PHYSICOCHEMICAL CHARACTERIZATION AND DIAGNOSTIC LEACHING OF COMPLEX COPPER-GOLD ORE

MUHAMMAD AIMAN BIN MOHD BUKHORI

UNIVERSITI SAINS MALAYSIA

2022

SCHOOL OF MATERIALS AND MINERAL RESOURCES ENGINEERING

UNIVERSITI SAINS MALAYSIA

PHYSICOCHEMICAL CHARACTERIZATION AND DIAGNOSTIC LEACHING OF COMPLEX COPPER-GOLD ORE

By

MUHAMMAD AIMAN BIN MOHD BUKHORI

Supervisor: DR NURUL 'AIN BINTI JABIT

Dissertation submitted in partial fulfillment of the requirements for the degree of

Bachelor of Engineering with Honours

(Mineral Resources Engineering)

Universiti Sains Malaysia

July 2022

DECLARATION

I hereby declare that I have conducted, completed the research work and written the dissertation entitled “Physicochemical Characterization and Diagnostic Leaching of Complex Copper-Gold Ore”. I also declare that it has not been previously submitted for the award of any degree or diploma or other similar title of this for any other examining body or university.

Name of the student: Muhammad Aiman Bin Mohd Bukhori Signature:

Date: 18 August 2022

Witness by,

Supervisor: Dr Nurul ‘Ain Binti Jabit Signature:

Date: 18 August 2022

ACKNOWLEDGEMENT

In the name of Allah, the Most Gracious and the Most Merciful. First and foremost, I thank Allah for providing me with the determination, fortitude and direction I needed to finish my dissertation and overcome all of the challenges I had during this project.

I would like to show my gratitude to my supervisor, Dr. Nurul'Ain binti Jabit, who had played a significant role in this project. It is an honour to work under her supervision and I will be eternally grateful for her endless encouragement, advice and suggestions during this project.

I would like to express my appreciation to the School of Materials and Mineral Resources Engineering for providing the student with all of the necessary facilities and equipment to complete this research. I am indebted to all of the technicians that had tirelessly assisted me and invested their time in this adventure.

I would also like to take this opportunity to thank my family for their unwavering physical, mental and financial support. Furthermore, I would like to express my gratitude to Fathin Atiqa Binti Merdan for being my source of inspiration and motivation. Working with her created wonderful moments that will be cherished. She is one of the reasons for me in choosing this title and I wish her a beautiful future ahead in life. Last but not least, I dedicated this to my friends, who have been involved in this project's success by lending a helping hand and encouraging words. Thank you very much.

TABLE OF CONTENTS

ACKNOWLEDGEMENT ..... **iii**

TABLE OF CONTENTS ..... **iv**

LIST OF TABLES ..... **viii**

LIST OF FIGURES ..... **ix**

ABSTRAK ..... **xii**

ABSTRACT ..... **xiii**

CHAPTER 1 INTRODUCTION **1**

1.1 Background 1

1.2 Problem Statement 2

1.3 Objectives 2

1.4 Significant of Research 3

1.5 Scope of Research 3

1.6 Thesis Outline 5

CHAPTER 2 LITERATURE REVIEW **6**

2.1 Introduction 6

2.2 Types of Gold 7

2.2.1 Free Milling Gold 7

2.2.2 Refractory Gold 7

2.3 Gold Mineralogy 8

2.3.1 Gold Properties 8

2.3.2 Gold Deposits 10

2.3.3 Geology of The Gold-Belt in East Malaysia 13

2.4 Classification of Gold 13

2.5 Factors Golds in Extractive Metallurgy 15

2.5.1(a) Gold grain size 15

2.5.1(b) Sub microscopic gold 16
2.5.1(c) Coatings on the surface of the gold 16
2.5.1(d) Silver in gold minerals 16
2.5.1(e) Gold tellurides, aurostibite and maldonite 16
2.5.1(f) Prescence of cyanide and oxygen consumers 16
2.6 Factors Affecting Gold in Dissolution 17
2.6.1(a) Temperature 17
2.6.1(b) pH 17
2.6.1(c) Degree of Agitation 18
2.7 Diagnostic Leaching 18
2.8 Fire Assay 21
2.8.1 Aqua Regia Dissolution 25
2.8.2 Bottle Roll Test 26
CHAPTER 3 METHODOLOGY 27
3.1 Introduction 27
3.2 Materials And Reagents 28
3.3 Ore Preparation 29
3.3.1 Drying 29
3.4 Grinding 29
3.4.1(a) Ring Mill 29
3.4.1(b) Agate Mortar 30
3.5 Sampling 30
3.5.1(a) Johns Riffle Splitting 30
3.6 Sieving 31
3.7 Fire Assay Analysis 31
3.8 Cyanidation/Bottle Roll Test 32
3.9 Solvent Extraction 33

