6.3 mm)	AI (weight % of -0.5 mm)
Corex	80-85	7 max
BF	80 min	10 max
DRI-Midrex	90 min	7 max
DRI-HYL	85 min	10 max
DRI- Rotary Kiln	90 min	7 max

(Source: DID, 2010)

The result of the TI and AI values of Akpafu-Todzi iron ore lumps meeting the physical requirements means that this iron ore lump can be handled, loaded and transported without the ore disintegrating into smaller fragments and dust.

The AI values of the Akpafu-Todzi iron ore lump were plotted against its TI values. The graph showed that Akpafu-Todzi iron ore lump can be used for various ironmaking process routes indicated in Table 4.7 except for the Corex process. This is because the TI value of Akpafu-Todzi iron ore lump obtained for the three samples tested were higher in terms of comparison with the Corex accepted limit. Figure 4.8 further highlights this observation.

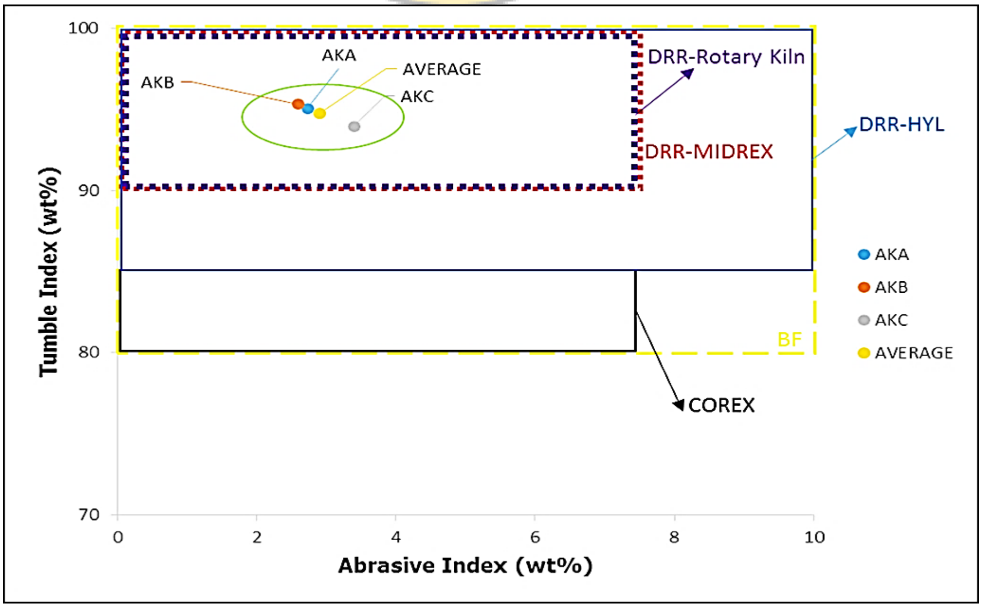

Figure 4.8 Graph of AI Versus TI Compared to Physical Requirements for Various Process Route

4.5 Bond Work Index (W_i)

The ball mill grindability (Gbp) in grams/revolution (g/rev) was calculated by averaging the results of the net mass per revolution from the last three cycles of the test. The average Gbp was calculated to be 0.82 g/rev. The P80 of the feed and product were estimated to be 2 791 µm and 86 µm respectively. The W_i of Akpafu-Todzi iron ore was then calculated to be approximately 20 kWh/t using equation 3.6. The feed and final product particle size analysis as well as the grindability test data can be found in appendix D.

The W_i of Akpafu-Todzi iron ore means that 20 kilowatts hour of energy is required to be able to grind 1 ton of the iron ore from infinite size to 80% passing 106 µm. Also, when the value of W_i obtained for the iron ore sample compared to typical values of hardness index (Table 4.8), it was deduced that Akpafu-Todzi iron ore is a hard ore since its W_i falls under the index range 14-20 kWh/t. The hardness nature of the ore could be associated to the cherty quartzites nature and the high silica content of the Akpafu-Todzi iron ore source. The value of the W_i is crucial in design of new grinding plant or circuit so it is recommended that further test should be carried on the Akpafu-Todzi iron ore to establish the exact value of W_i.

Table 4.8 Hardness Index for Various Bond Work Index Values

Property	Soft	Medium	Hard	Very Hard
Bond W_i (kWh/t)	7-9	9-14	14-20	>20

(Source: Anon, 2017)

4.6 Reducibility Studies

The ability of Akpafu-Todzi iron ore to undergo effective reduction using different reductant locally generated from waste polymers with less or no challenges is the main priority of these studies. Measurement of the temperature was a bit challenging but the maximum temperature attained by the pellet was about 1197 °C and 1013 °C for microwave and 'Sika Bukyia' firing processes. Reduction occurred in all samples for all reductants used under both heating methods employed. The nature of the reduced material, extent at which reduction occurred, rate of the reduction process, mechanisms and major reactions involved in the reduction are further discussed under this section.

4.6.1. Nature of Metal Produced

Reduced metals were obtained for various particle sizes deployed in the reduction studies. The reduced metal produced from the microwave irradiation where spherical in nature. These spheres of metal were embedded in the slag phase of the reduced material and has to be subjected to breakage to free the spherical metals. Physical separation of the mixture of reduced metals and slag components was effected using a low intensity handheld magnet. The spherical nature of the reduced metal could be attributed to the excess carbonaceous material present in the iron ore-carbon mixture causing reduced iron to pick up or absorb these excess carbons causing the reduced iron to melt at a lower temperature into a molten mass that solidifies into sphere when the microwave power is put off. According to the iron-carbon system (Figure 4.9) the melting point of iron changes from 1538 ˚C to about 1147 ˚C when the carbon content in iron is about 4.30 w%. The Figure 4.9 below highlights the iron carbon phase diagram.

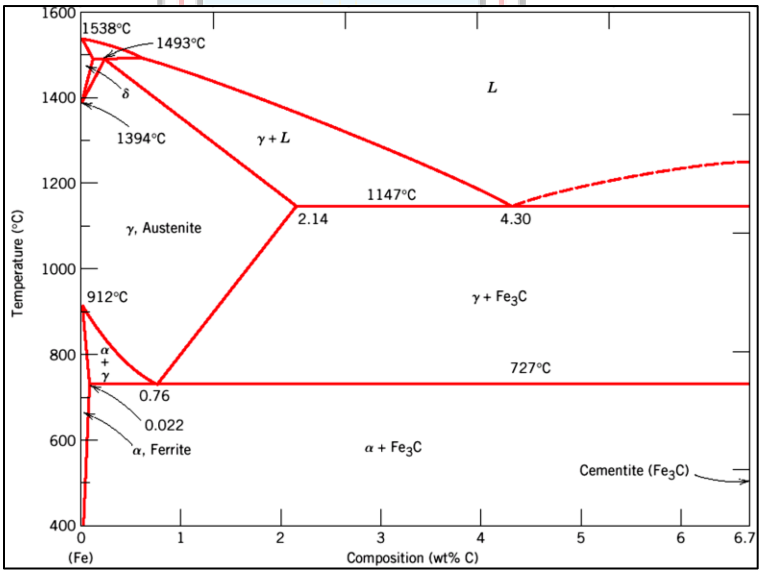

Figure 4.9 The Iron–Iron Carbide (Fe–Fe$_3$C) Phase Diagram
(Source: Callister, 2007)

Reduced metals obtained from the convectional heating using ‘Sika Bukyia’ were like iron filings in nature without any distinct difference between the reduced metal and slag component as observed in reduced materials of the microwave heating. Low intensity handheld magnet was used to separate the reduced metal from a pool of unreacted reductant. Figures 4.10 and 4.11 show a photograph of metals produced under microwave irradiation and ‘Sika Bukyia’ gas heating, respectively.

Figure 4.10 Reduce Metal Produced from Microwave Reduction held on a Magnet

Figure 4.11 Reduce Metal Produced from 'Sika Bukyia' Reduction held on a Magnet

The iron filing nature of the reduced metal produced under 'Sika Bukyia' gas heating was due to the fact that reduced metal was not able to pick up carbon there by not able to melt into molten phase and subsequently not solidifying into spheres when the heating source is turned off. The picture printed here is that the initial reduced metal formed was not able or picked less amount of carbon (below 2 wt.%) which is nowhere near the liquidus line in the Fe-C system (Figure 4.9).

