Characterisation of Muko Iron Ores (Uganda) for the Different Routes of Iron Production

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Cover picture:
LOM picture showing the microstructure of Rushekye iron ore sample. Mainly grey crystalline platy structure with some area of fibrous texture. Dark impurity inclusions located between crystalline plates and have a chaotic arrangement in the ore matrix.

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© Abraham JB Muwanguzi
Ekitibwa kidde eri Yesu

To Sarah my wife
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Abstract

Iron and its products, especially the various forms of steel, have been and still are a vital material in many sectors of life. It is utilized in many industrial activities ranging from production of heavy duty mechanical equipment to light electrical appliances and home appliances. With the world’s iron ore consumption estimated to stand at 1.3 billion tonnes by 2025, exploitation of any existing natural deposits is of increasing importance to meet the demands of the expanding world economy.

Large deposits of iron ore exist in Uganda in the eastern (Tororo) regions and south-western (Kisoro-Kabale) regions of the country. The ore deposits of Kisoro-Kabale consist of an iron-rich hematite grade with less deleterious impurities as compared to that of Tororo. Prospective quantification puts the deposits at 30-50 million tonnes of raw-ore reserves. To date the deposits lay unexploited, with small holder black smith activities taking place in the area.

This work involves understanding the occurrence, quantity and quality of the ore plus its properties and characteristics in a bid to pave way for its exploitation for economic use in Uganda and beyond. Characterisation was done on the samples collected from the deposits, to establish its physical, chemical and metallurgical properties. Literature detailing the natural occurrence of the deposits plus the genesis of the parent rocks and ore and the prospective tonnage is included. The economic situation in Uganda as far as demand and consumption of iron and steel is concerned is also briefly highlighted.

The chemical, physical and metallurgical characteristics that could facilitate the initial exploitation of the ore are examined with conclusive results from the representative samples examined. The results present Muko ore as a high grade of hematite with an Fe content averaging 68%. The gangue content (SiO$_2$+Al$_2$O$_3$) of 5 of the 6 samples investigated is $<4\%$, which is within the tolerable limits for the dominant iron production processes, with its S and P contents being $<0.1\%$ and $0.07\%$ respectively. Thus, Muko iron ore can be reduced in the furnace without presenting major difficulties. With respect to mechanical properties, Muko ore was found to have a Tumble Index value $>85\ wt\%$, an Abrasion Index value $<4\ wt\%$ and a Shatter Index value $<2.5\ wt\%$. This implies that the ore holds its form during the processes of mining, transportation, screening and descent when loaded in the furnace for reduction. Its reducibility index was found to be $0.868%/min$. This is well within the desired reduction limits for the major iron reduction processes. It implies that a high productivity (in terms of iron reduced) can be realised in the reduction processes in a given period of time.

Muko iron ore was found to meet most of the feed raw material requirements (physical, chemical and metallurgical) for the blast furnace and the major direct reduction processes (Midrex, HYL III and SL/RN). Furthermore, for those desired for sinter and pellet making. It can thus serve well as a feed raw material for smelting reduction and direct reduction processes.
Keywords: iron ore, iron, characterization, physical and metallurgical properties, sinter, pellet, blast furnace, direct reduction, Muko, Uganda
Preface

The biggest part of this work was carried out at the Department of Material Science and Engineering, Royal Institute of Technology, Sweden. Other experiments were carried out at KIMAB, NILAB and Luleå University all in Sweden, Geological Survey and Mines Department, Entebbe and Faculty of Technology, Makerere University Kampala, in Uganda.

This thesis deals with the iron ore that naturally occurs in the south-western part of Uganda, in East Africa. It investigates the characteristics of the ore in order to understand its response to processing conditions, from handling, transportation, to loading into the furnace for reduction and during the reduction process to iron. The thesis is made up of the following supplements:

**Supplement 1:** “State-of-the-Art Paper on the Exploitation of Uganda’s Iron Ore for the Manufacture of Iron and Steel in Uganda”, Internal Report No. ISRN KTH/MSE-09/14-SE+MEK/TR, at KTH, Abraham J.B Muwanguzi\textsuperscript{a,b}, Ragnhild E. Aune\textsuperscript{b}, Stefan Jonsson\textsuperscript{b}, Joseph K. Byaruhanga\textsuperscript{a}

Covers literature on; iron ore occurrences, qualities, characterisation methods, mechanical processing, thermodynamic and thermophysical properties and metallurgical extraction. The paper includes a section about the iron ore deposits occurring in Uganda and the current situation of the iron and steel industry in Uganda.

**Supplement 2:** “Characterisation of Chemical Composition and Microstructure of Raw Iron Ore from Muko Deposits in Uganda”, Manuscript submitted to the Journal of Mineral Processing and Extractive Metallurgy, ISRN KTH/MSE--10/36--SE+APRMETU/TR Abraham J. B. Muwanguzi\textsuperscript{a,b}, Andrey V. Karasev\textsuperscript{a}, Joseph K. Byaruhanga\textsuperscript{b} and Pär G. Jönsson\textsuperscript{a}

This is based on the characterisation of the iron ore from the 6 hills in Muko, Uganda, including; morphology by SEM, chemical analysis, and mineralogical analysis by XRD. The ores characteristics are compared with those of ores from the major iron ore producing nations and to world market standards to ascertain its potential for global exploitation.

