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A THESIS REPORT ENTITLED

A COMPARATIVE GOLD LEACHING STUDY USING CYANIDE, JINCHAN AND JINFU

BY

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SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF SCIENCE IN MINERALS ENGINEERING

THESIS SUPERVISORS

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DECLARATION

I declare that this thesis is my own work. It is being submitted for the degree of Master of Science in Minerals Engineering at 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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(Signature of Candidate)

…...day of……..2019

ABSTRACT

The main objective of a gold mining company is to extract gold from its ores economically. Minerals present in ores can be linked to grindability, recovery, reagents consumption, and challenges in metallurgical accounting. Cyanide has been the lixiviant of choice for many years but due to its toxicity, others reagents have been recommended as possible replacements. This project focused on ore characterisation and a comparative study between the efficiency of cyanide, Jinchan and Jinfu on underground ore from Loulo Gold Mine at Gara. The methodology used included mineralogical studies, work and abrasion index determination to characterize the ore. Kinetic gold leaching and Carbon-In-Leach (CIL) was done to optimize gold recovery using cyanide and gold dressing agents (Jinfu and Jinchan). The ore investigated composed of mainly quartz, minor chlorite, sericite and feldspars. Ore minerals were mainly pyrite and carbonate. The work index of the ore was 14.5 kWh/t and abrasion ore parameter was 0.5 which meant the ore was medium hard rock due to the high quartz content as stated earlier. The gravity recoverable gold was 20.7%. Leaching at 1000 ppm reagent concentration was the best reagent concentration for all the reagents used and 75 µm was the best particle size for the three reagents studied in terms of gold recovery. At 500 ppm, the best particle size was also 75 µm for the three reagents. The 106 µm performed poorly compared to the 75 µm particles due to a possible higher gold liberation and surface area exposure. The maximum recoverable gold after 24 hours was 95% for cyanide, 60% for Jinfu, and 18% for Jinchan which was the lowest. This work suggests that Jinfu will be an excellent replacement for cyanide in gold leaching albeit more studies are required to understand its behaviour in a CIL systems.

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DEDICATION

First of all, this project is dedicated to the Almighty Allah for giving me strength and wisdom to the successful completion of this project, and to my lovely parents Mr ADAMA NIARÉ and Mrs MADINA DEMBÉLÉ who always taught me to never give up on my dreams.

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CHAPTER ONE

INTRODUCTION

1.1 Statement of problem

Gold is a noble metal, it will not undergo corrosion, and is not easily dissolved. Gold is commonly associated with other metals and minerals such as silver, platinum, copper, iron, and sometimes with some carbonaceous matter and sulphides (Chryssoulis and Cabri, 1990). Gold dissolves in the presence of strong oxidizing agents and the complexing agents cyanide, chlorine, bromine, halide, and oxygen which is the most commonly used oxidant in cyanide gold leaching (Marsden and House, 2006).

The universal chemical used as a ligand in gold leaching for complexation of the dissolved gold is cyanide. This is because of its relatively low cost, effectiveness for gold (silver) dissolution, selectivity of gold and silver over other metals and the stability of aurocyanide complex (Marsden and House, 2006). There are different processes developed for leaching, including agitation leaching, heap leaching, intensive cyanide leaching, vat leaching, and in situ leaching. These methods depend primarily on the relationship between particle size and recovery, capital and operating costs, and the dissolution rate in each case.

Is cyanide environmentally friendly? Cyanide is an acute toxin and extremely dangerous chemical to living things and the environment. Due to the toxicity, other non-toxin reagents must be considered. Chloride leaching was applied commercially in the 19th century. Thiosulphate, thiourea, thiocyanate, ammonia, alkaline sulphide, and other halide solutions have been investigated extensively in the laboratory, and several potential processes have been developed (Marsden and House, 2006). Leaching by thiosulphates is a more advantageous technology and more environmentally friendly (Miur and Aylmore 2005; Aylmore 2005).

There are two new products which have been put on the market and referred to as gold dressing agents, Jinchan and Jinfu. These gold dressing agents are new reagents in gold leaching and are believed to be applicable to heap leaching, pond leaching and agitation leaching of gold-bearing oxidized ore, which are high-tech patented products of Guangxi Senhe High Technology Ltd. (China). According to the manufacturers, the product has many advantages such as simple operation (similar to the conventional cyanide), high leaching rate, short leaching time, low toxicity and a high environmental safety (Beyuo *et al*, 2016).

Studies are yet to be done to compare these two agents with cyanide. This research focused on a comparative study of the efficiency of cyanide, Jinchan and Jinfu in gold recovery of ore from Loulo Gold Mine in Mali.

1.2 Objective(s) of research

The objectives of this research include:

- Characterization of the ore (Mineralogy, Abrasive and Bond Index);
- Determine leaching efficiency using cyanide at varying concentrations and particle sizes;
- Determine whether Jinchan and Jinfu can serve as replacement for cyanide in the leaching of Loulo Gold Mine ore; and
- Consider adsorption of gold onto activated carbon after leaching with the three reagents.

1.3 Methods used

- A bench scale study and literature on aqueous chemistry of gold, cyanide and non-cyanide reagent for gold ores were reviewed
- Various laboratory experiments on ore samples under various conditions using cyanide, Jinchan and Jinfu were performed
- The extractable and recoverable gold using the different reagents at 106 µm and 75 µm grind sizes were analysed and compared

1.4 Facilities used for research

The following facilities were used for the completion of this research

- Minerals Engineering Laboratory, UMaT, Tarkwa
- Internet facilities at the University of Mines and Technology, Tarkwa

- Library facilities available at the University of Mines and Technology, Tarkwa
- Laboratory facility at SOMILO (Loulo) Mali
- Ghana Standards Authority

1.5 Report organisation

This thesis has been organized in 5 chapters. Chapter 1 has the introduction, gives a brief outline of the work and how it has been handled. Chapter 2 gives the information about the products, discusses aqueous chemistry of gold, cyanide and non-cyanide reagents, the ore of SOMILO (Loulo) Mali, the processing operations in gold leaching and the literature review. Chapter 3 discusses the experimental investigation. Chapter 4 discusses the results and chapter 5 has the conclusions and recommendations from the study.

CHAPTER TWO

LITERATURE REVIEW

2.1 Ore deposits

An ore is a natural occurrence of mineral masses which can be treated/ extracted economically. The characteristics of ore deposits and its mineralogical factors determine the procedure to use to get the best efficiency in gold recovery. The more information on the ore, the less difficult it is to treat. The gold mineralogy in each ore deposit is exceptional, due to some variations in the following (Marsden and House, 2006):

- Mineralogical occurrence of gold;
- Gold grain size distribution;
- Host and gangue mineral type; and
- Host and gangue mineral grain size distribution.

Therefore, it is important to consider the type of ore deposit and mineralogical factors, which can affect the technology used in the ore processing strategy. The gold ore deposition is presented in (Figure 2.1).

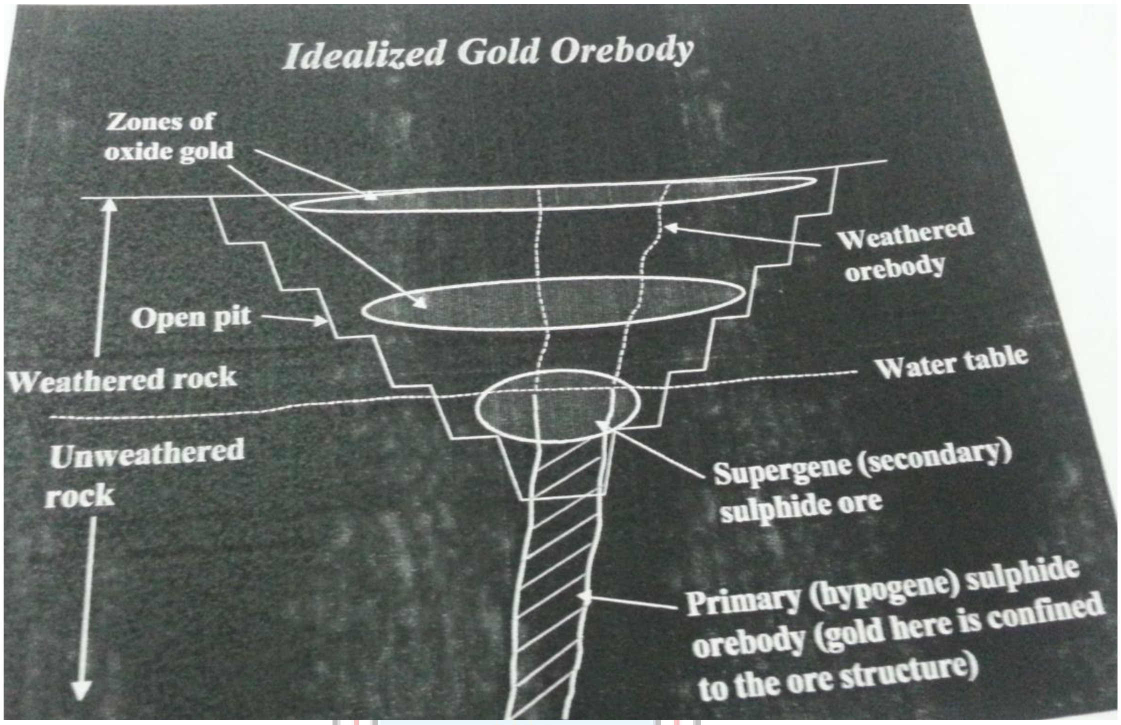

Figure 2. 1 Gold ore deposits (Vaughan, 2010)

2.2 Gold mineralogy

Gold is a precious metal which is considered as a symbol of purity and good fortune. The average concentration of gold in the earth`s crust is 0.005 g/t which is much lower than most of other metals such as silver and copper. In the early history, gold was used as a means of monetary payment in the form of grains and small bars. However, currently, the main application of gold has been in decoration and jewelry, as is the case today Figure 2.2 (King, 2019). Currently, the use of gold is very important in the development of a country in terms of financial and economic aspects of the country (Rani and Vijayalakshmi, 2014).