4.6.2 Extent of Reduction

The extent of reduction was calculated from the oxygen content and the weight loss during reduction process of Akpafu-Todzi with waste polymers and this saw microwave and 'Sika Bukyia' mode of heating attaining extent of reduction ranging between 69% to 98% and 55% to 89%, respectively. Figure 4.13 to 4.18 show the results obtained in several experiments in terms of percent reduction as a function of time for the various pellets tested. For both mode of heating used in these studies it could be seen that there is a close relationship between extent of reduction and time thus extent of reduction increases with increasing time to a point where reduction is said to be completed. The curve for extent of reduction using microwave irradiation showed a general trend of increasing extent of reduction with time to a point and then plateaus. The indication of the plateau means reduction is completed and this was observed to occur after 30 mins. 'Sika Bukyia' gas heating process also exhibited the trend of increasing extent of reduction with time but unlike the microwave, extent of reduction increased until the 60th minute for the 'Sika

Bukyia' gas heating process. This is because the rate of reduction is much slower under 'Sika Bukyia' gas heating process compared to the rate of reduction under microwave irradiation where reduction sharply rises up to a certain level and then remains approximately constant till the 60th minute. The maximum extent of reduction recorded for the studies was 97.52% and it occurred after 20 mins with saw dust as reducing agent and microwave as the mode of heating.

The rate of reduction (r) was estimated for all sample using the amount of sample reduced and the specific time taken to reduce that amount. Rate of reduction for Akpafu-Todzi iron ore is defined as amount of iron ore reduced in grams per unit time in seconds for both mode of heating. It was measured in $g.s^{-1}$. The expression for estimating the reduction rate (r) is given in equation 4.2 below.

$$r = \frac{x}{t} \tag{4.2}$$

where, $r =$ rate of reduction

$x =$ amount of iron reduced (weight loss) (g); and

$t =$ time taken for reduction (s)

The rate of reduction estimated for both heating modes is shown in table 4.9. Microwave was able to reduce Akpafu-Todzi iron ore recording an average rate of reduction of 0.00948 grams per seconds (0.00948 $g.s^{-1}$) and that of 'Sika Bukyia' gas heating recording an average rate of reduction of 0.00427 grams per seconds (0.00427 $g.s^{-1}$). This indicates that every seconds the average extent of reduction for microwave is 0.00948 g and 'Sika Bukyia' gas heating is 0.00427 g. Implication of these results is that microwave performed better compared to the 'Sika Bukyia' gas heating in terms of extent of reduction. The mode of heating was a major factor in this variation. Microwave heating is in the form of volumetric thus heating occurs from the inner core of the pellet to the outer of the pellets. When reduction begins at the core, gases (syngas- CO, H_2, CO_2) from the reaction diffuse across the layers of the pellets and as this occurs unreacted carbon reacts with carbon dioxide (CO_2) through the Boudouard reaction ($CO_2 + C = 2CO$) to produce carbon monoxide (CO) which is also a reducing gas. The syngas as they diffuse from the core to the outer of the pellet also achieve some form of reduction which together with the solid carbon contribute to the high extent of reduction achieved when microwave was used as a heating source. Table 4.9 summaries the obtained results for reduction rate estimation.

Table 4.9 Reduction Rate for Reduction of Composite Pellet under Microwave and 'Sika Bukyia' Energy

Pellet No.	**Reduction Rate ($g.s^{-1}$)**					
	Microwave			**'Sika Bukyia'**		
	215 μ	**143 μ**	**53 μ**	**215 μ**	**143 μ**	**53 μ**
1	0.01000	0.00944	0.00939	0.00469	0.00456	0.00433
2	0.00833	0.00722	0.00817	0.00431	0.00414	0.00433
3	0.00944	0.00833	0.00983	0.00483	0.00464	0.00381
4	0.01000	0.00944	0.00928	0.00475	0.00447	0.00419
5	0.01056	0.00889	0.00856	0.00489	0.00467	0.00439
6	0.00944	0.01000	0.00989	0.00411	0.00325	0.00306
7	0.00944	0.01056	0.01100	0.00417	0.00353	0.00378
8	0.01056	0.01083	0.01044	0.00422	0.00406	0.00319
9	0.00833	0.00944	0.00900	0.00447	0.00433	0.00442
10	0.00889	0.00889	0.00978	0.00503	0.00489	0.00425
11	0.00944	0.00944	0.00933	0.00414	0.00517	0.00369
12	0.00889	0.01056	0.01033	0.00414	0.00472	0.00414
13	0.00944	0.00944	0.00944	0.00447	0.00439	0.00383
Average	**0.00944**	**0.00942**	**0.00957**	**0.00448**	**0.00437**	**0.00396**

The slow rate of reduction observed for the 'Sika Bukyia' gas heating was as a result of the way heating occurs in this source of heating. Reduction begins on the outer periphery of the spherical pellets and a thin film of reduced metal forms on the surface. This film may prevent or limit diffusion of gases across the surface of the pellet depending on how porous and durable it is. This film may have inhibited the rate of reduction under 'Sika Bukyia' gas heating, resulting into the lower extent of reduction recorded for this heating source. The various carbonaceous materials and their blends were all efficient source of reductant since the lowest extent of reduction recorded was 69.34% with microwave as energy source and LDPE as reductant and 54.67% with 'Sika Bukyia' as energy source and PNS as reductant.

Reduction studies were also carried out for slag samples obtained from Akpafu-Todzi crude method of ironmaking discussed earlier. This was to confirm whether there is reducible iron metal in the slag sample and if the method used was effective or not. Figure 4.12 shows the extent of reduction versus time graph for Akpafu-Todzi slag samples.

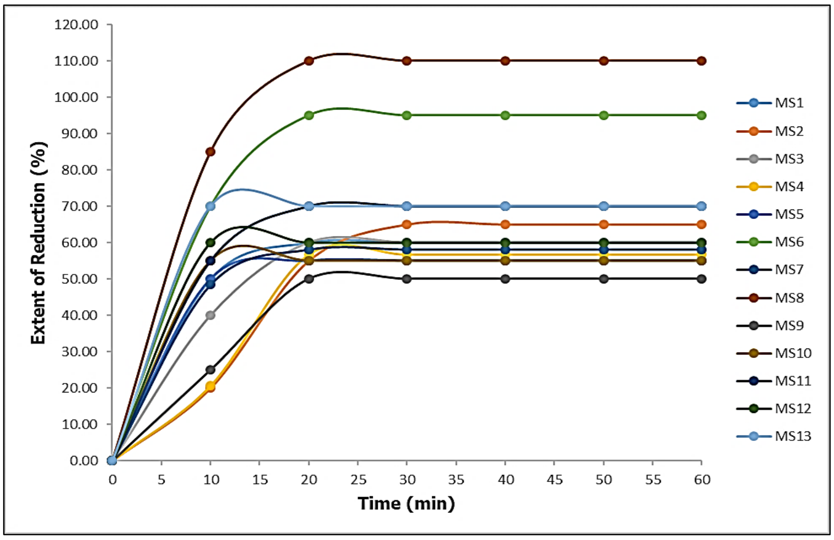

Figure 4.12 Graph of Extent of Reduction against Time using Microwave for -250 microns of Slag Samples

Result from the graph shows that the slag samples were reducible indicating that Akpafu-Todzi slag sample contains reducible iron metal and the crude method used by the artisans of the community was not efficient. The maximum extent of reduction recorded was approximately 110% and the minimum approximately 50%. The observed extent of reduction of 110% could be attributed to excess carbon in the system; after reduction of all the iron oxide available the unreacted carbon reduced the next available reducible metal oxides. Typical examples of metal oxides in this category could be SiO_2, MnO, Cr_2O_3, NiO_2, etc. The crude method of ironmaking of the Akpafu-Todzi folks was inefficient because the particle size of the iron ore used for the extraction process was too large and required higher energy source. Also the inefficient crude artisanal furnace design used by the folks of Akpafu-Todzi was also a contributing factor to the poor reduction process. Data of the extent of reduction for all pellets tested is shown in appendix E.

4.6.3 Effect of Particle Size on Reduction Behaviour

To study the effect of particle size on reduction of Akpafu-Todzi iron ore, three different particle size ranges were used -250 +180 µm, -180 +106 µm and -106 +0 µm. Figures 4.13, 4.14 and 4.15 all showed that increase in surface area of ore particle sizes decreases the time of reduction for ores reduced under microwave irradiation, thus for particle size -250 +180 µm after 30 mins most of the tested pellets reached complete reduction and for particle size -180 +106 µm and -106 +0 µm most tested pellets reached complete reduction after 20 mins and 15 mins respectively.