**Supplement 3:** “Characterisation of the Physical and Chemical Properties of Muko Iron Ore for Iron Production”, Manuscript Ready for Submission to an International Journal, Abraham J. B. Muwanguzi\textsuperscript{a,b}, Andrey V. Karasev\textsuperscript{a}, Joseph K. Byaruhanga\textsuperscript{b} and Pär G. Jönsson\textsuperscript{a}

The physical and metallurgical properties of the ore were assessed in relation to meeting the raw material feed requirements for furnace reduction.

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Acknowledgement

I thank the Swedish Government under Sida together with Makerere University for sponsoring this research work.

I express my gratitude to my supervisors; Assoc. Prof. Andrey V. Karasev and Prof. Pär G. Jonsson for taking me on when I seemed to have lost my way and giving me new direction and counsel and supporting me to complete this degree and renewing my hope. My appreciation goes to my Ugandan supervisor and coordinator, Assoc. Prof. J.K Byaruhanga for sharing his knowledge and experience and supporting me during the course of my study and work. I wish to thank my coordinator on the Swedish side, Prof. Stefan Jonsson for all the support and assistance during my study period.

I wish to thank all the people who assisted me in this research work. I appreciate my colleague Dr. P.W Olupot for the orientation and guidance he gave me during the period of joining the study programme and through the time of compiling my research work.

I want to thank and appreciate my family; Mr. G.W Ssemukaaya my father, Mrs. Tereza W. Ssemukaaya my mother and all my siblings; Immaculate, Josephine, Margaret, Ann, Kizito, Catherine and Jane, plus my big brothers Jim and Moses for their support and encouragement in the time of my study and for their confidence in me. I am so proud of you all!

I am grateful to Dr. Martin and Mrs. Tracy Ssempa for their love and support and encouragement to pursue greater heights as a world class leader. Their support and that from the family of MCC has enabled me to reach levels like this one, which I never aimed for before. I thank the community of SCCC in Sweden, for all the assistance; accommodation, financial, and otherwise, every time that I was in Sweden with my family for my studies.

My heartfelt appreciation goes to my beloved wife Sarah for her invaluable support, care, love, counsel, and encouragement especially during the times when everything seemed impossible. She always renewed my strength and went to great length in supporting me and keeping me accountable to completing my studies on time. To all our children for standing with us through the study period mostly when we were away from home, and special gratitude to Shaina who even had to endure the cold winters in order to encourage me complete this research.

Finally, to my Lord Jesus Christ for the grace and strength He gave me to go through my study period and carry out all the necessary research and finish this thesis. Without this, I wouldn’t have been able to go through the tough times that came my way. May He reward all those who supported me in my research work.

Abraham JB Muwanguzi
Stockholm, September 2010
1.0 Introduction

1.1 Background to the research

Uganda is a landlocked country located in East Africa. It’s endowed with a variety of natural resources among which is iron ore. Large deposits of iron ore exist in Uganda in the eastern (Tororo) and south-western (Kisoro-Kabale) regions of the country, Figure 1. The occurrence in Tororo is in the places known as Sukulu and Bukusu, and are estimated to be in the order of 50 million tonnes of raw ore reserve at a grade of 55% Fe with a titanium oxide content of 1.6%. In Kabale and Kisoro, the deposits occur in Muko area, covering six hills in the two districts. The estimated reserve is between 30-50 million tonnes at a grade of 68% Fe. The silica content is about 6% with negligible quantities of phosphorus, sulphur and titanium. This makes Muko ore more suitable for processing than the Tororo ore.

Currently, the iron and steel making industry in the country has not yet developed to the level of meeting the demand for these products. The combined production capacity is about 72,000 tonnes per annum, with demand standing at more than double this amount. Most of the big players in the industry depend on imports of raw materials from other countries. According to the Uganda Bureau of Statistics, the import value of iron and steel products has been on an upward trend since 2003, Table 1. In 2008, the imports of iron and steel ranked third at 6.84% among the total imports into the country, after petroleum and petrol products (18.50%) and road vehicles (7.48%). The export value is not corresponding to the import value, Table 2, and this represents a trade deficit for the nation.

Table 1: Imports of Iron and Steel into Uganda by Value (‘000 US$)

<table>
<thead>
<tr>
<th>Trade Item</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron &amp; Steel</td>
<td>77,755</td>
<td>96,019</td>
<td>118,823</td>
<td>141,632</td>
<td>173,423</td>
<td>309,514</td>
</tr>
<tr>
<td>Non-ferrous metals</td>
<td>7,077</td>
<td>12,522</td>
<td>12,937</td>
<td>16,210</td>
<td>22,948</td>
<td>25,765</td>
</tr>
</tbody>
</table>
Table 2: Uganda’s exports of Iron and Steel by Value (‘000 US$)

<table>
<thead>
<tr>
<th>Trade Item</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron &amp; Steel</td>
<td>10,229</td>
<td>16,934</td>
<td>29,698</td>
<td>31,325</td>
<td>62,637</td>
<td>102,593</td>
</tr>
<tr>
<td>Non-ferrous metals</td>
<td>121</td>
<td>307</td>
<td>261</td>
<td>135</td>
<td>4,117</td>
<td>4,078</td>
</tr>
</tbody>
</table>

Figure 1. Map of Uganda showing the occurrence of iron ore deposits

Sukulu and Bukusu iron ore deposits in Tororo district

Muko iron ore deposits in Kabale and Kisoro districts
Worldwide, iron ore consumption for steelmaking was standing at 850 million tonnes at the end of the twentieth century and was estimated to reach more than 1.3 billion tonnes over the first quarter of the twenty-first century. Two thirds of steel is produced using virgin iron ore and entails an intermediate product called “pig iron”. The remaining one third of steel is produced through the recycling of scrap metal and direct reduction processes.