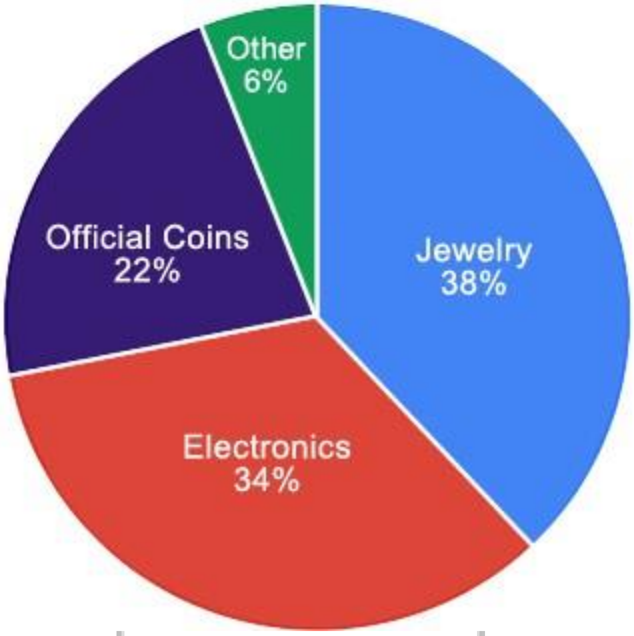

Figure 2. 2 Uses of gold in the United State in 2017 (Exclusive of Bullion)

As a noble metal, gold is used in many practical industries. It is the only metal that is not attacked in air or water by either oxygen or sulphur. It does not undergo corrosion. Gold is generally found in nature in the metallic state (Nicol *et al*., 1987). Native gold is the most common form of gold in ores which varies between 85% and 95% Au content, with silver as the main impurity (Marsden and House, 2006).

The most important minerals in gold ores are pyrite (FeS_2), galena (PbS), zinc blende (ZnS), arsenopyrite (FeAsS), stibnite (Sb_2S_3), pyrrhotite ($Fe_{(1-x)}S$), and chalcopyrite ($CuFeS_2$) (Adams, 2005).

According to the mode of occurrence, gold is classified into three categories: microscopic gold, submicroscopic gold and surface-bound gold. Gold minerals are defined as the minerals in which gold is present as a main constituent (e.g. native gold and electrum). Gold carriers are defined as both the gold mineral and the mineral in which gold occurs only in a small amount (such as pyrite and arsenopyrite) (Zhou *et al*. 2004).

2.3 Gold processing

2.3.1 Classification of gold ores

Gold ores are commonly classified in several ways, depending on the associated elements or the extraction method. According to metallurgists, gold ores are classified into two groups: refractory and non-refractory. Non-refractory ores include placer, free milling and oxidized ores where over 90% of gold can be recovered by gravity concentration and/or simple cyanidation. Refractory ores that give low gold recoveries and can be classified as follows: mildly refractory: 80–95%, moderately refractory: 50–80%, and highly refractory: < 50% (Vaughan, 2004).

The metallurgical recovery of gold from gold ore deposits depends on the nature and particle size of gold bearing minerals and the composition of associated gangue minerals (Spry *et al*., 2004). Based on the mineralogical characteristics and mineral processing methods required, gold ores can be classified into 11 types Table 1 (Zhou *et al*. 2004).

Table 2. 1 Gold Ore Types and Gold Occurrence (Reproduced after Zhou et al. 2004)

SN	Types of ores	Mode of occurrence
1	Placers	Gold is easily liberated or has been liberated prior to processing, and normally ranges from 50 - 100 µm in size.
2	Quartz vein-lode ores	Gold occurs mainly as native gold in quartz-veins, lodes or stockworks, some tellurides and occasionally aurostibite and maldonite commonly occurs as liberated gold particles but some disseminated gold may be present.
3	Oxidized ores	Gold usually occurs as either liberated or in the alteration products of sulfide minerals, and the degree of gold liberation is generally increased by oxidation
4	Silver-rich ores	Gold commonly occurs as electrum, although kustelite may be present in some ores. Native silver may be present.
5	Copper sulfide ores	Gold occurs as coarse liberated particles and fine particles locked in pyrite and copper sulfides.
6	Iron sulfide ores	Gold occurs as liberated particles, attachments to and inclusions in sulfide (commonly in pyrite, and less commonly in marcasite and pyrrhotite, and as submicroscopic gold in sulfide minerals
7	Arsenic sulfide ores	Gold occurs as liberated particles and inclusions, and submicroscopic gold in arsenopyrite and oxidized products.
8	Antimony sulfide ores	Gold occurs mainly as native gold, with minor to moderate amount of aurostibite, either liberated or locked in sulfides.
9	Bismuth sulfide ores	Gold occurs mainly as native gold, with minor to moderate amounts of maldonite. Submicroscopic gold can also be present in sulfides.
10	Telluride ores	Gold occurs as native gold and gold tellurides, either liberated or locked in sulfides. Submicroscopic gold may be present.
11	Carbonaceous sulfidic ores	Gold occurs mainly as fine-grained gold particles and submicroscopic gold in sulfides, and surface gold absorbed onto the surface of carbonaceous matter and FeOx.

2.3.2 Comminution

Comminution is the reduction process where bigger sized particles of ore are reduced to smaller sizes to liberate the mineral of interest using crushing and grinding if necessary. The product of comminution is a mixture of the mineral of interest's particles and gangue materials. Grinding is very important in mineral processing, but over grinding can lead to a high consumption of energy and make the efficiency of recovery poor creating with tailings management problem.

Abrasion Index

Abrasion Index gives more information about the abrasive resistance of the ore by friction and attrition in the mill. It is used to judge the wear rate of balls in the mill. By extension the abrasive work index relates to the hardness of the rock. Several abrasion tests are accessible (Cassapi, 1987). The most common method used on ores is the standard JKRMC test (Anon, 1992). It is performed in a 300 mm diameter × 300 mm long tumbling mill with four 10 mm lifter bars. 3 kg sample of -55+38 mm ore is ground for 10 minutes at 70% of critical speed (53 rpm). The product from mill is sieved to -38 µm on a series of sieves built according to the Tyler series. From the raw particle size data t_{10} values are generated using a program (Buah, 2017).

The three parameters relevant to AG/SAG milling are A, b and t_a. A and b are used to characterize the impact breakage of the ore and t_a is a measure of the resistance of the ore to abrasion. In both cases, the lower the value the greater the resistance of the ore to that type of breakage. The parameter (t_a) may be as low as 0.2 for very hard ores, to above 2 for very soft ores according to DK Drop Weight Test in Table 2.2.

Table 2. 2 Classification of Abrasive Index parameters (Anon, 1992)

Property	**Very hard**	**Hard**	**Mod. hard**	**Medium hard**	**Mod. Soft**	**Soft**	**Very soft**
A*b	<30	30-38	38-43	43-56	56-67	67-127	>127
t_a	<0.24	0.24-0.35	0.35-0.41	0.41-0.54	0.54-0.65	0.65-1.38	>1.38

Autogenous mill/Ball Mill

One of the major developments in the mining industry is the use of autogenous grinding (AG) and semi-autogenous grinding (SAG) mills. An AG mill is a mill that uses the ore itself as grinding media. The ore must contain sufficient competent pieces to act as grinding media. A SAG mill is an autogenous mill that uses steel balls in addition to the natural grinding media. The SAG and AG mills are shorter in length than the ball mill but wider in diameter than the ball mill. Nevertheless, SAG mills operate in the cataracting regime while ball mills operate in the cascading regime to reduce the rate of liner wear (Wills, 2006).

The ball mill is used in the final stages and helps produce a finished product of uniformly fine particles. The ball mill uses steel balls and can grind particles even finer. Ball mill is widely applied in cement industry, mining industry, chemical industry, new building materials, fire-resistant materials, fertilizer, and porcelain and glass industry (Amoah, 2011).

Grinding works on principle of critical speed (Wills and Munn, 2006). The critical speed is the speed at which the centrifugal force is sufficiently large to cause a small particle to adhere to the shell liners for the revolution of the mill is given in mill specification. Critical speed is determined from Equation 2.1:

$$C_s = \frac{42.3}{\sqrt{D}} \qquad 2.1$$

Where D is the diameter inside liners specified in metres and C_s is critical speed in rpm.
Grinding can be done by wet or dry depending on the product. Wet grinding is generally used in mineral processing operations because of its overall economies of operations (Wills, 2006).

Bond`s theory of comminution

Bond`s comminution theory relates the degree of grinding to the specific energy used in creating new surface areas of particles with mean size of 80% passing screen sizes. This theory is of great interest with regards to its application to optimize the mill throughput of a plant. The Bond`s comminution theory has been widely used for mill sizing and design. The model is an empirical equation based on analysis of data from laboratory and industrial mills. It is based upon two-power calculation approaches used in majority of ball and rod mill design processes. These are the determination of the power required to grind the ore from the given feed size to a specific product size, and the selection of milling circuit with the mill design that draw the required power.

Bond Work Index

The work index is very advantageous and suitable tool for comminution engineers. The test results obtained, when applied to the Bond Work Index formula gives an initial indicator of the specific power consumption (kWh/t) required to grind any particular ore. Also because the method requires only a small amount of sample and costs relatively little, the specific power consumption for grinding can be ascertained quickly and perfectly for a number of different ore types. The Work Index can be determined for different applications of comminution; e.g. crushing, rod milling, and ball milling. It is a false assumption to expect the work index to be uniform for all incremental stages of size reduction.

2.3.3 Gravity concentration

The use of gravity concentration is to separate minerals of different specific gravity by their relative movement of the particles in response to gravity and fluid resistance forces. Since the effect of fluid resistance forces are influenced by size and shape, it is important to present a closely sized feed to gravity separation units. Equation 2.2 is the concentration criterion given by (Wills, 2006; Sarpong and Amankwah, 2017):

$$\text{Criterion}_{\text{conc}} = \frac{D_h - D_f}{D_l - D_f} \qquad 2.2$$

Where:

D_h = density of heavy minerals

D_f = density of fluid medium

D_l = density of heavy minerals

Separation is relatively easy when the quotient is greater than + 2.5. Below 1.25 gravity concentration is generally not feasible. Different kinds of separators used include jigs, shaking tables, gold pans, sluices, spirals, cones and centrifugal concentrators (Wills, 2006). All centrifugal concentrators include Knelson, Knudson, and Falcon centrifuge operate on the same principle but the common type used is Knelson concentrator. The Knelson concentrator is a compact batch centrifugal separator with an active fluidized bed to capture heavy minerals (Knelson and Jones, 1994) and has been commonly applied in the recovery of gold, platinum, silver, mercury and native copper. The application of gravity concentration can be beneficial to overall gold recovery because the coarse gold particles are recovered before leaching which reduce the leaching retention time and the recovered gold can be treated separately (intensive cyanidation and smelting) depending on the ore mineralogy for maximum recovery. The use of gravity concentration increase the overall gold recovery.

2.3.4 Chemistry of gold leaching

Gold is a noble metal and very stable, as indicated by the absence of reactivity in air and in the majority of aqueous solution, including strong acids. Since the late 19th century, gold cyanidation has been used as the main procedure of gold extraction in the mining industry. Gold leaching is a hydrometallurgy process which dissolved gold in an aqueous solution by using suitable chemicals.