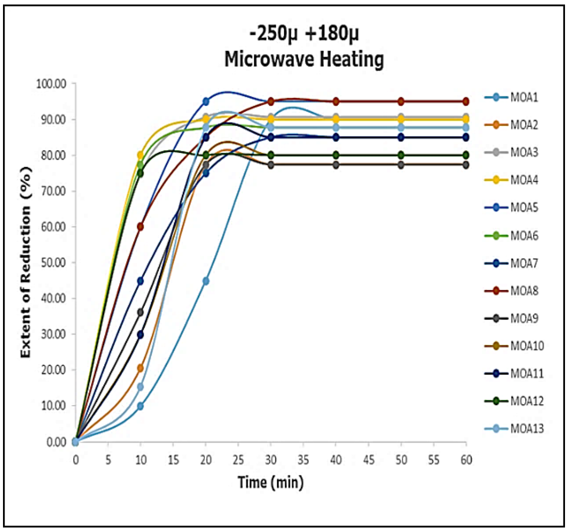

Figure 4.13 Graph of Time against Extent of Reduction using Microwave for -250 +180 μ of Ore Samples

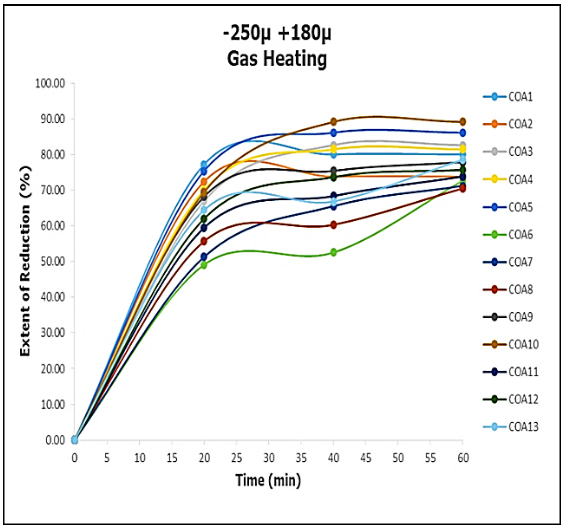

Figure 4.16 Graph of Time against Extent of Reduction using Gas Heating for -250 +180 μ of Ore Samples

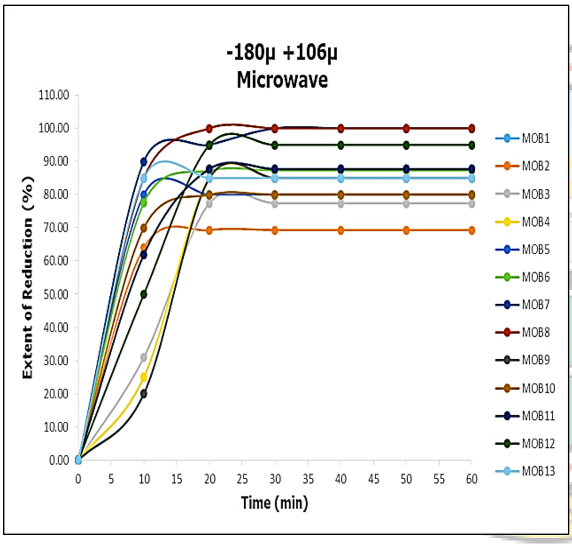

Figure 4.14 Graph of Time against Extent of Reduction using Microwave for -180+106 μ of Ore Samples

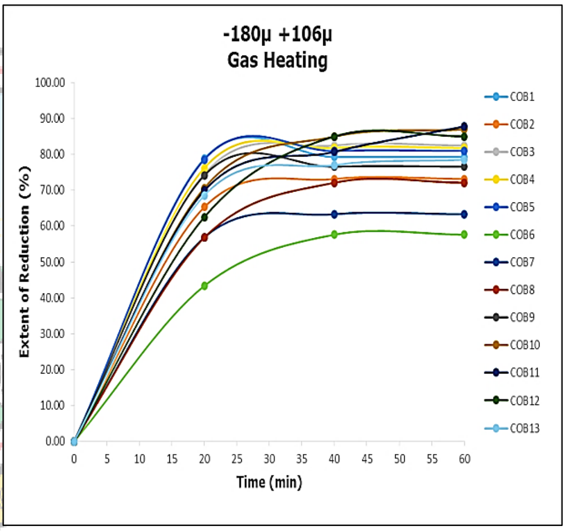

Figure 4.17 Graph of Time against Extent of Reduction using Gas Heating for -180 +106 μ of Ore Samples

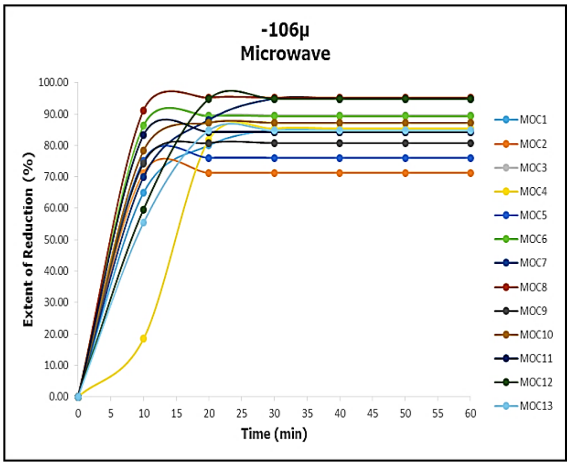

Figure 4.15 Graph of Time against Extent of Reduction using Microwave for -106 μ of Ore Samples

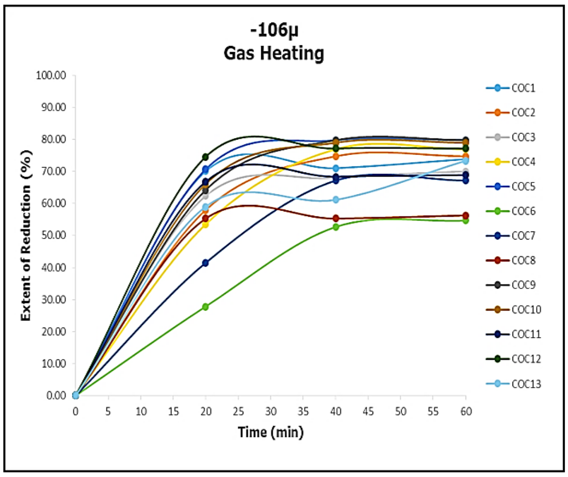

Figure 4.18 Graph of Time against Extent of Reduction using Microwave for -106 μ of Ore Sample

With ‘Sika Bukyia’ gas heating the reverse of what was observed in the microwave was observed and this was observed from Figure 4.16, 4.17 and 4.18. Increased surface area of the ore particles increases the time for reduction. This is due to the fact that when the surface area of the ore particles increases there is rapid formation of the thin metallic film on the surface of the pellet. The time required for reduction on the surface of the pellet will decrease which causes imminent formation of the thin metallic film. So, the finer the particle size the rapid formation of the metallic film and the slower the reduction process. From Table 4.9 it could be seen that the average rate of reduction for the various particle size under ‘Sika Bukyia’ gas heating had a decrease order of magnitude, thus as the particle size decreases the reduction rate also decreases in the order -250 +180 µm > -180 +106 µm > -106 +0 µm (0.00448 $g.s^{-1}$ > 0.00437 $g.s^{-1}$ > 0.00396 $g.s^{-1}$)

Generally, it was observed that smaller particle size increases carburisation of iron metal formed and this in turn enhances melting of the iron metal into molten state. As the molten metal solidifies when the microwave is switched off it assumes spherical shape. This explains the nature of metal formed when the particle size decreases.

4.6.4 Mechanism and Proposed Reactions of the Reduction Studies

The microwave oven transforms electrical energy into microwaves, which is a form of electromagnetic energy. The microwaves are then transformed into thermal energy as they are absorbed by the iron-carbon composite pellet. The microwave energy is first absorbed by the iron oxide which is responsible for transforming it into thermal energy. This energy is enough to cause the reductant to heat up to kick start the reduction process of the iron oxide. Plastics as reductant produces a mixture of gaseous hydrocarbons especially methane (CH_4) which is a gaseous reductant. The energy builds up at the core of the pellet and cause thermal decomposition of CH_4 into carbon and hydrogen and the reformation of carbon monoxide and hydrogen (Equation 4.4, 4.5 and 4.6) which causes subsequent reduction of the iron oxide. The initial traces of iron metal formed are also able to catalyse carbon formation from methane. This carbon is at the nano-scale and can easily be picked by the metal and subsequently causing melting and solidification of melt into spherical shapes. Charred biomass contains fixed carbon which is an important factor together with hydrogen in reduction of iron oxide (Dankwah (2014a). The reaction that occurs when iron oxide is reduced to metallic iron is detailed. The possible reaction implies that solid form of reductant

(C) and gaseous forms (H_2, CO, CH_4) all play major role in the reduction of Akpafu-Todzi iron ore.