3.10 Diagnostic Leaching 34

3.11 Determination of Gold Content and Associated Minerals by Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-MS) 38

3.12 Mineral Composition Analysis 39

3.12.1 X-Ray Diffraction (XRD) 39

3.12.2 X-Ray Fluorescence (XRF) 39

3.12.3 Loss Of Ignition (LOI) 39

3.13 Morphology Study 41

3.13.1 Polish Section Preparation 41

3.13.2 Optical Microscopy 41

3.13.3 Scanning Electron Microscopy (SEM) Analysis 42

CHAPTER 4 RESULTS AND DISCUSSION 43

4.1 Introduction 43

4.2 Particle Size Analysis (MALVERN) 44

4.3 Loss on Ignition 46

4.4 Mineral Composition Study 47

4.4.1 X-ray Fluorescence (XRF) 47

4.4.2 X-ray Diffraction (XRD) 53

4.4.3 Optical Microscope Study 57

4.4.4 Scanning Electron Microscopy (SEM) 62

4.5 Determination of Gold 65

4.5.1 Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) 65

4.5.2 Fire Assay Technique 66

4.5.3 Cyanidation/Bottle Roll Test 68

4.6 Diagnostic Leaching 69

CHAPTER 5 CONCLUSION AND FUTURE RECOMMENDATIONS 73

5.1 Conclusion 73

5.2 Recommendations for Future Research 74

REFERENCES 75

LIST OF TABLES

Page

Table 2.1 Physical properties of gold. 8

Table 2.2 Chemical properties of gold. 9

Table 2.3 Gold deposits (Gasparrini, 1993). 11

Table 2.4 Classification of gold (Zhou *et al*., 2004). 14

Table 2.5 Classification of Gold by Forms and Carriers (Zhou *et al.*, 2004). 15

Table 2.6 Selective pre-treatment leach stages and the minerals destroyed (Lorenzen, 1995). 19

Table 2.7 Composition and functions of chemical reagents used in flux (Michaud, 2016). 22

Table 3.1 Materials and chemical reagents used. 28

Table 3.2 Conditions of diagnostic leaching of ore sample. 38

Table 4.1 Loss on ignition value. 47

Table 4.2 Mineral composition of JIRA sample from XRF analysis. 48

Table 4.3 Mineral composition of C1 sample from XRF analysis. 49

Table 4.4 Mineral composition of C2 sample from XRF analysis. 51

Table 4.5 Mineral composition of EAB III sample from XRF analysis. 52

Table 4.6 Result from ICP-MS analysis for sample JIRA 65

Table 4.7 The mass recorded for each sample and process. 67

Table 4.8 The gold concentration of samples undergoing fire assay. 67

Table 4.8 The gold concentration of sample undergoing bottle roll test. 68

Table 4.9 Diagnostic leaching of JIRA sample. 70

Table 4.10 Result of Diagnostic Leaching 71

LIST OF FIGURES

Page

Figure 2.4 Effect of temperature on gold dissolution rate in aerated 0.25% KCN solution (Sarina Ramli and Osman, 2015) 17

Figure 2.5 The diagnostic leaching procedure (Lorenzen, 1995) 20

Figure 3.1 Overall process flowchart 27

Figure 3.2 Flowchart of diagnostic leaching procedure 37

Figure 4.1 Particle size analysis for JIRA sample 44

Figure 4.2 Particle size analysis for EAB III 45

Figure 4.3 Particle size analysis for C1 sample 45

Figure 4.4 Particle size analysis for C2 sample 46

Figure 4.5 XRF analysis of major compounds in JIRA sample 48

Figure 4.6 XRF analysis of major compounds in C1 sample 50

Figure 4.7 XRF analysis of major compounds in C2 sample 51

Figure 4.8 XRF analysis of major compounds in EAB III sample 52

Figure 4.9 XRD diffractogram showing the major phases of identified minerals in sample JIRA. 54

Figure 4.10 XRD diffractogram showing the major of phases identified in sample C1. 55

Figure 4.11 XRD diffractogram showing the major of phases identified in sample C2. 56

Figure 4.12 XRD diffractogram showing the major of phases identified in sample EAB III. 57