The world crude steel production was 1.3 billion tonnes in 2008. Statistics from the World Steel Association show that at the end of 2009, the world steel production was standing at about 1.1 billion tonnes.

Acquisition of a more reliable and stable source of supply for iron and steel will boost Uganda’s economic growth and at the same time contribute to the world iron and steel industry. This study thus aims at investigating Muko iron ore’s physical, chemical and metallurgical properties, in order to analyse the ore’s potential in serving as a reliable base raw material for an iron production.

1.2 Occurrence of Iron

In 2004, Ruth noted that, “since the construction of the great Iron Bridge in England during the 1970s, the use of iron and steel based products has come to be associated with the industrialisation of economies. Iron and steel are among the least expensive and most widely used metals to this day”. Iron and steel are used in such diverse applications as railroads and skyscrapers, automobiles and other durable consumer products, as well as many infrastructure systems of modern society. Iron, at 5% of the earth’s crust, is the second most abundant metal after aluminium and the fourth most abundant element in the surface of the earth. It is made from ores by removing oxygen and impurities from the iron oxides in ores. Chemical reaction is achieved with the help of coke, lime or other reduction agents.

A number of naturally occurring minerals contain iron and some are rich enough in iron to be classed as ores. The most commonly used iron-bearing minerals contain iron compounds as
hematite ($\text{Fe}_2\text{O}_3$, 70% Fe); magnetite ($\text{Fe}_3\text{O}_4$, 72.4% Fe) and of much less importance are limonite ($2\text{Fe}_2\text{O}_3.3\text{H}_2\text{O}$, 60% Fe); siderite ($\text{FeCO}_3$, 48.3% Fe); and pyrite ($\text{FeS}_2$, 46.6% Fe). These iron percentages are in their pure states and in ores the iron content is lowered according to the amount of impurities present.

1.3 Main routes of iron ore application for ironmaking

Today, iron is produced from raw iron ore through various reduction processes. Currently, the main routes for application of the natural iron ores for ironmaking are in three categories. Firstly is the use of high-grade natural iron ores as a part or a complete charge for blast furnace processes. Secondly, these types of ores are also used as a part or a complete charge for direct reduction processes. Thirdly, is the sintering of grind ed and enriched natural iron ores for the production of sinters and pellets. These can either be used in the blast furnace or direct reduction furnaces.

Blast furnace (BF) iron reduction involves raising the ore’s temperature above the melting point of iron. Reaction with a reducing agent then produces molten iron; the impurities being removed by a fluxing agent. Other than iron oxide, there are a number of raw materials used in the blast furnace but the main and common ones are metallurgical coke and limestone. Coke serves as the reducing agent and at the same time provides the necessary heat for the reduction reactions, while limestone acts as the fluxing agent.

Direct reduction of iron (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. The DRI processes can be classified into three major categories:

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

DRI processes have more strict feed-composition requirements than the BF process. In addition, DRI remains favourable in places where there is an abundance of natural gas. 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. 20-22 The Midrex process contributes the biggest share of the DRI produced, which corresponds to about 60% of the world production. 17-19

There are specific requirements for the raw material burden for the various iron production methods. These dictate material behaviour during transportation (physical properties), and most importantly during metallurgical treatment either in the blast furnace or direct reduction plants (metallurgical properties).

The main purpose of this study is to determine the quality of the natural iron ores from the different deposits of Muko and establish the possible prospects of using these ores for iron production. Based on the analysis of its composition and properties, it is possible to determine whether it can appropriately serve as a raw material for iron production using the production methods described above.

**Figure 2** highlights the general steps of this research work, including the correlation of the Supplements applied in this Thesis. Major characteristics (such as chemical composition, physical and metallurgical properties) were investigated in raw iron ores from the different deposits of Muko and compared with world market standards and those of iron ores from other countries. This study can facilitate the decision of selecting the best route for a particular ore type from Muko deposits.
Figure 2. General steps of this research work, including the correlation between the Supplements applied in this Thesis
2.0 Characterisation performed on Muko iron ore

Characterization of the iron oxides is important before the production of iron and steel starts in order to ascertain the properties and characteristics of the material that is being worked on i.e ore. The characteristics of a material are those parameters that specify the chemical and physical aspects of its composition and structure while the properties are its responses to changes in the physical or chemical environment. This aids in understanding the behaviour of the ore when subjected to the various production conditions, and also when it comes in contact with the raw materials used in iron production; metallurgical coke or gas and limestone. This is not only important in beneficiation, but enables the simulation/modeling of a production system that can be used to predict the behaviour of the iron ore during production.

The description of the experimental procedure of the tests carried out is given below with more technical description given in the appended papers:

Iron Ore Composition was determined using the means described below. For chemical and mineralogical analysis, the samples were crushed with a hand hammer and then ground to smaller particles with an electric grinder for about 1 minute. An appropriate amount of sieve passage below 100 µm was used.

- Chemical Analysis
- Mineralogical Analysis by XRD using a Phillips X-ray diffractometer. It was operated at a scan speed of 0.5 with increments of 0.02° from 20° to 80° 20 range. The data was retrieved from the computer and plots of the diffractions made
- Micro structural Analysis using a Field Emission Gun Scanning Electron Microscope (FEG-SEM). Small pieces from each hill-sample were put in bakelite and silica polished and then observed under the microscope at different magnifications of 50x, 100x, 200x, and 500x.
Mechanical Properties: were determined by evaluating the following parameters:

- Tumble Index (TI) and Abrasion Index (AI) were determined by tumbling a 15 kg iron ore lump in a circular drum rotating at 25rpm for 200 revolutions. This was done three times on three different blocks. The ore particles were screened and average values of the fractions + 6.3mm and -0.5 mm gave the TI and AI values respectively.