Leaching systems

Different processes have been developed for leaching, including agitation leaching which is the dissolution of gold in the tank by agitation (CIL, CIP). Non agitation leaching is the dissolution process of gold such as heap leaching, intensive cyanide leaching, vat leaching and in situ. The use of these leaching systems depend on economical, environmental and mineralogy factors (Mardsen and House, 2006).

2.3.5 Factors affecting leaching

- Mineralogy

The mineralogy of an ore gives more information on the ore which is required to design a gold extraction process for optimum efficiency. The gold mineralogy in each ore deposit is unique due to the mineralogical mode of occurrence of gold, etc. (Mardsen and House, 2006).

- Particle size

The rate of leaching increases with decreasing particle size. The bigger the particle size the more difficult it is to leach. The smaller the particle size the larger the surface area exposed to reaction and the easier the particles are kept in suspension by agitation.

- Residence Time

The residence time is the time required for gold to be leached by chemicals. The more gold is in a contact the more the dissolution rate is high. Short residence time usually increasing gold losses to tailings. Practically, this create short circuit and hence increase solids tailings grade.

- Reagent Types

Several reagents are used in mineral processing, they include cyanide, thiourea, thiosulfate, bromine, halide, etc. The universal chemical used as lixiviant for gold extraction is cyanide because of its availability, relatively low cost, effectiveness for gold-bearing dissolution, selectivity for gold and silver over other metals and the stability of aurocyanide (Marsden and House, 2006).

2.3.6 Chemistry of cyanide solution

Cyanide is a group of chemicals with a combination of nitrogen and carbon used to dissolve gold and silver. Cyanide occurs naturally, and it is found in the small quantities in several foods including cassava, bamboo, sweet potatoes, sugarcane and beans. Apart from natural occurrences, cyanide can be emitted by man-made such as coal combustion, refining of petroleum, iron and steel production (Ndur, 2018).

There are three types of simple salts cyanide sodium cyanide (NaCN), potassium cyanide (KCN) and calcium cyanide ($Ca(CN_2)$). They are different in terms of solubility and availability of cyanide content. They dissolve and ionize in water to form their particular metal cation and free cyanide ions (CN^{-}) as presented in Equation 2.3:

$$NaCN \Leftrightarrow Na^{+} + CN^{-} \qquad 2.3$$

The choice of cyanide type depends on the method of application, the solubility, the availability and the cost. The hydroxylation of cyanide ions in water form hydrogen cyanide (HCN) and hydroxyl (OH^-) ions as shown in equation 2.4 with increasing the pH. At pH of 9.3, the total cyanide is half of hydrogen cyanide and half of free cyanide ions. Above pH of 10 the most total cyanide present is free cyanide ions and lower pH increases the hydrogen cyanide ions. Under the right oxidizing conditions, the oxidation of hydrogen cyanide and free cyanide form the cyanate (CNO^-) (as presented in the equations 2.5 and 2.6) in the presence of oxygen. The formation of cyanate has an effect on the dissolution of gold because of the reduction of free cyanide concentration (Srithammavut, 2008).

$$CN^- + H_2O \Leftrightarrow HCN + OH^- \qquad 2.4$$

$$4HCN + 3O_2 \Leftrightarrow 4CNO^- + 2H_2O \qquad 2.5$$

$$3CN^- + 2O_2 + H_2O \Leftrightarrow 3CNO^- + 2OH^- \qquad 2.6$$

The use of cyanidation for gold processing is due to its effectiveness in treating a wide range of ores at a relatively low cost compared with other leaching reagents. Other factors include the high stability of the gold cyanide complex, higher capacity and lower corrosive nature. The overall reaction, where oxygen is reduced and hydrogen peroxide is formed to be the oxidizing agent in the second step is presented in Equations 2.7 and 2.8 (Simo, 2013):

$$2Au + 4CN^- + O_2 + 2H_2O \rightarrow 2Au(CN)_2^- + H_2O_2 + 2OH^- \qquad 2.7$$

$$2Au + 4CN^- + H_2O_2 \rightarrow 2Au(CN)_2^- + 2OH^- \qquad 2.8$$

Summation of these two equations is presented in Equation 2.9

$$4Au + 8CN^- + O_2 + 2H_2O \rightarrow 4Au(CN)_2^- + 2OH^- \qquad 2.9$$

This equation is called Elsner`s equation which is the most standard reaction accepted of cyanide and gold. The rate of cyanide consumption to dissolve gold is two moles of the cyanide to one equivalent of gold CN / Au = 2 : 1

Table 2. 3 Stability constants of some gold compounds

Complex	Au(I)	Complex	Au(III)
$Au(CN)_2^-$	2.0×10^{38}	$Au(CN)_4^-$	1.0×10^{56} to 1.0×10^{80}
$Au(S2O3)_2^{3-}$	5.0×10^{28}		
AuI_2^-	4.0×10^{19}	AuI_4^-	5.0×10^{47}
$Au(SCN)_2^-$	1.3×10^{17}	$Au(SCN)_4^-$	1.0×10^{32}
$AuCl_2^-$	1.0×10^{9}	$AuCl_4^-$	1.0×10^{26}

Due to its toxicity, several methods are available for the treatment of cyanides in waste water which contains free cyanide and WAD cyanide. Those methods are natural degradation, and chemical methods such as alkaline chlorination, and hydrogen peroxide detoxification. The natural degradation may be utilized when the wastewater is held for long periods in impoundments and degradation of may be due to a combination of biological, chemical, physical processes including photodecomposition, adsorption onto solid surfaces, hydrolysis and volatilization.

Chemical methods are generally expensive while natural degradation takes quite some time to go to completion. In recent times, the use of microbes has become prominent and bacterial cyanide destruction in the minerals industry is increasing due to its environmental friendliness and lower costs. Cyanide is generally also destroyed by strong oxidizing agents and three major cyanide degradation pathways identified are oxidative, hydrolytic and substitution/transfer.

Even though cyanide is very efficient in gold recovery and economically, it is also very poisonous to the surrounding environment and health. According to the National Institute of Occupational Safety and Health in USA, high HCN gas in air can be fatal for humans after exposure in the gas (Simo, 2013).

Since environmental awareness has increased and severe cyanide accidents happened, there is much public concern about the use and toxicity of cyanide around the world. Some countries such as Czech Republic, Argentina, Turkey and some states of USA have campaigned to prohibit cyanide in mineral processing applications (Duffield and May, 2003).

On 30th of January 2000, the inner embankment of the S.C Aural mine in Baia Mare (Romania) lost its strength and therefore collapsed. About 100,000 m^3 of water containing 100 tonnes of cyanide as well as heavy metals escaped into Tisza, Somes and Danube river systems (Duffield and May, 2003; Klemola, 2012). As a results of the accident thousands of tonnes of fishes died in the rivers (presented in Figure 2.3) where cyanide entered and 2.5 million people in 24 towns had their water contaminated. Fortunately cyanide decomposes in nature quite fast thus environmental impacts were not long-term.

Figure 2. 3 Dead fishes of the Tisza River (Duffield and May, 2003).

2.3.7 Chemistry of non- cyanide solution

Although cyanide leaching is still the universal lixiviant in the gold mining industry, it is extremely dangerous for human health and surrounding environment. Therefore, metallurgical researchers have provided more non-cyanide leaching processes which have some potential advantages over cyanide depending on the ore type. Those non-cyanide reagents include chlorine, thiourea, thiosulfate, ammonia, and other halides.

Chlorine

Aqueous solution of chlorine have strong oxidizing abilities and can be used in oxidizing carbonaceous materials, sulfide minerals, deactivation of preg-robbing materials, gold refining and cyanide detoxification (Mardsen and House, 2006). Gold dissolves in aqueous chloride solution to form both the Au(I) and Au(III) chloride complexes in equations 2.10 and 2.11

$$AuCl_2^- + e \Leftrightarrow Au + 2Cl^- \qquad 2.10$$

$$AuCl_4^- + 3e \Leftrightarrow Au + 4Cl^- \qquad 2.11$$

Because of the corrosion aspect, chloride leaching requires special stainless steel and rubber-lined equipment to resist the highly corrosive conditions (Yanhua *et al.*, 2012). The treatment of refractory sulfide ores by using chlorine is not profitable because of the high consumption of chlorine. In addition, chlorine is extremely toxic and the disposal of tailing is a very expensive practice (Amankwah, 2017).

Thiourea

Thiourea has been suggested as an alternative to cyanide for the treatment of sulfide, cyanide-consuming ores. It is used in those places where the use of cyanide is not allowed due to its negative effects on the environment. This chemical is a relatively non-toxic reagent and behaves as a plant fertilizer in the environment. However, the reagent is suspected to be carcinogenic and has the capacity to dissolve heavy metals in addition to gold and silver. Gold dissolves in thiourea solution to form a complex gold as shown in Equation 2.12:

$$Au + 2CS(NH_2)_2 \Leftrightarrow Au[CS(NH_2)_2]_2^+ + e^- \qquad 2.12$$

More than 95% of gold is extracted from ores in which most of the gold is liberated by using thiourea. But the consumption factors of thiourea such as oxidant concentrations, solution pH and the solution potential makes the process very expensive, at least twice the price for the same material with cyanide. Those factors are the reasons why it has not been used widely in industry up to now (Wu *et al*, 2008).

Thiosulphate

Due to the high toxicity of cyanide, thiosulphate has been proposed as an alternative to cyanide for the recovery of gold from gold bearing ores and concentrates (Anon, 2008). Although not as dangerous as cyanide as a leaching agent, thiosulphate has several advantages including its lower toxicity (Aylmore and Muir, 2001) and greater efficiency with gold deposits associated with ores with cyanide-consuming copper, carbonaceous preg-robbing materials, refractory sulfides (Marsden and House, 2006). Gold forms stable complex with thiosulphate in an aqueous solution as shown Equation 2.13:

$$Au + 2S_2O_3^{2-} \rightarrow Au(S_2O_3)_2^{3-} + e^- \qquad 2.13$$

In alkaline thiosulphate solution where oxygen is as an oxidant, the complex redox reaction is shown in Equation 2.14.

$$4Au + 8S_2O_3^{2-} + 2H_2O + O_2 \rightarrow 4Au(S_2O_3)_2^{3-} + 4OH^- \qquad 2.14$$

Even though thiosulphate leaching has a potential in gold leaching, there is one major problem remaining, that is, a high consumption of thiosulphate during gold leaching which is caused by its decomposition in solution and the unavailability of a cheap process for recovering gold. These make thiosulphate leaching uneconomical on a commercial scale.