The energy transformation involved in the ‘Sika Bukyia’ gas furnace heating process was from chemical energy to thermal energy. The ‘Sika Bukyia’ furnace burns a natural gas in a chemical reaction and as it burns, heat is released causing air molecules to move faster and the faster the movement of the air molecules the higher the thermal energy released. The thermal energy heats the iron oxide-carbon composite pellet and causes the particles on the surface to move vigorously; so as this happens, heat is conducted to other parts of the pellet. The mechanism of reduction is similar for both plastics and biomass as discussed previously under microwave irradiation but the only difference here is the mode of heating. Microwave heats from the inner core where thermal energy builds up before other parts of the pellet receives it but with ‘Sika Bukyia’ gas furnace, heating of the pellet happens on the surface before the inner parts receive it because air around the pellet gets heated first which in turn heats the surface. Proposed mechanism or reactions that took place in the microwave that accounted for the observed improvement in extent of reduction with blending are shown are as follows:

1. PWS which is a polymer is converted into methane and other hydrocarbons

$$\text{Polymer} \rightarrow CH_{4\,(g)} \tag{4.3}$$

2. The thermal decomposition of methane into carbon and hydrogen or reformation into CO and H_2

$$CH_{4\,(g)} = C_{(s)} + 2H_{2\,(g)} \tag{4.4}$$

$$CH_{4\,(g)} + CO_{2\,(g)} = 2CO_{(g)} + 2H_{2\,(g)} \tag{4.5}$$

$$CH_{4\,(g)} + H_2O_{(g)} = CO_{(g)} + 3H_{2\,(g)} \tag{4.6}$$

3. The reduction of Fe_2O_3 by carbon to produce Fe

$$Fe_2O_3 + \tfrac{1}{3}C = \tfrac{2}{3}Fe_3O_4 + \tfrac{1}{3}CO \tag{4.7}$$

$$Fe_3O_4 + C = 3FeO + CO \tag{4.8}$$

$$FeO + C = Fe + CO \tag{4.9}$$

4. The reduction of Fe_2O_3 by hydrogen to produce Fe

$$Fe_2O_3 + \tfrac{1}{3}H_2 = \tfrac{2}{3}Fe_3O_4 + \tfrac{1}{3}H_2O \tag{4.10}$$

$Fe_3O_4 + H_2 = 3FeO + H_2O$ (4.11)

$FeO + H_2 = Fe + H_2O$ (4.12)

5. The reduction of Fe_2O_3 by carbon monoxide to produce Fe

$e_2O_3 + \frac{1}{3}CO = \frac{2}{3}Fe_3O_4 + \frac{1}{3}CO_2$ (4.13)

$Fe_3O_4 + CO = 3FeO + CO_2$ (4.14)

$FeO + CO = Fe + CO_2$ (4.15)

6. Some side reactions that also occur

i) Water gas shift reaction: $H_2O_{(g)} + CO_{(g)} = H_{2(g)} + CO_{2(g)}$ (4.16)

ii) Gasification of C by H_2O: $H_2O_{(g)} + C_{(s)} = H_{2(g)} + CO_{(g)}$ (4.17)

iii) Gasification of C by CO_2 (Boudouard reaction): $CO_{2(g)} + C_{(s)} = 2CO_{(g)}$ (4.18)

4.7 Proposed Possible Processing Route for Akpafu-Todzi Iron Ore

Beyond the finding of this studies, it has being notice that there are few developments that needs to be looked at in future rejuvenating of iron ore mining at Akpafu-Todzi ironmaking industries. Firstly a geological survey has to be conducted again in the area to estimate the exert ore reserve and total recoverable Fe metal. In addition, a feasibility study towards rejuvenating iron ore mining at Akpafu-Todzi should be conducted since the community sits on the deposit. This might pose some issues of relocation but hopefully results from the feasibility studies could yield good results to create jobs for the youth since unemployment has become a major issue in the region.

Furthermore, the current studies has found out that Akpafu-Todzi iron ore is of a low-grade hematite ore with high gauge content (mostly silica). Despite its low-grade nature, the Akpafu-Todzi ore exhibited good physical properties and metallurgical properties. Based on the various test work carried out in these studies, it will be beneficial if the deposit is considered to be exploited on a small-scale bases where ore materials could be processed to extract the valuable iron ore grade. Base on the results from this studies two main processing routes has been identified by the current study as possible iron extraction path for the Akpafu-Todzi iron deposit.

The first route being suggested is the production of iron using the DRI process. Ore material will be comminute to an optimum size fraction, this will be followed by pelletisation using locally produced reductant. From the results obtained from this studies, RDF was found to have both reducing and energy generating properties. Due to this, it can be used as the reductant and also use to fuel a locally produced furnace. The suggested furnace is solely based on the previously feasibility studies carried out in 1975 by Bill (Kesse and Banson, 1975) and current state of the iron ore reserve as well as the low grade nature. If a new feasibility studies is carried and results indicates iron ore can be extracted profitability with a more advanced furnaces (most suitably microwaved based furnaces) then that could be used. Figure 4.19 below shows a simple flowchart summarising the proposed process route that could be used in future for processing the Akpafu-Todzi iron ore.

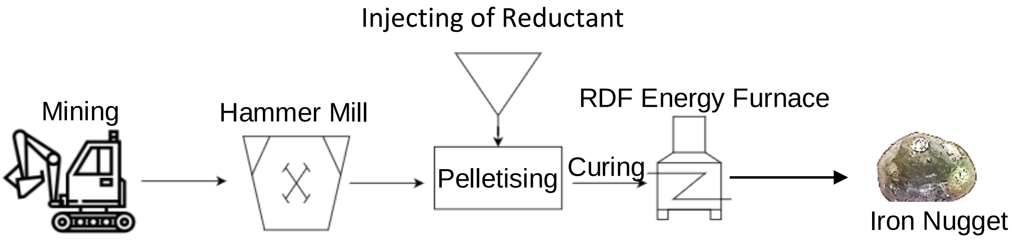

Figure 4.19 Suggested Process Route of Processing of Akpafu-Todzi Iron Ore

The second process route being suggested by the current thesis is the production of high grade pellets. This processing route is basically the production of pellets after the comminution processes to reduce the particles size into a workable feed. This route is being proposed if the cost of having a reduction plant might be too expensive and also due to the settlement of communities on the ore deposit. The dried pellets can be transported to offsite location for processing or can be exported for foreign exchange.

In summary, a laboratory simulated process routes should be carried out to develop a suitable and cost-efficient process routes for reducing the Akpafu-Todzi iron ore. In doing this, the flaws of the indigenous ironmaking route should be looked at and tackled in the new process route. Furthermore, Refused Derived fuels could be a vital source of energy and reductant due to the energy issue of Ghana and the high cost of metallurgical coke. In addition a laboratory studies should be conducted to study the possible methods to employ to reduce the silica content of the ore prior to palletisation and reduction process. This may contribute to reducing the energy consumption during the reduction process since high silica content iron ore requires more reduction energy. The laboratory testing that can be considered in reducing the amount of silica could be wash plant or early coarse gangue rejection approaches.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

A laboratory investigation has been conducted on the nature of Akpafu-Todzi iron ore deposit and how it responds to carbothermal reduction utilising various waste polymers and their blends as reducing agents. Iron ore was found to exist in Akpafu-Todzi in the Hohoe Municipality in the Volta Region of Ghana. The Akpafu-Todzi iron ore is of a low-grade hematite ore with high gauge content. Despite its low-grade nature, the Akpafu-Todzi ore exhibited good physical properties and metallurgical properties. Based on the various test work carried out in these studies, the following are major findings from the studies:

a. The Akpafu-Todzi iron ore is a low-medium grade hematite ore with an average grade of about 64.47 wt % Fe_2O_3 (43.91 wt % Fe) and with the presence of silica (19.61 wt%) and alumina (2.29 wt%).

b. PSD was conducted after stage crushing of the ore to determine the ease of disintegration of Akpafu-Todzi iron ore. The P80 obtained from the cumulative curve shows that 80% of the iron ore are passing 3317 µm which indicates that the ore does not disintegrate easily.

c. The iron ore has a strong negative correlation between porosity and bulk density. This means that when one parameter is known the other could be determined or estimated using the linear equation obtained on the porosity bulk density graph.

d. Akpafu-Todzi ore can easily be handled, loaded, transported without disintegrating into small particles in the form of dust because of the high values obtained from the tumbler index and abrasive index (averaging 94.79 wt% and 2.91 wt%. respectively).

e. The Akpafu-Todzi iron ore can be successfully reduced using carbonaceous materials generated locally.

f. Waste polymers, biomass and their blends can be used successfully to reduce Akpafu-Todzi iron ore.

g. The reduced samples were all attracted by a magnet, suggesting that Fe_2O_3 was transformed to either Fe_3O_4 or Fe. The reduced metal produced from microwave was spherical and that of “Sika Bukyia” was like iron filings. The spherical nature will be advantageous when it is used a feed in steel making (Electric Arc Furncae process) and the iron filling nature will be advantageous in alloy formation.

h. The measured extent of reduction ranged from about 69% to 98% and 55% to 89% with microwave and “Sika Bukyia” as energy sources respectively.

i. The highest extent of reduction achieve was about 98% and it was attained with saw dust as reducing agent and microwave as energy source.

j. It was observed that as particle size decreases reduction time also decreases due to the more exposed contact areas when microwave was used and the reverse when “Sika Bukyia” was used. This was because formation of metallic film on the surface of the pellet forms early as the particle sizes decreases thereby reducing the rate of reduction and increasing the reduction time.