- Shatter Index was determined by dropping a 10kg dried lump iron ore sample onto a cast iron floor (0.5m x0.5m x 0.03m) from a height of 2m. The lump was dropped four times from this height and the wt% passing a 5mm sieve was established. Four different lumps were used and the average value of these gave the Shatter Index value.

- Porosity was determined using the GeoPyc 1360 pycnometer. A quantity of helium was placed in the sample chamber and its volume was measured. 2.0g iron ore piece was then placed in the chamber together with the helium gas and the equipment reported the new volume values. The differences in the new volume and original helium volume give the sample’s envelope and skeletal volumes (the equipment reports both). The difference in the envelope and skeletal volumes indicates the percentage porosity of the sample.

- Particle Size Distribution using the sieve shaker AS 200 tap, with the 3.5mm sieve as the biggest size. The sample lumps were crushed in a jaw crusher and 2kg of the particle sizes below 4.0mm were sieved in the sieve shaker.

Metallurgical Properties were evaluated through:

- Thermo-analysis using the Thermogravimetry –Differential Thermal Analysis – Mass Spectrometry (TGA and DTA) with a Netzsch STA 409 operated in an argon atmosphere. An appropriate amount of particles below 100μm was put in an alumina crucible and placed on a balance in one side of the equipment’s heating chamber. It was balance by the same amount of an inert element in a similar alumina crucible. The temperatures were set on a computer with 20°C as a minimum and 1450°C as the maximum. Argon gas was released to flow over the samples and heating was
performed at a constant rate of 10°C min⁻¹. The temperature difference and thermo
effects were recorded on the computer. The plots of the sample behaviour (weight loss
and transformations) were also recorded on the computer.

- Reducibility was estimated using the using the Netzsch STA 409. Argon gas was first
released into the system and when the temperature reached 950°C, CO gas was
introduced into the system. In addition, the sample’s weight reduction were observed
and recorded on the computer.

3.0 Results and Discussion

The samples from the six hills of Muko deposits (Uganda) are designated in this study as Ug1 – Rushekye (a), Ug2 – Kamena (b), Ug3 – Kyanyamuzinda (c), Ug4 – Nyamiyaga (d), Ug5 – Butare (e) and Ug6 – Kashenyi (f).

3.1. Chemical composition and microstructure

Muko ore was found to be a rich hematite grade with small percentages of such impurities as SiO₂, Al₂O₃, P and S. The analysis results of the full chemical compositions for natural iron ores from the different deposits of Muko are given in Table 3. It can be seen that the main impurities in the ore are silica and alumina, with content for Ug1-Ug5 samples ranging from 0.4% to 1.2% and from 0.4 to 1.0% respectively. In all these samples, the hematite content is above 96%. The Ug6 sample exhibits a lower hematite content (86.7% Fe₂O₃) and higher gangue contents (5.1% SiO₂ and 6.0% Al₂O₃) than the other samples.

In order to assess its potential for worldwide commercial exploitation, the chemical composition of Muko natural iron ores was compared to iron ores from 5 of the world’s major iron ore producing nations and to world market standards for iron ores, Table 4. According to the Fe content, the iron ores in the World are classified as low- (< 58% Fe), medium- (60-64% Fe) and high-grade (> 65% Fe). Thus, considering both Fe and gangue contents, it can be concluded that the quality of most Muko iron ores (Ug1-Ug5) is comparable with the best
exported iron ores from Brazil and corresponds to the World high-grade hematite ores. The iron ore from Kashenyi deposit (Ug6 sample) corresponds to the medium-grade iron ore (about 61% Fe) though its gangue content (5% SiO₂ and 6% Al₂O₃) is above the recommended limit. 21-23

Table 3: Chemical Composition of Muko Iron Ore

<table>
<thead>
<tr>
<th>Ore Mine Marking</th>
<th>Ug 1</th>
<th>Ug 2</th>
<th>Ug 3</th>
<th>Ug 4</th>
<th>Ug 5</th>
<th>Ug 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rushekye a</td>
<td>0.26</td>
<td>0.82</td>
<td>0.26</td>
<td>0.10</td>
<td>0.33</td>
<td>0.46</td>
</tr>
<tr>
<td>Kamena b</td>
<td>97.8</td>
<td>97.2</td>
<td>98.3</td>
<td>98.7</td>
<td>96.6</td>
<td>86.7</td>
</tr>
<tr>
<td>Kyanyanuzinda c</td>
<td>0.96</td>
<td>0.80</td>
<td>0.41</td>
<td>0.62</td>
<td>1.20</td>
<td>5.10</td>
</tr>
<tr>
<td>Nyamiyaga e</td>
<td>0.58</td>
<td>0.65</td>
<td>0.35</td>
<td>0.43</td>
<td>1.00</td>
<td>6.00</td>
</tr>
<tr>
<td>Butare f</td>
<td>&lt;0.001</td>
<td>0.002</td>
<td>0.006</td>
<td>0.001</td>
<td>&lt;0.001</td>
<td>0.003</td>
</tr>
<tr>
<td>Kashenyi d</td>
<td>&lt;0.001</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

The contents of Fe and gangue (SiO₂ and Al₂O₃) in Muko natural iron ores were compared to the recommended ranges for commercial iron ores and the different iron reduction methods, Figure 3. It can be seen that most of Muko iron ore samples (Ug1-Ug5) fulfil the requirements for raw iron ores for the blast furnace process and all the direct reduction methods. The natural iron ore from Kashenyi deposit (Ug6 sample) can be used as a raw material for production of pellets and sinters without limitation or as some part of charge with other high-grade iron ores (Ug1-Ug5 samples) for BF or DRI processes.