Figure 4.13 fine JIRA 5X 58

Figure 4.14 fine JIRA 10X 58

Figure 4.15 coarse JIRA 5X 58

Figure 4.16 coarse JIRA 10X.....58

Figure 4.17 fine C1 5X.....59

Figure 4.18 fine C1 10X 59

Figure 4.19 coarse C1 5X.....60

Figure 4.20 coarse C1 5X.....60

Figure 4.21 fine C2 5X 60

Figure 4.22 fine C2 5X 60

Figure 4.23 coarse C2 10X.....61

Figure 4.24 coarse C2 10X.....61

Figure 4.25 fine EAB III 5X 61

Figure 4.26 coarse EAB III 10X 61

Figure 4.27 fine JIRA 500X.....62

Figure 4.28 fine JIRA 2000X.....62

Figure 4.29 coarse JIRA 500X.....62

Figure 4.30 coarse JIRA 500X.....62

Figure 4.31 fine C1 500X.....63

Figure 4.32 fine C1 2000X.....63

Figure 4.33 coarse C1 500X.....63

Figure 4.34 coarse C1 2000X.....63

Figure 4.35 fine C2 500X.....63

Figure 4.36 fine C2 2000X.....63

Figure 4.37 coarse C2 500X.....64

Figure 4.38 coarse C2 2000X.....64

Figure 4.39 fine EAB III 500X 64

Figure 4.40 fine EAB III 2000X 64

Figure 4.41 coarse EAB III 500X 64

Figure 4.42 coarse EAB III 2000X 64

Figure 4.43 Extraction of gold following each step in diagnostic leaching.....72

PHYSICOCHEMICAL CHARACTERIZATION AND DIAGNOSTIC LEACHING OF COMPLEX COPPER-GOLD ORE

ABSTRAK

Dalam kajian ini, bijih emas diperolehi dari Malaysia Timur. Empat sampel diperolehi daripada setiap telerang yang berbeza. Matlamat penyelidikan ini adalah untuk mengenal pasti mineral yang berkaitan dan kandungan emas dalam sampel yang diambil. Pelbagai analisis pencirian telah dijalankan untuk mengenalpasti morfologi, kandungan kimia dan pengenalpastian fasa mineral menggunakan mikroskop optik, XRF, XRD, dan analisis FESEM. Sebilangan besar komposisi sampel adalah saling berkait dengan kuarza, aluminosilikat, dan unsur karbon; pirit, kalkopirit, arsenopirit, magnetit, dan hematit. Daripada sampel bahagian pengilat di bawah mikroskop optik, pirit dan butiran kuarza telah dikenalpasti. Dua kaedah telah dijalankan bagi menentukan kandungan emas dalam sampel iaitu analisis ‘fire assay’ dan ‘bottle roll’. Kedua-dua kaedah analisis ini memerlukan AAS untuk menentukan jumlah kandungan kepekatan emas dalam larutan. Kandungan emas tertinggi di kalangan sampel ialah JIRA dengan 56.98 g/t dan sampel bijih ‘free mill’ bottle roll tertinggi juga daripada sampel JIRA dengan 2.548 g/t. Eksperimen pelarut resapan diagnostik hanya dijalankan pada sampel JIRA sahaja. Daripada keputusan yang didapati, kandungan kepekatan yang paling tinggi adalah daripada ‘direct cyanidation’ dengan 52.74%. Daripada dapatan ini, keputusan boleh diberi bahawa bijih emas daripada sampel JIRA adalah jenis refraktori kerana ‘direct cyanidation’ memberi keputusan kurang daripada 80%.

PHYSICOCHEMICAL CHARACTERIZATION AND DIAGNOSTIC LEACHING OF COMPLEX COPPER-GOLD ORE

ABSTRACT

In this study, the gold ores were obtained from East Malaysia. Four samples were obtained from each different vein. The goal of this research was to identify the associated minerals and the deportment of gold in the collected samples. Numerous characterization analyses were carried out to explore the morphology, chemical content and identification of mineral phases using optical microscope, XRF, XRD, and FESEM analysis. The majority of the samples' composition made up of quartz, aluminosilicates, and carbonaceous elements; pyrite, chalcopyrite, arsenopyrite, magnetite, and hematite. From the polish section sample under optical microscopy, pyrite, and quartz grains was identified. Two methods were conducted in order to determine the gold content in the samples, which are fire assay analysis and bottle roll test. The highest gold content among the sample is JIRA with 56.98 g/t and the highest free milling bottle roll ore sample obtained is also JIRA with 2.548 g/t. The diagnostic leaching experiment was conducted on JIRA sample only, highest recovery obtained from direct cyanidation giving results of 52.74%. From the result, it can be concluded that the gold ore is refractory type as direct cyanidation gives recovery less than 80%.