Ammonia

Gold is soluble in aqueous ammoniacal solution in the presence of oxygen, hypochlorite, hydrogen peroxide, or bromine which are suitable oxidant for the solubility of gold in the solution. The dissolution proceeds through the formation of Au(I) species, ($Au(NH_3)_2^+$), to potentially form the stable Au(III) amine complex (depending on the solution potential), as shown in Equation 2.15

$$Au + 2NH_3 \Leftrightarrow Au(NH_3)_4^+ + e \qquad 2.15$$

The use of oxygen as an oxidant required high ammonia concentrations, and temperatures above 100 °C must be applied for the reaction to proceed at an acceptable rate (Han and Meng, 1992, 1993).

The use of aqueous ammonia-cyanide mixtures has been proposed for leaching of gold from copper-gold ores, with Cu(II) and oxygen (air) as the oxidant and the effectiveness of gold leaching is reacting quickly to solution conditions. The concentrations of cyanide, ammonia, and copper, and solution pH all have an impact on the gold leaching rate and recovery, to maximize gold extraction, the concentrations of each must be optimized. Unfortunately, the copper-ammonia-cyanide system is a preferable complex, the three element are linked, and changes the concentration of one species affects the concentration of the other species and pH.

2.3.8 Chemistry of Jinchan and Jinfu

Gold dressing agents are new leaching reagents which are believed to be applicable to heap leaching, dump leaching, pond leaching, agitation leaching and carbon-in-leaching of gold-bearing oxidized ore, and are patented products of Guangxi Senhe High Technology Ltd. (China). In the gold mining industry, the products have many advantages such as simple operation (similar to the conventional cyanidation), high leaching rate, short leaching time, low toxicity and environmental protection, convenient transportation and storage. It is currently known to be the only patented non-cyanide product for environmentally friendly gold extraction around the world (Anon, 2015).

Chemistry of Jinchan

Jinchan environmental friendly gold dressing agent is a new high-tech product which was created by Senhe High Technology. The product is used in gold production directly as the replacement for sodium cyanide without original process and equipment changes. Jinchan is applicable to refractory and non-refractory gold ore in (Figure 2.4). According to the manufacturers, the product has many advantages such as simple operation (similar to the conventional cyanide) (Beyuo *et al*, 2006). The main chemical compounds in the product include $SC(NH_2)_2$, $NaSiO_3$, $NaOH$, $(NaPO_3)_6$ and the cyanide content in Jinchan is 0.34% (Ghana Standard Authority) and their chemical composition is presented in Table 2.4 (Beyuo, *et al*. 2016).

Table 2. 4 Chemical composition of JGD

Elements	Percentage by weight, %
Carbon	22.04
Sodium	38.3
Ammonia	15.42
Oxygen	22.92
Iron	0.96
chlorine	0.36

The product can be in granular or powdery form with a relative density of 1.05. It is very stable under normal conditions and 100% soluble in water. It can be used after being fully dissolved by water at room temperature. The pH is adjusted using either soda caustic or lime to get a stable pH between 11 and 12. It can be applied in heap leaching, pool leaching, agitation leaching and the leaching speed is relatively high. The use of cyanide, ammonia water, sodium sulfide, potassium ferricyanide, lead nitrate and sodium hypochlorite and other chemicals in complex ore pre-treatment with Jinchan at the same time does not reject the Jinchan gold leaching. The chemical is not flammable dangerous goods, radioactive dangerous goods or corrosive. It can be safely transported through highway, railway, shipping and air transportation. With high pH more than 12, the activity of carbon adsorption and the leaching efficiency will be affected (Guangxi Senhe High Technology).

Gold leaching by CIP (carbon-in pulp) process and “the rich oxygen leaching” have bad impact on Jinchan and the addition of strong oxidizers such as hydrogen peroxide and potassium permanganate together with Jinchan (pre-treatment can be made) is not recommended during leaching. The chemical is known to be hygroscopic (ability to absorb moisture from air) and it is not recommended to mix it with acid chemicals and edible chemicals.

Ore waste residue and waste water after production have relatively high alkalinity. It can join a small amount of chlorine acid calcium (bleach powder), ferrous sulfate for treatment, then discharge and stack them in special tailing facilities.

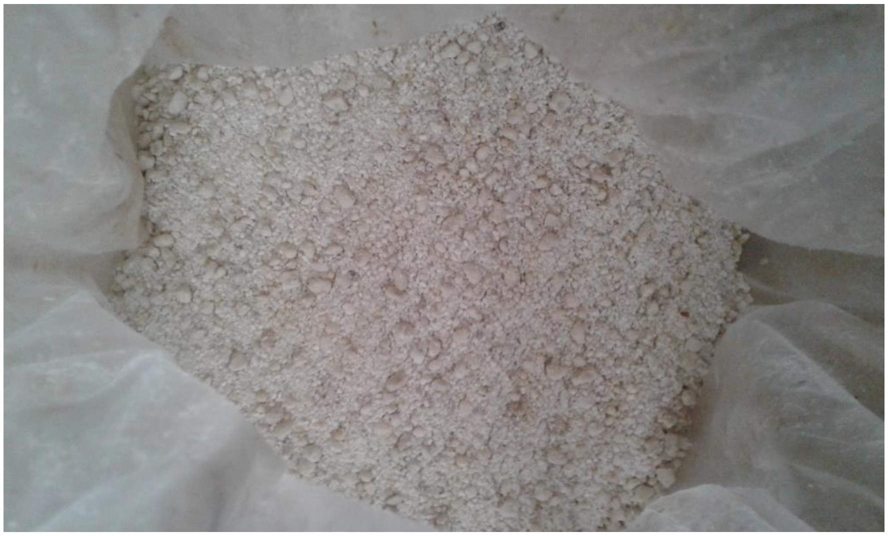

Figure 2. 4 Jinchan Gold Dressing Agent

Chemistry of Jinfu

Jinfu environmental friendly gold dressing agent is a new high-tech product which is created by Senhe High Technology and used in gold beneficiation as the substitute for sodium cyanide. The chemical properties of Jinfu dressing agent is sodium hydroxide (NaOH) and cyanuric acid trisodium salt ($C_3N_3Na_3O_3$) in (Figure 2.5). The cyanide content in Jinfu is 0.44%. The reaction of Au with the active ingredient in the Jinfu gold leaching agent in the presence of free oxygen produces the Au-complex which is adsorbed by the activated carbon. The chemical reaction is as shown in Equation 2.16

$$2C_3N_3Na_3O_3 + 2Au + 2H_2O + O_2 \Rightarrow 2Au(C_3N_3Na_3O_3)^{2+} + 4OH^- \tag{2.16}$$

Residuals in the process plant tailings and sewage was treated by oxidizer or bleaching powder then converted into harmless sodium chloride, sodium carbonate, nitrogen, carbon dioxide and water.

Figure 2. 5 Jinfu Gold Dressing Agent

2.3.9 Competitive Reactions in Alkaline Cyanide Solution

Several other minerals and elements are dissolved in alkaline cyanide solution as well. These competitive reactions may be high reagents consumers and reduce the efficiency of gold leaching. For example the sulfides are dissolved and produce metal cyanide complexes and sulfur containing species which are cyanide and oxygen consumer such as sulphate, sulphide, thiocyanate and thiosulphate ions. Several pretreatment methods such as pre-aeration, pressure oxidation and roasting are beneficial prior to cyanidation to reduce the cyanide and oxygen consumption.

2.4 General information on the Mine

La société des mines d`or de Loulo (SOMILO) SA is an affiliate of Randgold Resources Limited, established in 2005, of which the government of Mali holds 20% interest and the remaining 80% for Randgold Resources Limited. It is the biggest Gold Mine in Mali with 5 million tonnes ore treated per year in 2018.

The Gold Mine of Loulo is located in the South Western part of Mali near the Faleme river (natural border between Mali and Senegal) in the Kayes. The mine is at 350 km away from Bamako, 96 km from Sadiola, 28 km from Seguela and Tabakoto. That area is called BAMBOUK which counts nine main gold deposits: at Loulo, Yalea, Gounkoto, Segala, Koffi, Fakola, Sadiola, and Yatela. Figure 2.6 shows the location of Loulo Gold Mine on the Mali map.

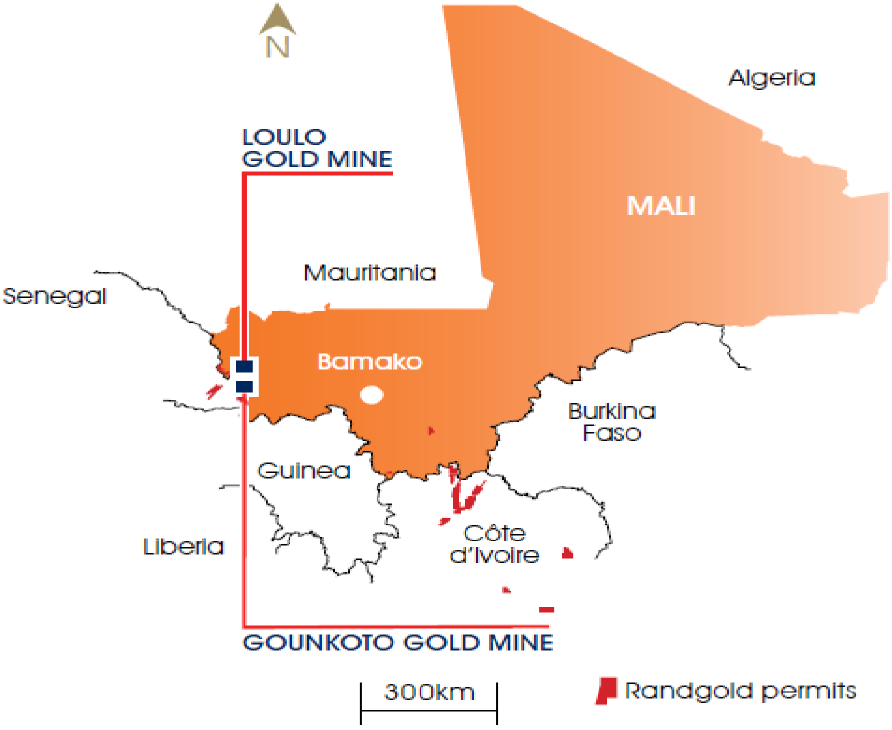

Figure 2. 6 Location of Loulo Gold Mines in the west of Mali (Anon, 2012)

Mali is located on the West Africa craton which is essentially composed of Archean aged land and Low Proterozoic (the Birimian) largely covered by new formations. In Mali, the Birimian is observed in 3 main locations.