It should also be pointed out that the contents of deleterious elements such as P (0.001-0.006%) and S (0.02-0.05%) in all Muko iron ores are significantly lower in
comparison with the acceptable world commercial level (< 0.07% P and < 0.1% S) \(^{21-24}\) for raw iron ores. Apart from the recommended commercial limits, the different iron production methods (BF and DRI) have strict limits for S and P contents, which depend on the production process and desired output quality. The commercial limits for S and P contents and those for the different iron production processes are highlighted in Figure 4. It is apparent that most of Muko iron ores (Ug1-Ug4, Ug6) can be used directly in BF and DRI processes based on the S and P content. The natural iron ore from Butare deposit (Ug5 sample) can also be used directly in BF and most DRI processes, except the SL/RN process.

Table 4: Complete chemical composition of iron ores from different nations

<table>
<thead>
<tr>
<th>Ore</th>
<th>Mine</th>
<th>Nation</th>
<th>Chemical composition, mass%</th>
<th>Ore</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total Fe</td>
<td>SiO(_2)</td>
<td>Al(_2)O(_3)</td>
</tr>
<tr>
<td>B1</td>
<td>Itabira</td>
<td>Brazil</td>
<td>68.9</td>
<td>0.35</td>
<td>0.60</td>
</tr>
<tr>
<td>B2</td>
<td>MBR</td>
<td>Brazil</td>
<td>67.3</td>
<td>0.79</td>
<td>0.72</td>
</tr>
<tr>
<td>B3</td>
<td>Carajas</td>
<td>Brazil</td>
<td>65.4</td>
<td>1.00</td>
<td>1.05</td>
</tr>
<tr>
<td>C1</td>
<td>Nanfen</td>
<td>China</td>
<td>63.4</td>
<td>6.28</td>
<td>1.17</td>
</tr>
<tr>
<td>A1</td>
<td>Goldsworthy</td>
<td>Australia</td>
<td>63.2</td>
<td>4.90</td>
<td>1.60</td>
</tr>
<tr>
<td>A2</td>
<td>Hammersley</td>
<td>Australia</td>
<td>62.7</td>
<td>4.20</td>
<td>2.73</td>
</tr>
<tr>
<td>A3</td>
<td>Irvine Island</td>
<td>Australia</td>
<td>54.4</td>
<td>21.3</td>
<td>0.23</td>
</tr>
<tr>
<td>I1</td>
<td>Goa</td>
<td>India</td>
<td>57.8</td>
<td>2.50</td>
<td>6.50</td>
</tr>
<tr>
<td>I2</td>
<td>Donimalai</td>
<td>India</td>
<td>63.5</td>
<td>3.00</td>
<td>3.00</td>
</tr>
<tr>
<td>I3</td>
<td>Bailadila</td>
<td>India</td>
<td>64.0</td>
<td>2.50</td>
<td>2.50</td>
</tr>
<tr>
<td>R1</td>
<td>Bakal</td>
<td>Russia</td>
<td>60.7</td>
<td>2.40</td>
<td>2.00</td>
</tr>
<tr>
<td>R2</td>
<td>Tula</td>
<td>Russia</td>
<td>52.2</td>
<td>10.10</td>
<td>1.25</td>
</tr>
<tr>
<td>U1</td>
<td>Mesabi</td>
<td>USA</td>
<td>57.5</td>
<td>10.10</td>
<td>0.70</td>
</tr>
<tr>
<td>U2</td>
<td>Minnesota</td>
<td>USA</td>
<td>54.3</td>
<td>6.80</td>
<td>0.40</td>
</tr>
<tr>
<td>U3</td>
<td>Reserve Pellet</td>
<td>USA</td>
<td>63.0</td>
<td>8.10</td>
<td>0.40</td>
</tr>
<tr>
<td>Ug 1</td>
<td>Rushekye</td>
<td>Uganda</td>
<td>68.4</td>
<td>0.96</td>
<td>0.58</td>
</tr>
<tr>
<td>Ug 2</td>
<td>Kamena</td>
<td>Uganda</td>
<td>67.9</td>
<td>0.80</td>
<td>0.65</td>
</tr>
<tr>
<td>Ug 3</td>
<td>Kyanyanuzinda</td>
<td>Uganda</td>
<td>68.7</td>
<td>0.41</td>
<td>0.35</td>
</tr>
<tr>
<td>Ug 4</td>
<td>Nyamiyaga</td>
<td>Uganda</td>
<td>69.0</td>
<td>0.62</td>
<td>0.43</td>
</tr>
<tr>
<td>Ug 5</td>
<td>Butare</td>
<td>Uganda</td>
<td>67.5</td>
<td>1.20</td>
<td>1.00</td>
</tr>
<tr>
<td>Ug 6</td>
<td>Kashenyi</td>
<td>Uganda</td>
<td>60.6</td>
<td>5.10</td>
<td>6.00</td>
</tr>
</tbody>
</table>

*: H, M and L are the high-, medium- and low-grade iron ores, respectively;
ps – present study
Figure 3. Recommended ranges for Fe and gangue content for commercial iron ores and the different iron production methods