Akpafu-Todzi Iron ore will be suitable for small scale operations, which will produce sponge iron for steel companies. It could also be used as raw material for producing pellet or sinter or could be blend with high grade iron ore which could be used as feed in direct reduction process. The carbonaceous material employed in this investigation could be used as reducing agent to reduce the ore and the product could serve as feedstock to the steelmaking companies in the country.

5.2 Recommendation

Due to various facts and observations obtained in this investigation, the following are recommendations made pertaining to this investigation;

a. Feasibility study towards rejuvenating iron ore mining at Akpafu-Todzi should be conducted, and hopefully this could yield good results to create jobs for the youth.

b. Laboratory simulated process routes should be carried out to develop a suitable and cost-efficient process routes for reducing the Akapu-Todzi iron ore.

c. Future work should look at the reduction behaviour of Akpafu-Todzi iron ore under different temperatures and also study the kinetics involved.

d. Some of the issues concerning waste in Ghana could be solved by using waste materials in reduction processes.

e. Iron metals produced from this ore could serve as an alternative raw material to scraps for steel companies in the country.

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APPENDICES

APPENDIX A

MASSES AND BLENDS OF THE VARIOUS RAW MATERIALS USED FOR THE PELLET FORMATION

Pellet Number	**Pellet Composition**									
	Mass of Iron ore (g)	**Blend Ratio of Carbonaceous Materials**	**Mass of HDPE (g)**	**Mass of LDPE (g)**	**Mass of PS (g)**	**Mass of PP (g)**	**Mass of PET (g)**	**Mass of PNS (g)**	**Mass of CNS (g)**	**Mass of SD (g)**
1	21	100% HDPE	**9**	-	-	-	-	-	-	-
2	21	100% LDPE	-	**9**	-	-	-	-	-	-
3	21	100% PS	-	-	**9**	-	-	-	-	-
4	21	100% PP	-	-	-	**9**	-	-	-	-
5	21	100% PET	-	-	-	-	**9**	-	-	-
6	21	100% PNS	-	-	-	-	-	**9**	-	-
7	21	100% CNS	-	-	-	-	-	-	**9**	-
8	21	100% SD	-	-	-	-	-	-	-	**9**
9	21	40% HDPE+ 20% LDPE+30%PP+10%PS	**3.6**	**1.8**	**0.9**	**2.7**	-	-	-	-
10	21	40% HDPE+ 20% LDPE+30%PP+10%PET	**3.6**	**1.8**	-	**2.7**	**0.9**	-	-	-
11	21	40% HDPE+ 20% LDPE+30%PP+10%PNS	**3.6**	**1.8**	-	**2.7**	-	**0.9**	-	-
12	21	40% HDPE+ 20% LDPE+30%PP+10%CNS	**3.6**	**1.8**	-	**2.7**	-	-	**0.9**	-
13	21	40% HDPE+ 20% LDPE+30%PP+10%SD	**3.6**	**1.8**	-	**2.7**	-	-	-	**0.9**

APPENDIX B

PARTICLE SIZE DISTRIBUTION OF IRON ORE AND SLAG MATERIAL

Table B.1 Results of particle size distribution for slag samples

Sieve Size (µm)	Weight Retained (g)	% Weight Retained	Normal Aperture size(µm)	Cumulative % Weight Retained	Cumulative % Weight Passing	Log of Sieve Size
+4750	236.1	9.46	4750	9.46	90.54	3.68
-4750 +2000	959.3	38.45	4750	47.91	52.09	3.30
-2000 +1700	212.1	8.50	2000	56.42	43.58	3.23
-1700 +850	552	22.13	1700	78.54	21.46	2.93
-850 +600	102	4.09	850	82.63	17.37	2.78
-600 +425	109.9	4.40	600	87.03	12.97	2.63
-425 +212	156.3	6.26	425	93.30	6.70	2.33
-212 +150	43.4	1.74	212	95.04	4.96	2.18
-150	123.8	4.96	150	100.00	0.00	

Table B.2 Results of particle size distribution for ore

Sieve Size (µm)	Weight Retained (g)	% Weight Retained	Normal Aperture size(µm)	Cumulative % Weight Retained	Cumulative % Weight Passing	Log of Sieve Size
+4750	333.20	13.42	4750	13.42	86.58	3.68
-4750 +2000	962.60	38.78	4750	52.20	47.80	3.30
-2000 +1700	181.80	7.32	2000	59.53	40.47	3.23
-1700 +850	475.40	19.15	1700	78.68	21.32	2.93
-850 +600	141.20	5.69	850	84.37	15.63	2.78
-600 +425	89.80	3.62	600	87.98	12.02	2.63
-425 +212	144.60	5.83	425	93.81	6.19	2.33
-212 +150	36.70	1.48	212	95.29	4.71	2.18
-150	117.00	4.71	150	100	0	

APPENDIX C

RESULTS OBTAINED FROM BULK DENSITY TEST AND POROSITY TEST

Table C.1 Bulk Density Data Sheet

Sample No.	**SAMPLE B**					**SAMPLE B1**				
No. of Test	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
Mass wet Specimen (g)	190.1	159.4	143.7	159.4	188.4	164.4	126.6	115.2	134.4	194.6
Mass wet Specimen+ wax (g)	195.1	163.8	148.2	163.5	192.9	169.7	130.6	118.6	137.9	200.0
Mass of wax (g)	5.0	4.4	4.5	4.1	4.5	5.3	4.0	3.4	3.5	5.4
Water displaced (cm3)	61.0	50.0	40.0	50.0	60.0	65.0	48.0	45.0	49.0	62.0
Volume of wax (cm3)	5.5	4.8	4.9	4.5	4.9	5.8	4.4	3.7	3.8	5.9
Volume of specimen (cm3)	55.5	45.2	35.1	45.5	55.1	59.2	43.6	41.3	45.2	56.1
Bulk Density (tones/m3)	3.4	3.5	4.1	3.5	3.4	2.8	2.9	2.8	3.0	3.5
Average Bulk Density	3.6					3.0				
Average Bulk Density of B+B1	3.3									

Table C.2 Porosity Data Sheet

Sample Name	**SAMPLE B**					**SAMPLE B1**				
No. of Test	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
Mass of Specimen (g)	189.1000	206.1000	179.2000	161.2000	141.2000	165.5000	170.9000	179.1000	173.6000	193.5000
Mass of Saturated Specimen (g)	195.3000	210.1000	183.7000	164.9000	146.4000	170.8000	175.2000	183.1000	178.7000	197.0000
Mass of dry specimen (g)	188.3000	204.1000	176.2000	159.8000	140.3000	163.1000	169.3000	176.3000	171.1000	191.8000
Volume of water displaced (cm3)	58.0000	71.0000	55.0000	43.0000	40.0000	54.0000	55.0000	53.0000	56.0000	58.0000
Volume of voids	7.0000	6.0000	7.5000	5.1000	6.1000	7.7000	5.9000	6.8000	7.6000	5.2000
Porosity	12.0690	8.4507	13.6364	11.8605	15.2500	14.2593	10.7273	12.8302	13.5714	8.9655
Average porosity (%)	12.2533					12.0707				
Average porosity B+B1 (%)	12.1620									

APPENDIX D

BOND BALL MILL WORK INDEX DETERMINATION

Table D.1 Bond Index Work Data Sheet

Cycle No.	New Feed (g)	No. of Rev	Mass of +106 in product (g)	Mass of -106 in Product (g)	Loss from Mill (g)	Total Refill (g)	Net gram/rev	Mass of -106 in feed (g)	time in sec	time in mins
1	1372	100.0000	1245.0000	119.0000	8.0000	127.0000	1.2700	0	85.71428571	01:26
2	1372	308.6614	1117.0000	246.0000	9.0000	255.0000	0.8261	0	264.5669291	04:25
3	1372	474.4913	990.0000	374.0000	8.0000	382.0000	0.8051	0	406.7068087	06:47
4	1372	486.9125	970.0000	393.0000	9.0000	402.0000	0.8256	0	417.3535838	06:57
5	1372	474.8003	990.0000	371.0000	11.0000	382.0000	0.8045	0	406.9716539	06:47
6	1372	487.2296	970.0000	393.0000	9.0000	402.0000	0.8251	0	417.6253621	06:58
IPP	392	3.5	70	60	86400					
	100									

Table D.2 PSD for Bond Index Sample Feed

Screen (mm)	Weight (g) Oversize	% Oversize	Cumulative % Oversize	Cumulative % Passing
+4	0	0.00	0	100.00
+2	219	43.80	43.80	56.20
+1.4	73	14.60	58.40	41.60
+0.5	113	22.60	81.00	19.00
+0.25	47	9.40	90.40	9.60
+0.125	37	7.40	97.80	2.20
+0.106	9	1.80	99.60	0.40
+0.00	2	0.40	100.00	0.00
Total	500.00			