The South of Bamako included Sikasso region at Bougouni, North and South of Kayes region included Kayes windows and Kedougou-Kenieba`s window respectively. The permit of Loulo is located on Kedougou-Kenieba`s window. It hosts two main deposits namely Gara and Yalea which have been developed into corresponding open pit and underground mines.

Loulo project area is characterized by a sequence of sandstones, limestones and greywackes. Gara and Yalea deposits have been discovered with several other satellite deposits in the area. Both deposits are underground mines and were opened in November 2005. The geology and mineralization of Loulo is described in detail in (Lawrence *et al*., 2013). The lithology is the main different rocks that are observed on the permit. At Gara, the ore body lays within meta-sedimentary rocks intruded and the ore is found in Quartz Tourmaline rocks. The ore zone at Gara is characterized by 3 criteria: the presence of tourmaline indicated by the black color, the presence of quartz and carbonate veins which are white veins. The mineralization of Gara is mainly hosted in pyrite. The process plant operates both undergrounds (Yalea and Gara) and open surface (Gounkoto and Baboto) mines. The process plant is a closed circuit which is composed by four sections.

- Comminution section

It is composed by crushing, grinding circuits and hydrocyclones

- Hydrometallurgy section

It is Carbon-in-Leach system with 14 tanks

- Recovery section

It is Zadra system with two elution columns

- Electrowinning and smelting section

It is composed by seven electrowinning cells and smelting.

- Tailings disposal section

All the tailings are sent to I-Plant (Intermediate-Plant) for treatment and separation. The heavy particle is mixed with cement for backfill in to the undergrounds and the light particle is sent to the tailings dams.

CHAPTER THREE

EXPERIMENTAL WORK

The main objective of the experiment is to determine the best lixiviant between cyanide, jinchan and jinfu for gold leaching on the ore samples from SOMILO (Loulo).

3.1 Sample and Investigations

30 kg of the gold ore was taken from underground mine (Gara) at SOMILO (Loulo). The sample was used for metallurgical studies which included: the mineralogy, abrasive index, Bond work index, grindability test, gravity concentration and bottle roll test.

3.2 Mineralogical Analysis

The mineralogical analysis was conducted by thin and polish section studies.

3.2.1 Petrography

Thin and polished sections were prepared at the Geological Engineering laboratory (UMaT) with 10 samples collected randomly from the parent field for petrographic analysis in both reflected and transmitted light microscope (Leica DM 2700P).

3.3 Metallurgical Analysis

3.3.1 Abrasion Index determination

The Abrasive Index was determined using Julius Kruttschnitt abrasive index method. The mill had both internal diameter and length, 30 cm and equipped with 10 mm lifters. 3 kg of ore particles between -55 mm + 40 mm were milled for 10 min at 53 revolutions/min. The products were screened with test sieve sizes of (40 mm, 22.4 mm, 13.2 mm, 6.7 mm, 4 mm, 2.36 mm, 1.18 mm, 425 microns and 106 microns). The T_{10} of the last sieve for the feed which is 40 mm is determined below:

$$T_{10} = \frac{40mm}{10} = 4mm$$

NB: This value was determined to get the abrasive work index

The Abrasive Index was calculated in Equation 3.1

$$\text{Abrasive Index value} = \frac{(\text{cumulative \% passing 4mm})}{10} \qquad 3.1$$

3.3.2 Grindability Test Determination

Standard feed was prepared and screened using 106 µm and 75 µm sieve screens. The oversize of both sieves were weighed to get the percentages. The sample was milled using the ball mill within different times and the discharge was screened with the two sieves. The grinding and screening process were repeated until a time where the undersize is approximately equal to 75% of material passing 106 and 75 µm. A graph of cumulative % passing against time in min was plotted (Appendix). 75% of the product (in microns) passing 106 and 75 µm was extrapolated. The mass of -75 µm in the feed is determined as shown in Equation 3.2.

$$\text{Mass of -75 µm in feed (g)} = \frac{(\text{\% oversize of - 75 } \mu\text{m} \times \text{new feed})}{100} \qquad 3.2$$

%passing through the particle sizes (106 and 75 µm)

%passing = (mass of undersize/initial mass)*100

3.3.3 Bond Work Index determination

Sample of size -3.35 mm m was used for this test. A standard ball mill of size 0.305 m × 0.305 m with rounded corners and running at 70 rpm was charged with feed weight equivalent to 700 mL and steel balls of a specified number, weighing approximately 20.1 kg. The sample was ground initially at 100 revolutions. The ground sample was screened with 106 µm sieve and the undersize sample was weighed and recorded. A representative amount of new feed was added to the test sieve oversize to bring the combined mass up to the initial mill charge. The number of revolution for the next period was determined from the previous period. This procedure was repeated five (5) times until the weight of undersize produced per mill revolution reached equilibrium. Average of net grams per revolution from the last three cycles was taken as the ball mill grindability (G_{bp}) in g/rev. A representative sample of product is sized to determine the P_{80}. Finally, the BBMWI is calculated using the Bond equation (1960).

The time for 100 revolution was calculated in Equation 3.3

$$\text{Revolution time} = \frac{\text{required revolution}}{\text{speed of the mill}} \qquad 3.3$$

The ideal potential product (IPP) was calculated in Equation 3.4

$$\text{IPP} = \frac{\text{weight of the 700ml feed}}{3.5} \qquad 3.4$$

The undersized and the oversized was weighed and the loss to the mill was found:

Loss to the mill = (weight of feed) – (the sum weight of undersize and oversize)

The + 75 was topped up with fresh feed to the weight original:

Top up weight = weight of (-75) + losses to the mill

The net gram/ rev was calculated in Equation 3.5

$$\text{Net gram/ rev} = \frac{\text{total fill}}{\text{number of revolutions}} \qquad 3.5$$

The number of revolutions for the second cycle was calculated in Equation 3.6

$$= \frac{\text{IPP}}{\text{net gram/rev of the subsequent cycle}} \qquad 3.6$$

Mass of -75 in feed (g) = (% oversize of -75µm * new feed)/ 100

The screen size at 80% of milled product passed was determined using graphical techniques P_{80} using Equation 3.7

$$W_I = \frac{44.5}{(P_{75})^{0.23} \times (Gbp)^{0.82} \times 10\left(\frac{1}{\sqrt{P_{80}}} \cdot \frac{1}{\sqrt{F_{80}}}\right)} \text{ kWh/t} \qquad 3.7$$

Where

W_i is the work index

P_{75} is the screen test size in microns

Gbp = average value of the 3 and 5 cycles net gram per rev

P_2 = 80% passing the product in microns

F_2 = 80% passing the feed in microns

3.3.4 Gravity concentration

5 kg of the feed was milled using the ball mill at 40% passing 106 µm. The 40% of the product passing 106 µm was used to conduct the gravity test using centrifugal concentrator (Knelson concentrator). The flowrate was 3.5 with a pressure in between 1 and 2.The concentrate and the tailings were collected and taken for fire assay to determine the grade of the concentrate and tailings.

3.3.5 Bottle Roll Test

Sample were crushed to 1 mm. The product of the 1 mm was milled to 75% passing 75 µm and 106 µm respectively. One kilogram of milled sample was leached at 50% solids for each reagents with the two grind sizes. The strength of the three reagents (cyanide, jinchan and jinfu) were 500 and 1000 ppm. The natural pH of the sample was approximately 9 and raised to12 by the addition of lime. Samples were taken at predetermined intervals to monitor leaching kinetics for 24 hours. Solutions and solids sample were analysed by atomic adsorption spectroscopy (AAS) and fire assaying respectively.

Carbon-in-Leach (CIL) test was conducted using 3 kg of milled sample at 75% passing 75 µm. The milled sample was leached at 50% solids with the three reagents at a strength of 1000 ppm. The test conditions includes pH at 12, 12 g of carbon addition and 24 hours residence time for all the reagents.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Mineralogical analysis

The ore contained feldspars, chlorite, sericite**,** quartz, pyrite and carbonate as the major mineral phases shown in Figure 4.1. Percentage wise the ore studied is composed mainly of quartz (20-25%), feldspars (10-20%), minor chlorite (3-5%), sericite (3-4%), pyrite (4-6%) and carbonate (5-15%) (Table 4.1).

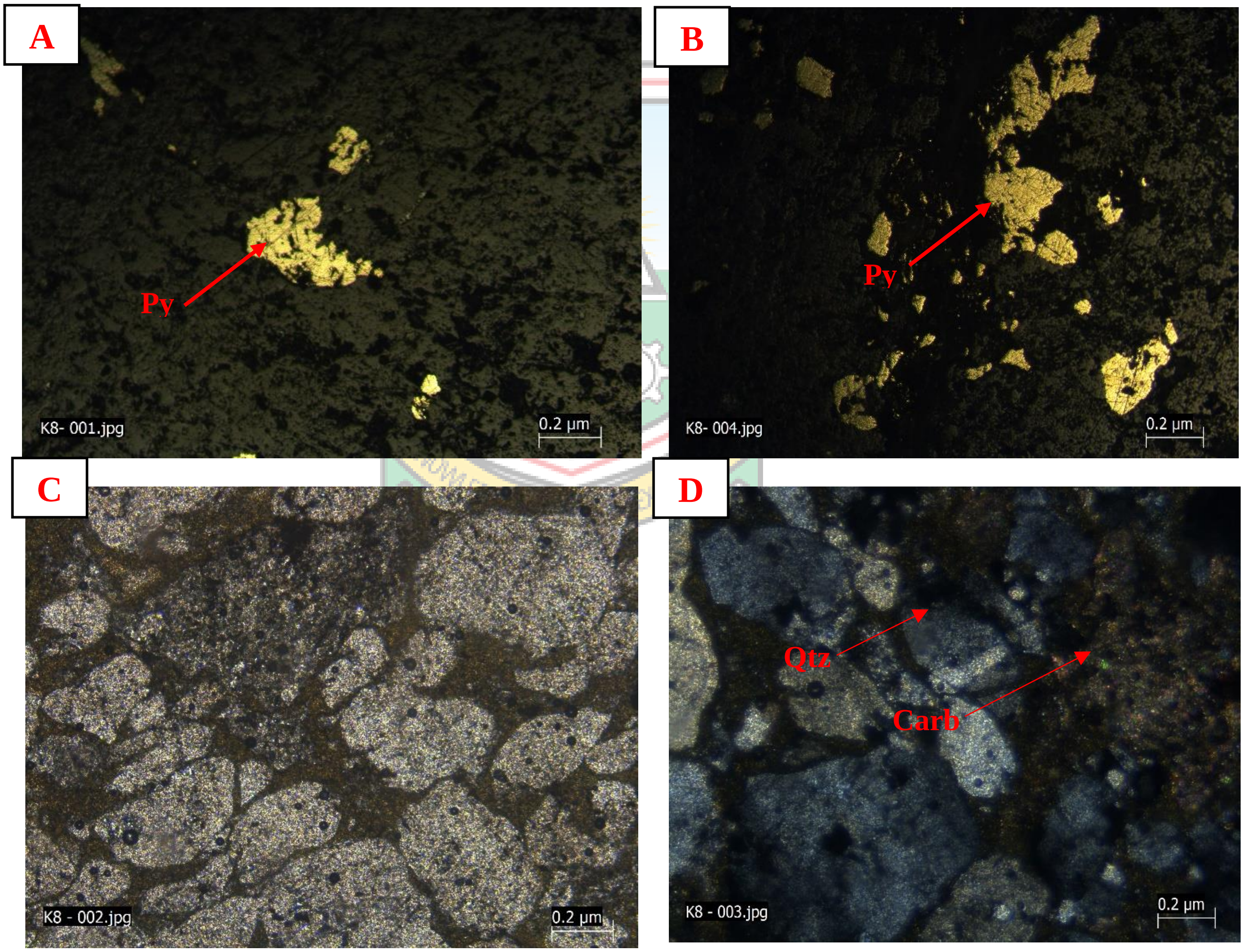

Figure 4. 1 Photomicrograph of sample showing A) and B) Some grains of Pyrite (Py) are observed C) and D) Quartz (Qtz) and carbonate (Carb) are observed