Figure 4. Recommended percentage ranges for P and S contents for commercial iron ores and the various iron production processes
Although the chemical composition of iron ores from the different deposits of Muko is almost similar, Ug1-Ug6 samples have varying microstructures in terms of grain size, texture and inclusion distribution within the hematite matrix. Typical shapes of microstructure are shown in Table 5. It was found that the ore samples Ug3 (c) and Ug4 (e) exhibit generally the Type1 (almost pure grey hematite matrix with little amounts of small size dark inclusions) microstructures with a relatively low number of impurity inclusions. They also exhibit Type 2 (mainly a grey crystalline platy structure with some area of fibrous texture, the dark impurity inclusions are located between crystalline plates and have a chaotic arrangement in the ore matrix). As a result, these samples have highest Fe content (68.7 and 69.0%, respectively) and lowest gangue content (0.76 and 1.05%, respectively). The microstructures of Ug 1 (a) and Ug2 (b) samples exhibit mostly Type 3 (very fine grey crystalline platy structure with approximately the same direction of neighbouring crystalline plates) and Type 4 (mainly the granular structure with a grain size in the ranges from 10 to 90 µm) structures. The ore samples Ug5 (f) and Ug6 (d) have relatively large area with Type 5 (largest irregular structure with grain size from 30 to 350 µm) and Type 6 (layer shaped structure with length of grains and dark impurity inclusions > 500 µm) microstructure. Larger inclusions are also found located in the grain boundaries and within the grains. These samples, and particularly Ug6 sample from Kasheniyi hill, have the highest gangue content (2.2 and 11.1% for Ug5 and Ug6, respectively). The impurities were mainly those of Si, Al and K in varying percentages in the different samples. The differences in the micro-structure may be explained by the different natural conditions that prevailed on the different hills of Muko during the ore formation.

Mineralogically, the chemical species observed in their decreasing order were $\alpha$-Fe$_2$O$_3$, $\gamma$-Fe$_2$O$_3$, and Fe$_3$O$_4$. The $\alpha$-Fe$_2$O$_3$ was the major phase observed in all XRD scans. More specifically, the main peaks where appearing at 20 of 33°; 36° and 56° for Cu-K$_a$ radiation. Therefore, all observed samples of Muko iron ores are mainly of a hematitic nature.
<table>
<thead>
<tr>
<th>Ore samples</th>
<th>Ug 4 (e)</th>
<th>Ug 3 (c)</th>
<th>Ug 1 (a)</th>
<th>Ug 2 (b)</th>
<th>Ug 5 (f)</th>
<th>Ug 6 (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Fe Content, mass%</td>
<td>69.0</td>
<td>68.7</td>
<td>68.4</td>
<td>67.9</td>
<td>67.5</td>
<td>60.6</td>
</tr>
</tbody>
</table>

**Microstructure:**

**Type 1**

![Type 1 Microstructure Image]

many       many       few

**Type 2**

![Type 2 Microstructure Image]

many       many       some       few

**Type 3**

![Type 3 Microstructure Image]

few       few       many       some       some

**Type 4**

![Type 4 Microstructure Image]

many       few       Some
3.2. Physical properties

The physical 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 furnace.

The cold strength tests such as tumbler and shatter tests were carried out for the different Muko iron ores. The obtained results for the Tumble Index (TI, wt% of +6.3 mm), the Abrasion Index (AI, wt% of -0.5 mm) and the Shatter Index (wt% of -5.0 mm) are given in Table 6. The Tumbler Index of Muko ores was found to lie between 88 and 93 wt%. Furthermore, the Abrasion Index was found to be between 0.54 to 3.41 wt%. A comparison of the TI and AI values obtained for Muko iron ores with the physical requirements for the lump iron ores used for blast furnace and direct reduction processes is shown in Figure 5. The recommended values of TI and AI values for the blast furnace feed material is >70 wt% and <5 wt%, respectively. It is apparent that the TI and AI values for all Muko iron ores lie...
within these limits. This implies that all Muko iron ores can be handled, loaded and transported without disintegration to small particles and formation of dust. In addition, it can be seen from Figure 5 that all Muko iron ores can be used for the different processes of direct reduction of iron. Only samples Ug1, Ug2 and Ug6 the HYL III process standard due to the lower TI values in comparison with the accepted level (≥ 90 wt%).

Table 6: Physical Properties of Muko Iron Ores

<table>
<thead>
<tr>
<th>Iron ore, deposit</th>
<th>Tumble Index (wt% of +6.3 mm)</th>
<th>Abrasion Index (wt% of -0.5 mm)</th>
<th>Shatter Index (wt% of -5.0 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ug1, Rushekye</td>
<td>89.72</td>
<td>0.83</td>
<td>1.17</td>
</tr>
<tr>
<td>Ug2, Kamena</td>
<td>88.45</td>
<td>1.50</td>
<td>1.21</td>
</tr>
<tr>
<td>Ug3, Kyanyamuzinda</td>
<td>91.68</td>
<td>0.54</td>
<td>0.57</td>
</tr>
<tr>
<td>Ug4, Nyamiyaga</td>
<td>90.39</td>
<td>0.88</td>
<td>1.31</td>
</tr>
<tr>
<td>Ug5, Butare</td>
<td>92.96</td>
<td>3.41</td>
<td>2.01</td>
</tr>
<tr>
<td>Ug6, Kashenyi</td>
<td>89.28</td>
<td>0.67</td>
<td>1.45</td>
</tr>
</tbody>
</table>

The Shatter Index for Muko iron ores was found to lie between 0.57 and 2.01% (Table 6). These values are similar to those for iron ores from ten different mines from Orissa in India (0.68-1.80 wt%). Moreover, it should be mentioned that the preferred Shatter Index value for iron ore for coal-based direct reduction methods is < 5 wt% and for the DRI Midrex process it is < 10 wt%. Thus, Muko iron ore meets the Shatter Index requirements for these iron production processes.