Table D.3 PSD for Bond Work Index Product

Screen (μm)	Weight (g) Oversize	% Oversize	Cumulative % Oversize	Cumulative % Passing
106	0	0.00	0.00	100.00
90	75	15.21	15.21	84.79
+75	131	26.57	41.78	58.22
0	287	58.22	100.00	0.00
Total	493			

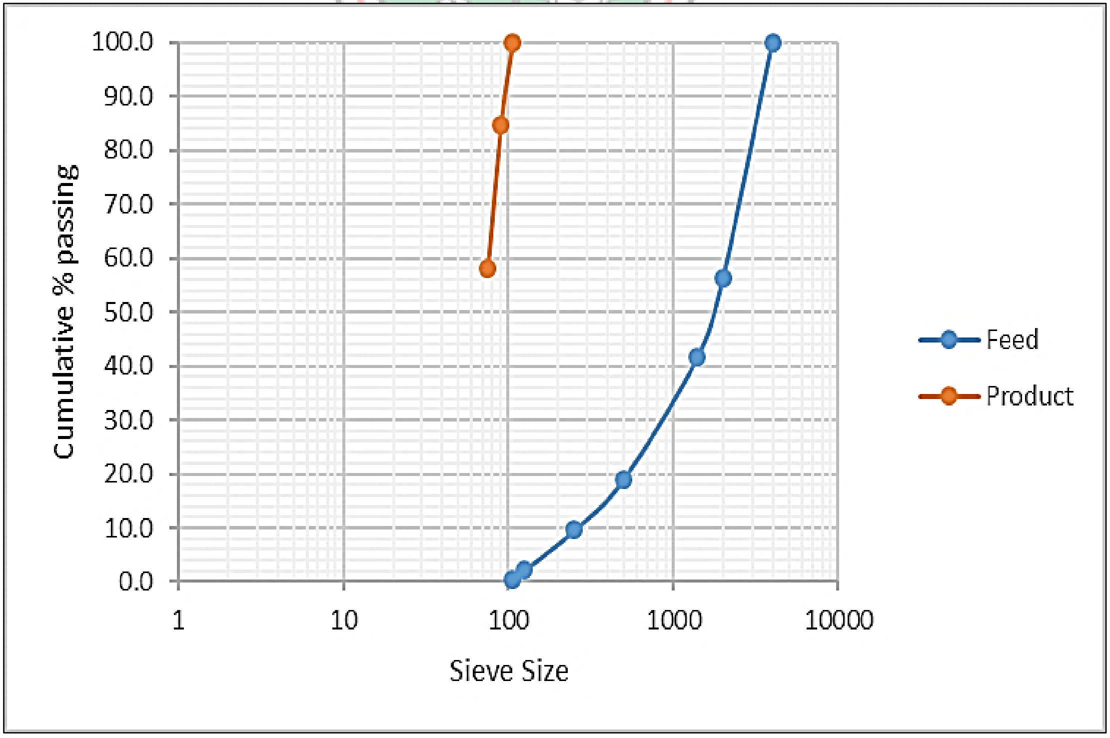

Figure D.1 Cumulative % Passing Curve for Feed Material and Product Material

APPENDIX E

EXTENT OF REDUCTION VALUES OBTAINED AFTER THE REDUCTION STUDIES

Table E.1 Result of Extent of Reduction for -250+180 µm of Ore Using Microwave as Energy Source

Sample Name	Initial Weight (g)	Crucible Weight (g)	Crucible Weight + Sample Weight After Heating (g)							Sample Weight After Heating (g)							Percent Weight Loss (%)							Percent Reduction (%)						
			0	10	20	30	40	50	60	0	10	20	30	40	50	60	0	10	20	30	40	50	60	0	10	20	30	40	50	60
MOA1	32	606	638	636	629	620	620	620	620	32	30	23	14	14	14	14	0.00	6.25	28.13	56.25	56.25	56.25	56.25	0.00	10.00	45.01	90.01	90.01	90.01	90.01
MOA2	31	242	273	269	258	258	258	258	258	31	27	16	16	16	16	16	0.00	12.90	48.39	48.39	48.39	48.39	48.39	0.00	20.65	77.43	77.43	77.43	77.43	77.43
MOA3	32	226	256	242	239	239	239	239	239	30	16	13	13	13	13	13	0.00	46.67	56.67	56.67	56.67	56.67	56.67	0.00	74.68	90.68	90.68	90.68	90.68	90.68
MOA4	32	237	269	253	251	251	251	251	251	32	16	14	14	14	14	14	0.00	50.00	56.25	56.25	56.25	56.25	56.25	0.00	80.01	90.01	90.01	90.01	90.01	90.01
MOA5	32	265	297	285	278	278	278	278	278	32	20	13	13	13	13	13	0.00	37.50	59.38	59.38	59.38	59.38	59.38	0.00	60.01	95.02	95.02	95.02	95.02	95.02
MOA6	31	251	282	267	265	265	265	265	265	31	16	14	14	14	14	14	0.00	48.39	54.84	54.84	54.84	54.84	54.84	0.00	77.43	87.76	87.76	87.76	87.76	87.76
MOA7	32	240	272	263	257	255	255	255	255	32	23	17	15	15	15	15	0.00	28.13	46.88	53.13	53.13	53.13	53.13	0.00	45.01	75.01	85.01	85.01	85.01	85.01
MOA8	32	205	237	225	220	218	218	218	218	32	20	15	13	13	13	13	0.00	37.50	53.13	59.38	59.38	59.38	59.38	0.00	60.01	85.01	95.02	95.02	95.02	95.02
MOA9	31	242	273	266	258	258	258	258	258	31	24	16	16	16	16	16	0.00	22.58	48.39	48.39	48.39	48.39	48.39	0.00	36.13	77.43	77.43	77.43	77.43	77.43
MOA10	32	254	286	280	270	270	270	270	270	32	26	16	16	16	16	16	0.00	18.75	50.00	50.00	50.00	50.00	50.00	0.00	30.00	80.01	80.01	80.01	80.01	80.01
MOA11	32	216	248	242	231	231	231	231	231	32	26	15	15	15	15	15	0.00	18.75	53.13	53.13	53.13	53.13	53.13	0.00	30.00	85.01	85.01	85.01	85.01	85.01
MOA12	32	217	249	234	233	233	233	233	233	32	17	16	16	16	16	16	0.00	46.88	50.00	50.00	50.00	50.00	50.00	0.00	75.01	80.01	80.01	80.01	80.01	80.01
MOA13	31	225	256	253	239	239	239	239	239	31	28	14	14	14	14	14	0.00	9.68	54.84	54.84	54.84	54.84	54.84	0.00	15.49	87.76	87.76	87.76	87.76	87.76

Table E.2 Result of Extent of Reduction for -180+106 µm of Ore Using Microwave as Energy Source

Sample Name	Initial Weight (g)	Crucible Weight (g)	Crucible Weight + Sample Weight After Heating (g)							Sample Weight After Heating (g)							Percent Weight Loss (%)							Percent Reduction (%)						
			0	10	20	30	40	50	60	0	10	20	30	40	50	60	0	10	20	30	40	50	60	0	10	20	30	40	50	60
MOB1	32	234	266	262	249	249	249	249	249	32	28	15	15	15	15	15	0.00	12.50	53.13	53.13	53.13	53.13	53.13	0.00	20.00	85.01	85.01	85.01	85.01	85.01
MOB2	30	260	290	278	277	277	277	277	277	30	18	17	17	17	17	17	0.00	40.00	43.33	43.33	43.33	43.33	43.33	0.00	64.01	69.34	69.34	69.34	69.34	69.34
MOB3	31	255	286	280	271	271	271	271	271	31	25	16	16	16	16	16	0.00	19.35	48.39	48.39	48.39	48.39	48.39	0.00	30.97	77.43	77.43	77.43	77.43	77.43
MOB4	32	225	257	252	240	240	240	240	240	32	27	15	15	15	15	15	0.00	15.63	53.13	53.13	53.13	53.13	53.13	0.00	25.00	85.01	85.01	85.01	85.01	85.01
MOB5	32	226	258	242	242	242	242	242	242	32	16	16	16	16	16	16	0.00	50.00	50.00	50.00	50.00	50.00	50.00	0.00	80.01	80.01	80.01	80.01	80.01	80.01
MOB6	33	209	242	226	224	224	224	224	224	33	17	15	15	15	15	15	0.00	48.48	54.55	54.55	54.55	54.55	54.55	0.00	77.59	87.29	87.29	87.29	87.29	87.29
MOB7	32	193	225	207	206	206	206	206	206	32	14	13	13	13	13	13	0.00	56.25	59.38	59.38	59.38	59.38	59.38	0.00	90.01	95.02	95.02	95.02	95.02	95.02
MOB8	32	285	317	300	298	297.5	297.5	297.5	297.5	32	15	12.5	12.5	12.5	12.5	12.5	0.00	53.13	60.94	60.94	60.94	60.94	60.94	0.00	85.01	97.52	97.52	97.52	97.52	97.52
MOB9	32	330	362	358	345	345	345	345	345	32	28	15	15	15	15	15	0.00	12.50	53.13	53.13	53.13	53.13	53.13	0.00	20.00	85.01	85.01	85.01	85.01	85.01
MOB10	32	266	298	284	282	282	282	282	282	32	18	16	16	16	16	16	0.00	43.75	50.00	50.00	50.00	50.00	50.00	0.00	70.01	80.01	80.01	80.01	80.01	80.01
MOB11	31	342	373	354	345	345	345	345	345	31	19	14	14	14	14	14	0.00	38.71	54.84	54.84	54.84	54.84	54.84	0.00	61.95	87.76	87.76	87.76	87.76	87.76
MOB12	32	371	403	393	384	384	384	384	384	32	22	13	13	13	13	13	0.00	31.25	59.38	59.38	59.38	59.38	59.38	0.00	50.01	95.02	95.02	95.02	95.02	95.02
MOB13	32	224	256	239	239	239	239	239	239	32	15	15	15	15	15	15	0.00	53.13	53.13	53.13	53.13	53.13	53.13	0.00	85.01	85.01	85.01	85.01	85.01	85.01