Table 4. 1 Modal composition of Mineral in the ore types

Minerals Modal	**Weight (%)**
Quartz	20-25
Feldspars	10-20
Carbonate	5-15
Sericite	3-4
Chlorite	3-5
Pyrite	4-6

From Figure 4.1, the photomicrograph of samples A and B which are polish section showed that there is a presence of some grains of pyrite. As an iron sulfide mineral, gold is commonly associated with pyrite. The presence of this mineral is usually a problem during gold cyanidation. Its dissolution during leaching can affect the rate of gold dissolution and may lead to a high reagents consumption (cyanide and oxygen) as showing in Equations 4.1 and 4.2. Currently most mines reduce the effect of pyrite on leaching in the CIL circuit by adding lead nitrate $Pb(NO_3)_2$.

$$2FeS + 12CN^- + 5O_2 + 2H_2O \Leftrightarrow 2Fe(CN)_6^{4-} + 2SO_4^{2-} + 4OH^- \qquad 4.1$$

$$2FeS_2 + 7O_2 + 2H_2O \rightarrow 2FeSO_4 + 2H_2SO_4 \qquad 4.2$$

From the photomicrograph of samples C and B (which are thin sections), quartz and carbonate are observed. Quartz is a silicate mineral which is formed from magma. From the Moh`s scale of hardness it is the 7th hardest mineral (Tetteh, 2017). The presence of this mineral can affect the comminution circuit. A high quartz content leads to an increase in the bond index which means the ore will consume more energy as the particle sizes are reduced in the grinding circuit. The presence of carbonate on the other hand may have an impact on the leaching and adsorption processes in the CIL circuit. The calcium content may have an advantage in the CIL by reducing the lime consumption in case of the presence of calcium carbonate. Feldspars, chlorite and sericite have insignificant effect on the gold processing.

4.2 Metallurgical analysis

4.2.1 Bond Ball Mill Grindability Test

Comminution is a process of liberating a mineral of interest from the associated gangue minerals by crushing and grinding. The Bond Ball Mill Grindability test gives an initial indication of the specific power consumption required to grind any particular ore. The mill power can be calculated from the Bond Work Index.

Figures 4.2 and 4.3 show the cumulative % passing against the particle sizes for the feed and the product. The 80% passing size for feed and products were 2860 µm and 58.26 µm respectively. Table 4.2, shows that the Bond Work Index was 14.5 kWh/t which is high. From the mineralogical test there is a high modal presence of quartz which is classified to be hard in the Moh`s scale table, the presence of this mineral in the ore may be contributing to its high Bond Work Index. Quartz requires more energy to grind and this will affect the Bond work index value and the time required for grinding. Figure 4,4 shows the grindability curve used in estimating the time required for grinding to a specific size.

Table 4. 2 Summary of Bond Ball Work Index determination

Sample	Gbp(g/rev)	Test Aperature P_i (µm)		Bond Ball Work Index (kWh/t)
		F_{80}	P_{80}	
GARA	1.0128	58.26	2860	14.5

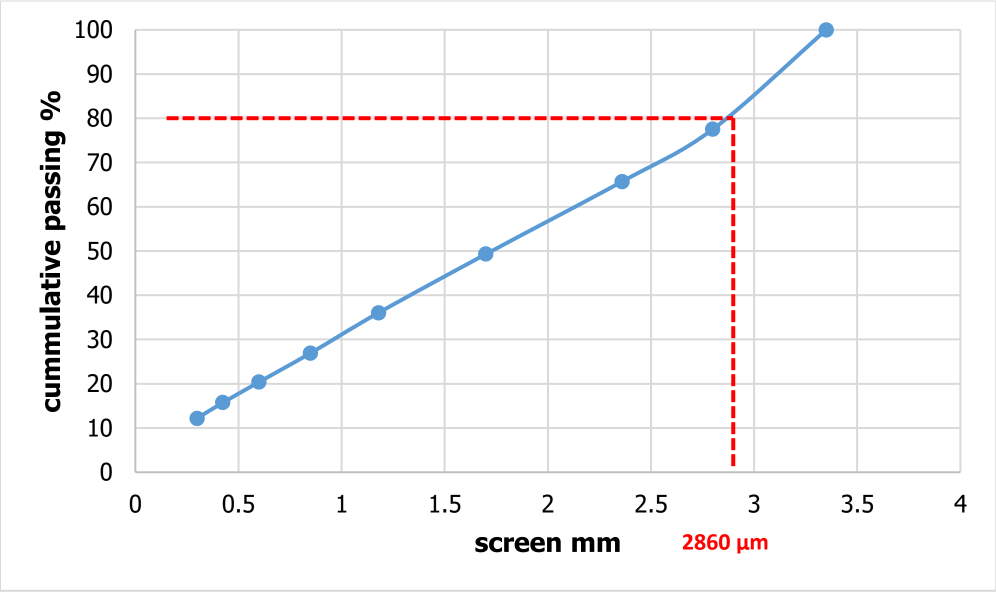

Figure 4. 2 Cumulative % passing against Particle Size (mm) for the Feed

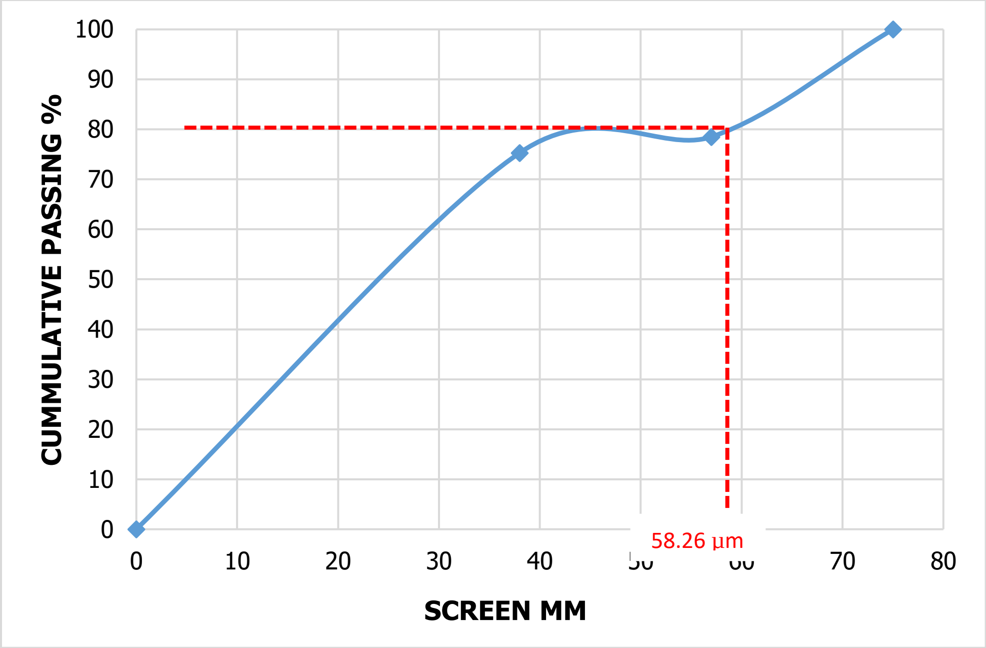

Figure 4. 3 Cumulative % passing against Particle Size (mm) for the product (-75 µm)

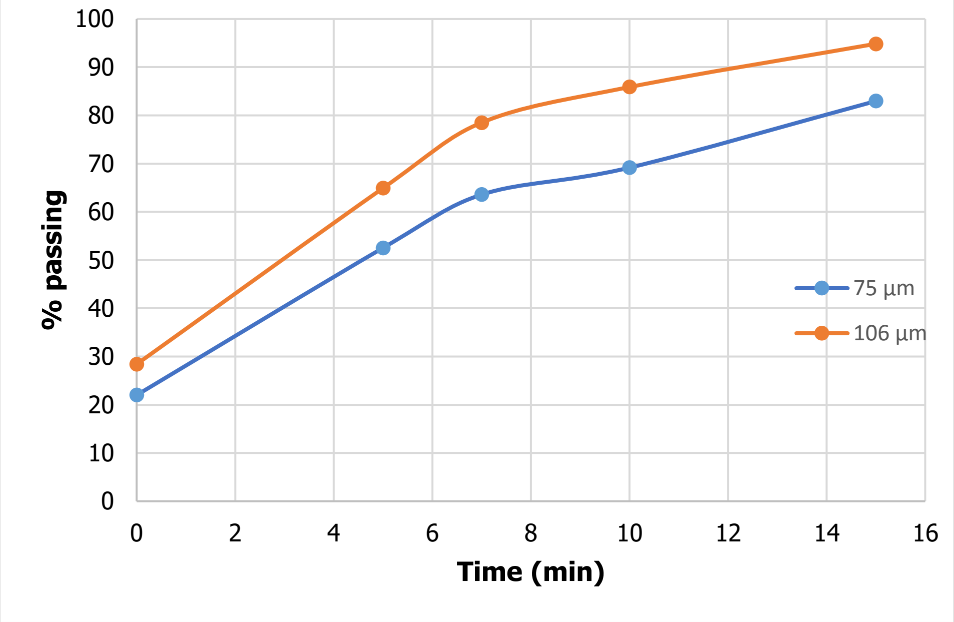

Figure 4. 4 Cumulative % passing against Time (min)

4.2.2 Ore Abrasive Test

The abrasive index was conducted to ascertain its abrasive resistance by friction and attrition in the mill. It is used to judge the wear rate of steel balls in the mill. By extension the abrasive work index determines the hardness of the rock (Cassapi, 1987). Table 4.3 shows the abrasion index is 0.5, from the section 2.3.2 in the literature review abrasive index parameters have been tabulated as shown in Table 2.2. The value of t_a obtained in this study suggest that the material is classified to be medium hard. The high quartz content in the ore have an impact on the bond work and the abrasion indices. The presence of quartz means more energy will be used in grinding and there will be a high liner wear rate during grinding.