3.3. Metallurgical properties

The metallurgical properties such as those realised by thermo-analysis and reducibility test experiments can clarify the behaviour of raw materials during heating and reduction processes. Thus, Thermo-analysis, TG-DTA, was performed on natural iron ore samples from the
different deposits of Muko to investigate its behaviour when subject to reducing temperatures.

![Diagram](image)

**Figure 5.** Comparison of physical properties of raw iron ores from Muko deposits to physical requirements for lump ores used for blast furnace (BF) and direct reduction (Midrex, HYL III and SL/RN) processes

The obtained thermo-grams are given in Figure 6. It can be seen that a small weight reduction was observed in all the samples below 200°C. This was due to the loss of the physically combined water from the ore samples. The further reduction of sample weight in the temperature range between 200°C and 450°C occurs due to the decomposition of hydrates, equation 1, and the dehydroxylation reaction of goethite to hematite, (equation 2). Also, the value of endothermal effect of this process increases with increased value of the mass change in this temperature interval.

\[
2OH^- \xrightarrow{\text{heat}} O^2^- + H_2O \tag{1}
\]

\[
2\alpha - FeOOH \xrightarrow{\text{heat}} \alpha - Fe_3O_4 + H_2O \tag{2}
\]

Furthermore, an additional endothermal reaction was observed in samples Ug1-5 in the
temperature interval 365-632°C. This phenomenon can be explained by the transformation of

γ-hematite to α-hematite in these iron ore samples. The Ug3 and Ug2 samples have the biggest values (1076J/g and 929J/g, respectively) of the absorption energy (Peak 1). The Ug4 (745J/g) and Ug5 (505J/g) samples showed medium peaks. Furthermore, the smallest peak (454J/g) was
detected in the Ug1 sample. The absence of the $\gamma$-$\alpha$ hematite phase transition in the Ug6 sample may be due to the larger content of chemically bonded water (goethite and Fe$_2$O$_3$ hydrate), which when driven off leaves only $\alpha$-hematite. This statement is confirmed by the highest value of weight loss (1.57%) in the Ug6 sample below 800°C among all studied samples.

The total energy requirements for heating up each sample up to 1100°C were also estimated by calculating the endothermal effect. It was found that Ug6 and Ug5 iron ore samples, which have a broader size range of irregular grains (~30 to >500 µm) as well as the biggest inclusions had the largest values of endothermal effect (5.57 and 4.98 mW/mg, respectively). The other samples exhibited endothermal effects of (mW/mg): Ug1 – 3.27; Ug2 – 3.95; Ug3 – 4.09; and Ug4 – 4.98. Therefore, it may be safely suggested that the energy consumption for heating of Muko iron ores up to 1100°C increases in the samples in the following order Ug1 < (Ug2, Ug3, Ug4) < Ug5 < Ug6.

All samples of Muko iron ores exhibited an exothermic peak in the temperature range from 1267°C to 1361°C. It was noted that the peak area of released energy (154-188 J/g) was almost the same for all the samples. This is also true with respect to the corresponding weight loss above 1100°C (3.22-3.50 wt%). This implied that the phase transformations occurring in this temperature range were entirely due to the thermal decomposition of hematite to magnetite, according to equation (3):

$$3\text{Fe}_2\text{O}_3 \xrightarrow{\text{heat}} 2\text{Fe}_3\text{O}_4 + 0.5\text{O}_2(g)$$  \hspace{1cm} (3)

The rate of O$_2$ removal from the iron ore is of major importance in the reduction process as this dictates the residence time of the ore in the reduction furnaces. In order to understand the ease with which O$_2$ combined with Fe can be removed from the ore, a reducibility test was performed on sample Ug6. This particular sample was selected since it was considered to be least in quality of all the 6 Muko Iron ore samples. The results of the reducibility test for the Ug6 sample are shown in Figure 7. In this study, the reducibility index (RI) was calculated as 0.868 %min$^{-1}$ and the reduction degree (RD) (180 min at 950°C) as 91.28%. As sample Ug6
has the lowest content of Fe₂O₃ (86.7%) among the Muko iron ore samples, it is safe to assume that the reducibility parameters of samples Ug1-5 will be better than those obtained from the tests on the Ug6 samples.

Usually the reduction rate of iron ores should be 0.5-1.0 % min⁻¹ for the blast furnace process and at least 0.4% for the direct reduction in the HYL III process (gas as reductant). Furthermore, at least 0.5-0.6 % min⁻¹ for the direct reduction in the rotary kiln process, which is one of the methods using coal as a reductant. In practice, the values of reduction rate for iron ores vary in the range from 0.4 to 0.9 % min⁻¹. It is apparent that the RI value for the Ug6 sample is significantly larger than the acceptable value for direct reduction processes. Moreover, it lies within the appropriate interval of the reduction rate for the blast furnace process. Thus, it may be concluded that all studied iron ores from the different Muko deposits can easily be reduced to iron within the required tolerances in blast furnaces and direct reduction furnaces.