Table E.3 Result of Extent of Reduction for -106 µm of Ore Using Microwave as Energy Source

Sample Name	Initial Weight (g)	Crucible Weight (g)	Crucible Weight + Sample Weight After Heating (g)							Sample Weight After Heating (g)							Percent Weight Loss (%)							Percent Reduction (%)						
			0	10	20	30	40	50	60	0	10	20	30	40	50	60	0	10	20	30	40	50	60	0	10	20	30	40	50	60
MOC1	31.8	610.9	642.7	629.8	626.8	625.8	625.8	625.8	625.8	31.8	18.9	15.9	14.9	14.9	14.9	14.9	0.0	40.6	50.0	53.1	53.1	53.1	53.1	0.0	64.9	80.0	85.0	85.0	85.0	85.0
MOC2	33.0	602.5	635.5	620.8	620.8	620.8	620.8	620.8	620.8	33.0	18.3	18.3	18.3	18.3	18.3	18.3	0.0	44.5	44.5	44.5	44.5	44.5	44.5	0.0	71.3	71.3	71.3	71.3	71.3	71.3
MOC3	31.6	621.1	652.7	635.7	635.0	635.0	635.0	635.0	635.0	31.6	14.6	13.9	13.9	13.9	13.9	13.9	0.0	53.8	56.0	56.0	56.0	56.0	56.0	0.0	86.1	89.6	89.6	89.6	89.6	89.6
MOC4	31.3	622.6	653.9	650.3	637.9	637.2	637.2	637.2	637.2	31.3	27.7	15.3	14.6	14.6	14.6	14.6	0.0	11.5	51.1	53.4	53.4	53.4	53.4	0.0	18.4	81.8	85.4	85.4	85.4	85.4
MOC5	32.4	606.8	639.2	624.0	623.8	623.8	623.8	623.8	623.8	32.4	17.2	17.0	17.0	17.0	17.0	17.0	0.0	46.9	47.5	47.5	47.5	47.5	47.5	0.0	75.1	76.1	76.1	76.1	76.1	76.1
MOC6	31.9	615.8	647.7	630.5	629.9	629.9	629.9	629.9	629.9	31.9	14.7	14.1	14.1	14.1	14.1	14.1	0.0	53.9	55.8	55.8	55.8	55.8	55.8	0.0	86.3	89.3	89.3	89.3	89.3	89.3
MOC7	33.4	604.8	638.2	623.6	619.8	618.4	618.4	618.4	618.4	33.4	18.8	15.0	13.6	13.6	13.6	13.6	0.0	43.7	55.1	59.3	59.3	59.3	59.3	0.0	70.0	88.2	94.9	94.9	94.9	94.9
MOC8	31.6	601.3	632.9	614.9	614.1	614.1	614.1	614.1	614.1	31.6	13.6	12.8	12.8	12.8	12.8	12.8	0.0	57.0	59.5	59.5	59.5	59.5	59.5	0.0	91.2	95.2	95.2	95.2	95.2	95.2
MOC9	32.1	605.1	637.2	622.3	621.0	621.0	621.0	621.0	621.0	32.1	17.2	15.9	15.9	15.9	15.9	15.9	0.0	46.4	50.5	50.5	50.5	50.5	50.5	0.0	74.3	80.8	80.8	80.8	80.8	80.8
MOC10	32.3	604.3	636.6	620.8	619.0	619.0	619.0	619.0	619.0	32.3	16.5	14.7	14.7	14.7	14.7	14.7	0.0	48.9	54.5	54.5	54.5	54.5	54.5	0.0	78.3	87.2	87.2	87.2	87.2	87.2
MOC11	31.9	606.8	638.7	622.1	621.9	621.9	621.9	621.9	621.9	31.9	15.3	15.1	15.1	15.1	15.1	15.1	0.0	52.0	52.7	52.7	52.7	52.7	52.7	0.0	83.3	84.3	84.3	84.3	84.3	84.3
MOC12	31.4	614.7	646.1	634.4	627.5	627.5	627.5	627.5	627.5	31.4	19.7	12.8	12.8	12.8	12.8	12.8	0.0	37.3	59.2	59.2	59.2	59.2	59.2	0.0	59.6	94.8	94.8	94.8	94.8	94.8
MOC13	32.1	612.9	645.0	633.9	628.0	628.0	628.0	628.0	628.0	32.1	21.0	15.1	15.1	15.1	15.1	15.1	0.0	34.6	53.0	53.0	53.0	53.0	53.0	0.0	55.3	84.7	84.7	84.7	84.7	84.7

Table E.4 Result of Extent of Reduction for -250+180 µm of Ore Using "Sika Bukyia" Gas Furnace as Energy Source

Sample Name	Initial Weight (g)	Crucible Weight (g)	Crucible Weight + Sample Weight After Heating (g)				Sample Weight After Heating (g)				Percent Weight Loss (%)				Percent Reduction (%)			
			0	20	40	60	0	20	40	60	0	20	40	60	0	20	40	60
COA1	33.8	607.2	641	624.7	624.1	624.1	33.8	17.5	16.9	16.9	0.00	48.22	50.00	50.00	0.00	77.17	80.01	80.01
COA2	33.6	617.2	650.8	635.6	635.3	635.3	33.6	18.4	18.1	18.1	0.00	45.24	46.13	46.13	0.00	72.39	73.82	73.82
COA3	33.7	608.6	642.3	628.2	624.9	624.9	33.7	19.6	16.3	16.3	0.00	41.84	51.63	51.63	0.00	66.95	82.62	82.62
COA4	33.6	618.7	652.3	637.6	635.2	635.2	33.6	18.9	16.5	16.5	0.00	43.75	50.89	50.89	0.00	70.01	81.44	81.44
COA5	32.7	604	636.7	621.3	619.1	619.1	32.7	17.3	15.1	15.1	0.00	47.09	53.82	53.82	0.00	75.36	86.13	86.13
COA6	32.6	617.8	650.4	640.4	639.7	635.6	32.6	22.6	21.9	17.8	0.00	30.67	32.82	45.40	0.00	49.09	52.52	72.65
COA7	33.7	606.7	640.4	629.6	626.6	625.4	33.7	22.9	19.9	18.7	0.00	32.05	40.95	44.51	0.00	51.28	65.53	71.23
COA8	34.5	604.9	639.4	627.4	626.4	624.2	34.5	22.5	21.5	19.3	0.00	34.78	37.68	44.06	0.00	55.66	60.30	70.50
COA9	33.1	610.5	643.6	629.5	628	627.5	33.1	19	17.5	17	0.00	42.60	47.13	48.64	0.00	68.17	75.42	77.84
COA10	32.5	604.4	636.9	622.8	618.8	618.8	32.5	18.4	14.4	14.4	0.00	43.38	55.69	55.69	0.00	69.43	89.12	89.12
COA11	32.3	608.6	640.9	628.9	627.1	626	32.3	20.3	18.5	17.4	0.00	37.15	42.72	46.13	0.00	59.45	68.37	73.82
COA12	31.5	607.3	638.8	626.6	624.3	623.9	31.5	19.3	17	16.6	0.00	38.73	46.03	47.30	0.00	61.98	73.66	75.69
COA13	32.8	609.2	642	628.8	628.3	625.9	32.8	19.6	19.1	16.7	0.00	40.24	41.77	49.09	0.00	64.40	66.84	78.55

Table E.5 Result of Extent of Reduction for -180+106 µm of Ore Using “Sika Bukyia” Gas Furnace as Energy Source