Table 4. 3 Summary of Abrasive Index Determination

Sample Identify	rev/min	Screen size (mm)	Abrasive Index (mm)
Sample	53	4	0.5

4.2.3 Gravity concentration

Gravity concentration is used commonly for the recovery of free gold and gold associated with heavier minerals (Wills, 2006). The application of gravity concentration is useful in gold processing. The coarse gold particles recovered can be treated for maximum recovery and reduce the leaching retention time.

From Table 4.4, the concentrate grade was 20.48 g/t with a weight of 86.23 g, the feed grade was 1.71 g/t with a weight of 5000 g and a tailings grade of 0.83 g/t. Table 4.5, shows a gravity recovery of 20.65%. Currently the gravity concentration circuit is offline at the Loulo Process Plant. With this gold recovery %, there is a need to bring online the gravity circuit in the Loulo Process Plant, to recover the coarse gold particles and secondly to increase the efficiency of the leaching circuit.

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Table 4. 4 Summary of the gravity concentration test

Parameters	**Concentrate grade; c (g/t)**	**Weight of the concentrate; C (g)**	**Feed grade; f (g/t)**	**Feed weight; F (g)**	**Tailings grade (g/t)**
Value	20. 48	86.23	1.71	5 000	0.83
Recovery %	**20.65**				

4.2.4 Bottle Roll Test

Leaching was conducted for 24 hours with cyanide (C), Jinchan (J) and Jinfu (F) at 500 and 1000 ppm for 106 and 75 µm. Figures 4.5, 4.6 and 4.7 show various aspects of the leaching behavior.

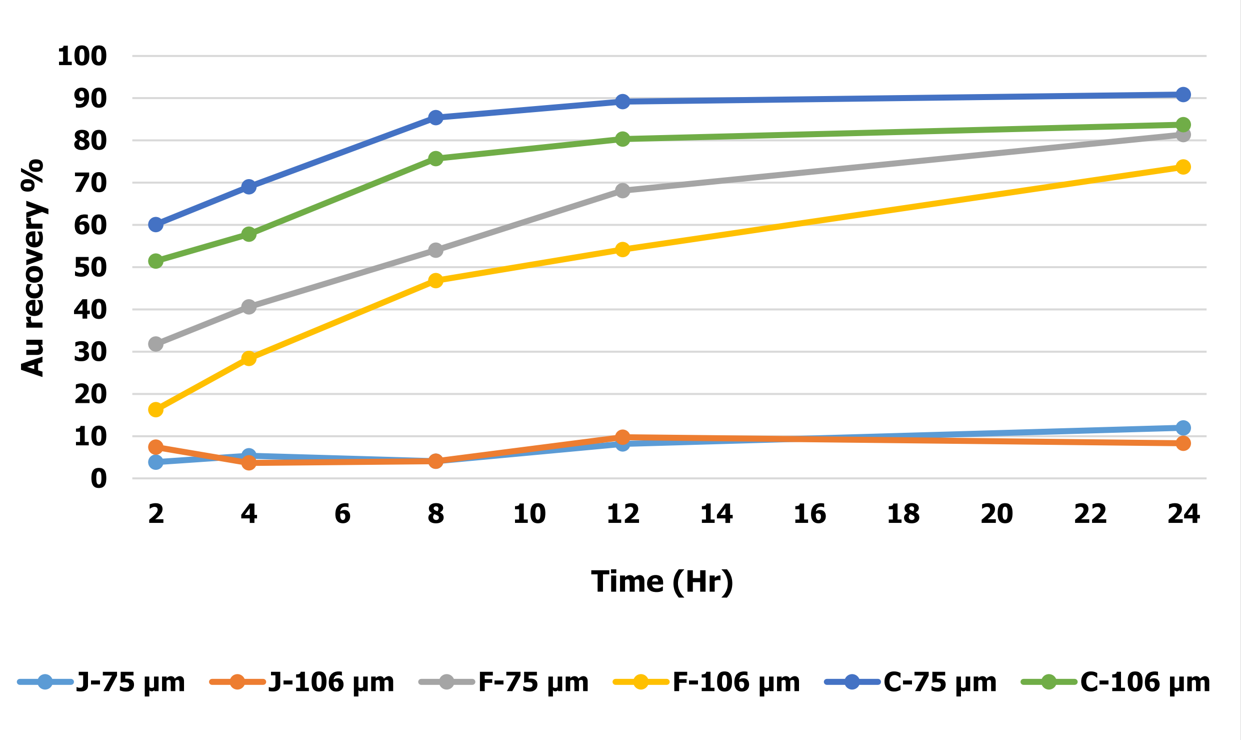

Figure 4. 5 Leaching Kinetics with the three reagents at 106 and 75 µm for 500 ppm

Leaching kinetics were conducted to have an idea on the dissolution rate of the mineral of interest within the time.

Effect of particle size 106 and 75 µm

- Cyanide

From Figure 4.5, it was observed that after 12 hours, 90% of gold is dissolved in solution for the 75 µm particles. 84% of gold is dissolved after 24 hours for the 106 µm particles. It can be deduced that the dissolution rate of gold at 75 µm is faster and higher than the 106 µm, this is due to the fact that grinding reduced the particles size significantly and hence the finer particles had a faster dissolution rate to their high surface area and higher degree of mineral liberation. Efficient grinding is known to increase the dissolution rate of gold by reducing the leaching time (Mardsen and House, 2006).

- Jinfu

It is observed in Figure 4.5 that at 24 hours 84% of gold is dissolved into solution for the 75 µm particles and 74% for the 106 µm particles. The highest gold recovery obtained using Jinfu is at 75 µm because of the particle size which increases the dissolution rate. Jinfu performed better when the particle size was finer. This followed the leaching behaviour using cyanide albeit with slightly lower recovery.

- Jinchan

Figure 4.5 shows that after 24 hours the dissolution rate of gold is still low with the two particle sizes (106 and 75 µm). The recovery of 75 µm is insignificantly higher than the 106 µm. Jinfu performed poorly. It is possible that higher concentrations may work better but may not offer a basis for comparison.

The particle size may have had an impact on the leaching circuit. When the particle sizes are coarser the contact time between gold and the lixivant increases due to the lower exposure surface area of gold. This leads to a slow leaching rate and requires a longer leaching time to observe any appreciable gold recovery (Marsden and House, 2006).