Figure 7. Graph showing the reduction of Kashenyi Iron Ore. The curves represent: 5 – weight loss in sample (TG), 6 – gas ion intensity for CO₂, 7 – relationship between time (x-axis) and temperature, and 8 – water loss from sample.
4.0 Concluding Discussion

As can be observed in Figure 2, in Supplement 1, literature on iron ore in general and Muko iron ore in particular was gathered and studied. This provided an understanding of the occurrence and structures of iron ores, plus the methods used in its extraction and processing. The various methods were applied to Muko iron ore and the results and discussion were presented in Supplements 2 and 3. The obtained properties and characteristics of Muko iron ores can be applied in simulated models to predict Muko iron ore’s behaviour when subject to the real reduction environment.

Therefore, based on the obtained results of chemical composition, physical and metallurgical properties for natural iron ores from the different deposits of Muko, the following deductions can be made:

1. From Supplement 2, it was observed that the natural iron ores from Rushekye, Kamena, Kyanyamuzinda, Nyamiyaga and Butare deposits (Ug1-Ug5 samples) correspond to typically high-grade ores. Furthermore, that the ore from the Kashenyi deposit corresponds to the qualities of the medium-grade hematite iron ores.
2. These have a high quality level quality comparable to the best exported natural iron ores from Brazil.
3. The high level of the physical properties, observed in Supplement 3, (tumbler, abrasion and shatter characteristics) enables the handing, loading and transportation of all these ores without disintegration of the lumps to small particles and dust. Therefore, Muko iron ores can be profitably exported for the production of iron.

Furthermore, according to the obtained results in Supplement 2 and 3, the possible prospects of using the natural iron ores from the different deposits of Muko for iron production can be summarised as follows based on the classification given in Figure 2:

- Sintering process for sinters and pellets production (Route 1) - all samples;
- Direct reduction for iron processing (Route 2):
Midrex process - all samples,
SL/RN process - all samples,
HYL III process - Ug3~Ug5 samples;

Blast furnace process with direct loading of natural iron ores (Route 3) - Ug1~Ug5 samples.

Although the content of Fe, SiO$_2$ and Al$_2$O$_3$ in Ug6 samples falls short of the given requirements for direct reduction (Route 2) and for direct charging into the BF (Route 3), the other characteristics of this sample (such as physical properties and reducibility) are within the acceptable limits. Therefore, the natural iron ore from Kashenyi deposit (Ug6 sample) can also be used as a raw material for production of pellets and sinters (Route 1) or as some part of charge if mixed with other higher-quality ores (Ug1-Ug5 samples) in the DR process (Route 2).

5.0 Conclusion

Iron ore occurs in the districts of Kabale/Kisoro (Muko) in the south-western part of Uganda. All Muko iron ores occur as a rich grade of hematite ore (above 95% Fe$_2$O$_3$) with low gangue (such as SiO$_2$ and Al$_2$O$_3$) contents. The total Fe content in five iron ore deposits (Ug1-Ug5 samples) is above 67%, with correspondingly low levels of silica (0.4-1.2%) and alumina (0.4-1.0%). These also have low levels of deleterious elements such as S (0.001-0.006%) and P (0.01-0.05%). Based on the comparison to world market standards and high quality exported iron ores from other nations, it can be concluded that these natural Muko iron ores are regarded as a high-grade iron ores. The iron ore from Kashenyi deposit (Ug6 sample) has a lower total Fe content (about 61%) with higher gangue levels (5%SiO$_2$ and 6%Al$_2$O$_3$). However, it has low concentrations of the deleterious elements (0.02% P and 0.003% S). The iron ore from this deposit corresponds to the middle-grate iron ores according to the World classification.
Although the chemical composition of iron ores from different Muko deposits is almost similar, Ug1-Ug6 samples have varying microstructures in terms of grain size, texture and inclusion distribution within the hematite matrix.

The natural iron ores from all Muko deposits have high level of physical properties. More specifically, the tumbler index is 88~93 wt%, the abrasion index is 0.5~3.4 wt% and the shatter index is 0.5~2.0 wt%. Therefore, these ores can easily be handled, loaded, transported and charged into a reduction furnace without disintegrating into small particles in the form of dust.

The thermo-analysis shows that all Muko iron ores exhibit endothermal and exothermal effects below 700ºC and above 1100ºC, respectively. The endothermal effect is due to the loss of physically and chemically combined water and the γ-α hematite phase transition (except Ug6 sample). Furthermore, the exothermal effect is due to thermal decomposition of hematite to magnetite. The obtained value of the reducibility index (0.868 % min⁻¹) for the lowest quality iron-ore sample (Ug6) is acceptable for direct reduction and blast furnace processes.

The value of total endothermal effect during heating up to 1100ºC depends on the microstructure of the iron ore as well as the content of physically and chemically combined water. It may be safely suggested that the energy consumption for heating of Muko iron ores up to 1100ºC increases in the samples in the following order Ug1 < (Ug2, Ug3, Ug4) < Ug5 < Ug6.

The physical and metallurgical properties of Muko iron ores meet the raw material requirements for the blast furnace and different methods for direct reduction of iron (Midrex, HYL III and SL/RN processes). Thus, Muko iron ores can profitably be exploited as a raw material for production of pellets and sinters (Route-1). Furthermore, they can be used for full or partial charging into the furnace for direct reduction (Route-2) and blast furnace (Route-3) processes without additional enrichment and sintering.
6.0 Future Research Work

Owing to this research, various aspects have been identified that can be investigated further in order to facilitate the exploitation of the different Muko iron ores in Uganda. These include among others:

a) investigating the thermo-degradation of the ore as it undergoes reduction both at low and high temperatures,

b) modelling of different iron production processes by using the characteristics of Muko iron ores for prediction of process effectiveness and quality of final products,

c) reducing the different raw Muko iron ores in the BF and DRI processes and evaluating the properties of the products.
References


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