Sample Name	Initial Weight (g)	Crucible Weight (g)	Crucible Weight + Sample Weight After Heating (g)				Sample Weight After Heating (g)				Percent Weight Loss (%)				Percent Reduction (%)			
			0	20	40	60	0	20	40	60	0	20	40	60	0	20	40	60
COB1	33.1	611.3	644.4	628.1	628.0	628.0	33.1	16.8	16.7	16.7	0.0	49.2	49.5	49.5	0.0	78.8	79.3	79.3
COB2	32.6	612.4	645.0	631.7	630.1	630.1	32.6	19.3	17.7	17.7	0.0	40.8	45.7	45.7	0.0	65.3	73.1	73.1
COB3	32.4	610.7	643.1	628.0	626.4	626.4	32.4	17.3	15.7	15.7	0.0	46.6	51.5	51.5	0.0	74.6	82.5	82.5
COB4	31.5	607.3	638.8	623.8	622.7	622.7	31.5	16.5	15.4	15.4	0.0	47.6	51.1	51.1	0.0	76.2	81.8	81.8
COB5	33.2	612.6	645.8	629.5	629.0	629.0	33.2	16.9	16.4	16.4	0.0	49.1	50.6	50.6	0.0	78.6	81.0	81.0
COB6	32.5	618.3	650.8	642.0	639.1	639.1	32.5	23.7	20.8	20.8	0.0	27.1	36.0	36.0	0.0	43.3	57.6	57.6
COB7	32.1	606.1	638.2	626.8	625.5	625.5	32.1	20.7	19.4	19.4	0.0	35.5	39.6	39.6	0.0	56.8	63.3	63.3
COB8	32.4	604.6	637.0	625.5	622.4	622.4	32.4	20.9	17.8	17.8	0.0	35.5	45.1	45.1	0.0	56.8	72.1	72.1
COB9	32.6	614.0	646.6	631.5	631.0	631.0	32.6	17.5	17.0	17.0	0.0	46.3	47.9	47.9	0.0	74.1	76.6	76.6
COB10	32.4	622.5	654.9	640.6	637.7	637.3	32.4	18.1	15.2	14.8	0.0	44.1	53.1	54.3	0.0	70.6	85.0	86.9
COB11	33.9	621.2	655.1	640.3	638.0	636.5	33.9	19.1	16.8	15.3	0.0	43.7	50.4	54.9	0.0	69.9	80.7	87.8
COB12	32.0	620.6	652.6	640.1	635.6	635.6	32.0	19.5	15.0	15.0	0.0	39.1	53.1	53.1	0.0	62.5	85.0	85.0
COB13	32.2	607.3	639.5	625.7	624.0	623.7	32.2	18.4	16.7	16.4	0.0	42.9	48.1	49.1	0.0	68.6	77.0	78.5

Table E.6 Result of Extent of Reduction for -106 µm of Ore Using “Sika Bukyia” Gas Furnace as Energy Source

Sample Name	Initial Weight (g)	Crucible Weight (g)	Crucible Weight + Sample Weight After Heating (g)				Sample Weight After Heating (g)				Percent Weight Loss (%)				Percent Reduction (%)			
			0	20	40	60	0	20	40	60	0	20	40	60	0	20	40	60
COC1	33.8	612.5	646.3	631.5	631.3	630.7	33.8	19	18.8	18.2	0.00	43.79	44.38	46.15	0.00	70.07	71.02	73.86
COC2	33.4	612.1	645.5	633.4	629.9	629.9	33.4	21.3	17.8	17.8	0.00	36.23	46.71	46.71	0.00	57.97	74.74	74.74
COC3	31.3	619.8	651.1	638.9	637.8	637.4	31.3	19.1	18	17.6	0.00	38.98	42.49	43.77	0.00	62.37	68.00	70.04
COC4	31.4	606.4	637.8	627.3	622.7	622.7	31.4	20.9	16.3	16.3	0.00	33.44	48.09	48.09	0.00	53.51	76.95	76.95
COC5	31.7	612.6	644.3	630.3	628.5	628.5	31.7	17.7	15.9	15.9	0.00	44.16	49.84	49.84	0.00	70.67	79.76	79.76
COC6	32.2	615.1	647.3	641.7	636.7	636.3	32.2	26.6	21.6	21.2	0.00	17.39	32.92	34.16	0.00	27.83	52.68	54.67
COC7	32.4	606.5	638.9	630.5	625.3	625.3	32.4	24	18.8	18.8	0.00	25.93	41.98	41.98	0.00	41.49	67.17	67.17
COC8	32.7	605.3	638	626.7	626.7	626.5	32.7	21.4	21.4	21.2	0.00	34.56	34.56	35.17	0.00	55.30	55.30	56.28
COC9	31.9	612.6	644.5	631.7	628.6	628.6	31.9	19.1	16	16	0.00	40.13	49.84	49.84	0.00	64.21	79.76	79.76
COC10	31	610.7	641.7	628.9	626.4	626.4	31	18.2	15.7	15.7	0.00	41.29	49.35	49.35	0.00	66.08	78.98	78.98
COC11	30.9	609.5	640.4	627.5	627.2	627.1	30.9	18	17.7	17.6	0.00	41.75	42.72	43.04	0.00	66.81	68.36	68.88
COC12	30.9	608.3	639.2	624.8	624.3	624.3	30.9	16.5	16	16	0.00	46.60	48.22	48.22	0.00	74.58	77.16	77.16
COC13	30.1	607.3	637.4	626.3	625.9	623.6	30.1	19	18.6	16.3	0.00	36.88	38.21	45.85	0.00	59.01	61.14	73.37

Table E.7 Result of Extent of Reduction for -250 µm Slag Material Using “Sika Bukyia” Gas Furnace as Energy Source

Sample Name	Initial Weight (g)	Crucible Weight (g)	Crucible Weight + Sample Weight After Heating (g)							Sample Weight After Heating (g)							Percent Weight Loss (%)							Percent Reduction (%)						
			0	10	20	30	40	50	60	0	10	20	30	40	50	60	0	10	20	30	40	50	60	0	10	20	30	40	50	60
MS1	32	219	251	241	239	239	239	239	239	32	22	20	20	20	20	20	0.00	31.25	37.50	37.50	37.50	37.50	37.50	0.00	50.01	60.01	60.01	60.01	60.01	60.01
MS2	32	473	505	501	494	492	492	492	492	32	28	21	19	19	19	19	0.00	12.50	34.38	40.63	40.63	40.63	40.63	0.00	20.00	55.01	65.01	65.01	65.01	65.01
MS3	32	388	420	412	408	408	408	408	408	32	24	20	20	20	20	20	0.00	25.00	37.50	37.50	37.50	37.50	37.50	0.00	40.01	60.01	60.01	60.01	60.01	60.01
MS4	31	474	505	501	494	494	494	494	494	31	27	20	20	20	20	20	0.00	12.90	35.48	35.48	35.48	35.48	35.48	0.00	20.65	56.78	56.78	56.78	56.78	56.78
MS5	32	230	262	252	251	251	251	251	251	32	22	21	21	21	21	21	0.00	31.25	34.38	34.38	34.38	34.38	34.38	0.00	50.01	55.01	55.01	55.01	55.01	55.01
MS6	32	364	396	382	377	377	377	377	377	32	18	13	13	13	13	13	0.00	43.75	59.38	59.38	59.38	59.38	59.38	0.00	70.01	95.02	95.02	95.02	95.02	95.02
MS7	33	447	480	470	468	468	468	468	468	33	23	21	21	21	21	21	0.00	30.30	36.36	36.36	36.36	36.36	36.36	0.00	48.49	58.19	58.19	58.19	58.19	58.19
MS8	32	422	454	437	432	432	432	432	432	32	15	10	10	10	10	10	0.00	53.13	68.75	68.75	68.75	68.75	68.75	0.00	85.01	110.02	110.02	110.02	110.02	110.02
MS9	32	443	475	470	465	465	465	465	465	32	27	22	22	22	22	22	0.00	15.63	31.25	31.25	31.25	31.25	31.25	0.00	25.00	50.01	50.01	50.01	50.01	50.01
MS10	32	289	321	310	310	310	310	310	310	32	21	21	21	21	21	21	0.00	34.38	34.38	34.38	34.38	34.38	34.38	0.00	55.01	55.01	55.01	55.01	55.01	55.01
MS11	32	378	410	399	396	396	396	396	396	32	21	18	18	18	18	18	0.00	34.38	43.75	43.75	43.75	43.75	43.75	0.00	55.01	70.01	70.01	70.01	70.01	70.01
MS12	32	401	433	421	421	421	421	421	421	32	20	20	20	20	20	20	0.00	37.50	37.50	37.50	37.50	37.50	37.50	0.00	60.01	60.01	60.01	60.01	60.01	60.01
MS13	32	463	495	481	481	481	481	481	481	32	18	18	18	18	18	18	0.00	43.75	43.75	43.75	43.75	43.75	43.75	0.00	70.01	70.01	70.01	70.01	70.01	70.01

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