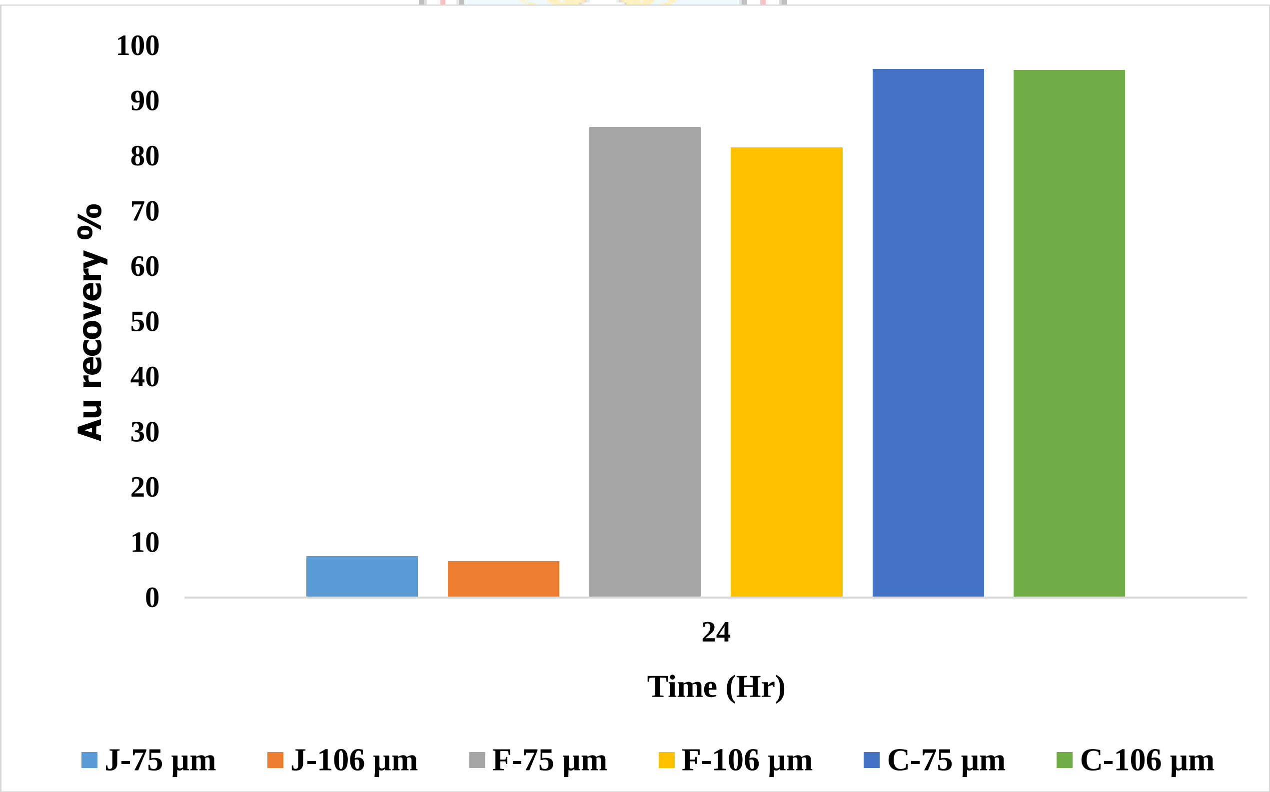

Figure 4. 6 Leaching with the three reagents at 106 and 75 µm for 1000 ppm

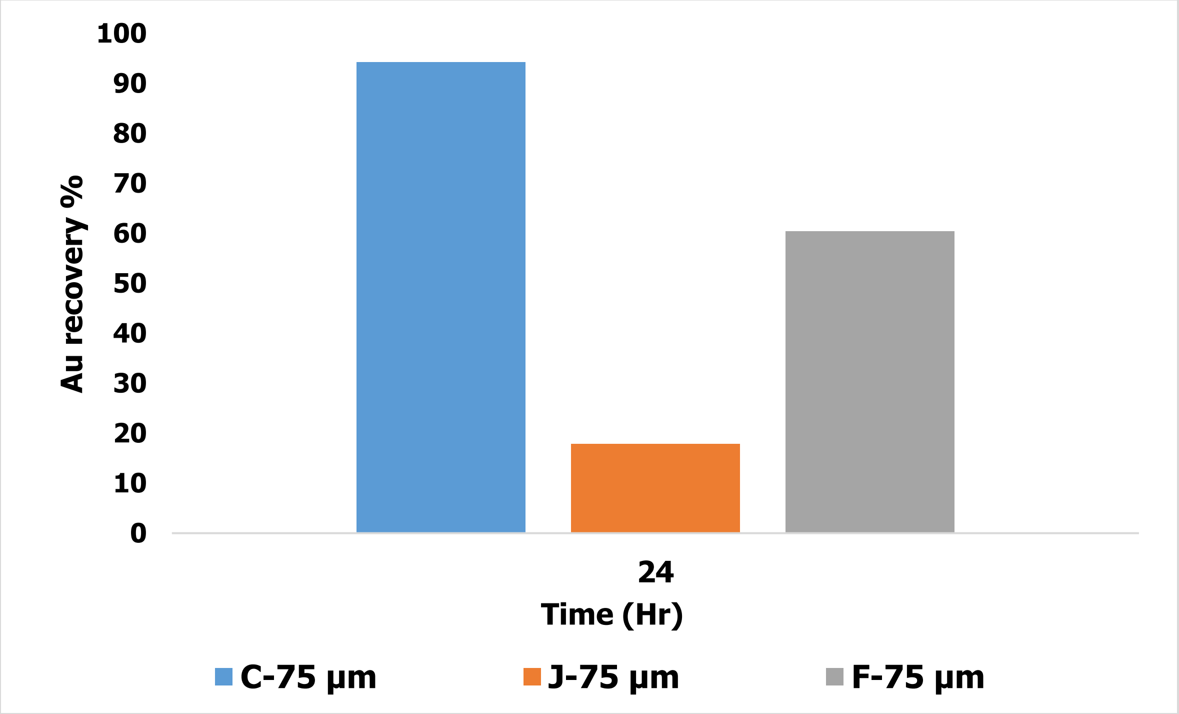

Figure 4. 7 Carbon-in-Leach with the three reagents at 1000 ppm for 75 µm

- Cyanide

From Figure 4.7, it is observed that the recovery of gold from CIL is much higher at 24 hours. 95% of gold is recovered, this may be due to the activated carbon addition.

- Jinfu

It is observed in Figure 4.7 that the recovery of gold was not high, 60% of gold is recovered from CIL. From Figure 4.6, the gold dissolution with Jinfu was 85%, only 60% was adsorbed by activated carbon and 25% of gold is left in the solution as deduced from leaching without activated carbon addition. It is likely that there might be some interactions between the activated carbon and Jinfu which requires further investigation.

- Jinchan

Figure 4.7 shows that Jinchan performed poorly with a recovery of 18% of gold which is really low compared to those obtained using the other reagents. From Figures 4.5 and 4.6 the dissolution rate of gold after 24 hours was low.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the various test works carried out in this study, the following are major conclusions:

a. The ore at Gara in Loulo Mine was primary rock which was composed mainly of quartz, feldspars, minor minerals which were chlorite, sericite and other minerals like pyrite and carbonate;

b. The ore reported a high work index of 14.5 kWh/t, this may be due the high quartz content in the ore;

c. Abrasion index was 0.5 and the rock from Loulo underground gold mine (Gara) was classified as medium hard rock which can increase the liner wear rate and energy usage in grinding;

d. Gravity concentration gave a recovery of about 20% which suggests that the ore may contain gravity recoverable gold;

e. The results from bottle roll tests showed that at 500 ppm and at 75% passing 75 µm, about 90% of gold was recovered by cyanidation, 84% and 12% of gold were recovered by Jinfu and Jinchan respectively at 24 hours. At 75% passing 106 µm, the results from cyanide, Jinfu and Jinchan were 84%, 74% and 8% respectively. The results of the three lixiviants at 75 µm performed better than the 106 µm; and

f. At 1000 ppm, 75% passing 75 µm, 96% and 86% of gold were recovered using cyanide and Jinfu at 24 hours. Jinchan which is a poor low alternative to cyanidation for the concentrations studied. The 75 µm with the three lixiviant performed better than the 106 µm system, this is due to the fine particle size which presented a higher surface area for leaching. The results from CIL test at 1000 ppm for 75 µm with the three lixiviants showed that cyanide gave the best recovery at 95% followed by Jinfu at 60% and Jinchan at 18%. The low recovery for Jinfu and Jinchan may be due to the interactions between the activated carbon and Jinfu which should be probed further. Cyanide performed better than Jinfu which performed better than Jinchan.

5.2 Recommendations

It is recommended that:

a. The mine should consider a gravity circuit since the ore contains gravity gold.
b. Further studies on a CIL system using Jinfu should be conducted to understand the interaction it has with the activated carbon.
c. Further work should be conducted on the cost benefit of the other lixiviants, since this work did not take into consideration the economic implications of selecting a particular lixiviant.

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APPENDICES

APPENDIX A Particle Size Distribution Results for Bond Index Feed

Screen (mm)	Weight (g) oversize	% oversize	Cumulative % oversize	Cumulative % passing
3.35	0	0.00	0.00	100.00
2.8	111.4	22.47	22.47	77.53
2.36	58.6	11.82	34.29	65.71
1.7	81.3	16.40	50.69	49.31
1.18	65.7	13.25	63.94	36.06
0.85	45.2	9.12	73.05	26.95
0.60	32.5	6.56	79.61	20.39
0.425	23	4.64	84.25	15.75
0.3	17.6	3.55	87.80	12.20
0.212	15.2	3.07	90.86	9.14
0.15	10.1	2.04	92.90	7.10
0.106	9.1	1.84	94.74	5.26
0.09	3.2	0.65	95.38	4.62
0.075	4.6	0.93	96.31	3.69
0	18.3	3.69	100.00	0.00
Total	495.80		**F_{80},mm**	**2.86**
			F_{80},µm	**2860**

APPENDIX B Particle Size Distribution Results for Bond Index Product

PSD FOR SAMPLE -75µm				
Screen (µm)	**Weight (g) Oversize**	**% Oversize**	**cumulative % Oversize**	**cumulative % Passing**
75	0.0	0.00	0.00	100.00
57	43.0	21.50	21.50	78.50
38	6.4	3.20	24.70	75.30
0	150.6	75.30	100.00	0.00
Total	200.00		**P_{80}, µm**	**58.26**

APPENDIX C Net gram /Rev determination of Bond Work Index

Cycle No.	**New feed, g**	**No of rev**	**Mass of +75um mesh produced, g**	**Mass of -75 mesh produced, g**	**Loss from milling, g**	**Total refill, g**	**Net g per rev**	**Mass of -75 in feed, g**	**Time for rev, sec**	**Time for rev, min**
1	1247.1	100.0000	1057.4000	185.9000	3.8000	189.7000	1.4367	46.03	85.7142857	1:26
2	1247.1	248.0097	993.2000	249.3000	4.6000	253.9000	0.9955	7.00183542	212.579761	3:33
3	1247.1	357.9184	860.0000	383.2000	3.9000	387.1000	1.0553	9.37146027	306.787237	5:07
4	1247.1	337.6273	893.6000	350.1000	3.4000	353.5000	1.0047	14.2878782	289.3948	4:49
5	1247.1	354.6495	887.1000	355.7000	4.3000	360.000	0.9783	13.0477007	308.985308	5:04
IPP	**356.3142857**	3.5	70	60	86400		**1.0128**			
	100									

APPENDIX C Cumulative % passing the two Particle Sizes against the time

time (min)	**initial mass(g)**		**mass of oversize(g)**		**mass of undersize (g)**		**% passing**	
	75µm	**106µm**	**75µm**	**106µm**	**75µm**	**106µm**	**75µm**	**106µm**
0	129	129	100.61	92.35	28.39	36.65	22.00775	28.41085
5	129	129	61.23	45.24	67.77	83.76	52.53488	64.93023
7	129	129	46.99	27.73	82.01	101.27	63.57364	78.50388
10	129	129	39.78	18.21	89.22	110.79	69.16279	85.88372
15	129	129	21.96	6.65	107.04	122.35	82.97674	94.84496

APPENDIX D Particle size Distribution Results for Abrasive Index

Screen size(mm)	Mass (g)	% of retained	Cumulative % oversize	Cumulative % undersize
+40	1922.8	64.08	64.08	35.92
-40+22.4	553	18.43	82.51	17.49
-22.4+13.2	262.5	8.75	91.26	8.74
-13.2+6.7	89	2.97	94.23	5.77
-6.7+4	27.8	0.93	95.16	4.84
-4+2.36	13.3	0.44	95.6	4.4
-2.36+1.18	10.9	0.36	95.96	4.04
-1.18+0.425	20.3	0.68	96.64	3.36
-0.425+106	53.8	1.79	98.43	1.57
-106+0	47	1.57	100	0
Total	3000.4			

APPENDIX E Leaching Kinetics Results at 500 and 1000 ppm for 75 and 106 µm

Concentration ppm	500						1000		Head grade g/t
g/t	Solution					Solid	Solution	Solid	
Hrs	2	4	8	12	24	Tails	24	Tails	
J-75 µm	0.063	0.088	0.067	0.134	0.196	1.44	0.102	1.26	1.71
J-106 µm	0.091	0.045	0.05	0.12	0.102	1.13	0.094	1.35	
F-75 µm	0.563	0.72	0.957	1.207	1.442	0.33	1.385	0.24	
F-106 µm	0.315	0.55	0.908	1.051	1.429	0.51	1.495	0.34	
C-75 µm	0.987	1.134	1.402	1.465	1.492	0.15	1.6	0.44	
C-106 µm	0.98	1.102	1.442	1.53	1.595	0.31	1.607	0.3	

APPENDIX F Carbon-in-Leach Results at 1000 ppm for 75 µm 24 hours

conc, ppm	1000		Head grade g/t
g/t	Solution	Solid	
Hrs	24	Tails	
C-75 µm	0.1	2.63	48.14
J-75 µm	<0.005	39.54	
F-75 µm	<0.005	19.04	

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