CHAPTER 1

INTRODUCTION

1.1 Background

The country's largest gold producer is found in Pahang and Kelantan, which are located in Peninsula Malaysia's Central Belt. Before the establishment of significant gold deposits, such as those in Australia and South Africa, Malaysia was one of the top producers of the metal. Prior to the Portuguese invasion of Malacca in 1511, it was also known as "Aurea Chesonese" or "Golden Peninsula." (Ariffin & J Hewson, 2007). Small-scale gold mining has historically been practised widely throughout Malaysia, especially in the Central Belt of Peninsular Malaysia. Those areas may have a better potential for the gold deposit sector.

The Central "Gold" Belt, a 20 km wide, significant N-S trend of gold mining location, demonstrates the crucial part hydrothermal fluids had in the growth of gold in Peninsular Malaysia, particularly in the North Pahang and Kelantan region. (Ariffin, 2012).

The gold mining industry has recently faced challenges due to the exhaustion of easily extracted oxide ores and the emergence of sulphide ores beneath the oxide deposits. Therefore, the most important factor in creating an optimal extraction path is a deeper understanding of the linked minerals and gold distribution (Goodall, et al., 2005). The exploration has now shift to other region that has a history of gold mining such as Sabah, East Malaysia, that previously famous with porphyry copper. Porphyry copper region usually associated with a complex mineralogy of epithermal gold.

1.2 Problem Statement

A wide range of geological processes can result in the formation of gold deposits. Primary deposits, alluvial or placer deposits, and laterite deposits are the three principal types of deposits classified. In the deposit, all three forms of ore are frequently mixed. Gold ore formation varies depending on where it is found. Mineral decomposition and phase differ for each ore. The sample used in this study is a complex gold ore comes from East Malaysia.

The samples from this location are still recent, and due to lack of information estimation on mineralogy of the samples can only be taken from exploration on surrounding area. Composition and phase studies are required to identify the grade of gold ore and the mineral with which it is linked. Furthermore, the mineralization of this complex gold ore must be investigated, whether it exists as free gold or is interlocked with other minerals. It is critical to characterize this complicated orebody in order to determine the most efficient method and processing for extracting gold. Mineral composition study can lead to increased accuracy and precision in decision-making when it comes to identifying the sort of mineral that is correlated with gold.

1.3 Objectives

The following objectives are expected to achieve:

1) To characterize gold ore and gold-bearing minerals and its associate mineral after pre-concentration process.

2) To determine total gold contain and free milling gold in the samples.

3) To evaluate the refractory behavior of gold in cyanidation process.

1.4 Significant of Research

Gold is a valuable mineral with a broad range of applications. Some ores can be treated directly with cyanide, while others require pre-treatment to remove gangue minerals before the gold can be recovered. The main reasons on conducting this project are to provide enough information for the collected samples on gold ore and associated mineral. A quantitative analysis is done to provide numerical data towards the concentration of gold that will represent the actual sampling site. Deportment of gold can be studied using diagnostic leaching experiment and its design is flexible due to dependent on mineralogical data of the sample to be examined. Mineralogical data can be obtained from a detailed mineralogical characterization. This crucial experiment was developed by Anglo American Research Laboratories (AARL) in the mid-1980's (Lorenzen, 1995). The objective behind diagnostic leaching is to utilize selective oxidative acid leaching to remove the least stable mineral in a sample matrix, then cyanide will be added to extract the gold released by the breakdown of this mineral. The process is repeated as the residue obtained will be further leached with a more oxidative acid leach to destroy other minerals, amount of gold that encapsulated in each mineral can be recorded (Lorenzen and Van Deventer, 1992). With data retrieved from this experiment, modification on ways to treat the ore can be done by responsible metallurgist at the plant.

1.5 Scope of Research

This research work conducted to identify the associate minerals and deportment of gold in the samples obtained from East Malaysia. Four samples obtained from East Malaysia were named as Jira, C1, C2, and EAB III. The earliest stage of this work was sample preparation for polish section to conduct Optical Microscopy (OM)

and Scanning Electron Microscopy (SEM). Then, the samples will go through drying before proceed with comminution to prepare ground sample. Grinding process using ring mill was carried out. The purpose of grinding is to liberate and reduce the size of the ore to a desired size, and in this occasion is less than 75μm. To obtain representative and avoiding bias, sampling was conducted using Johns Riffle splitter. Particle size analysis was conducted to ensure grounded samples achieve desired particle size for further experimental work. Each of the samples were divided into three parts for characterization study, determination of gold content and diagnostic leaching.

Mineralogical characterization using OM and SEM, X-ray Diffraction (XRD) spectroscopy and X-ray Fluorescence (XRF) spectroscopy were conducted to study chemical composition, morphology and phase identification.

All samples were also subjected to fire assay analysis and cyanidation bottle roll test. Fire assay was carried out to determine total gold content in ore while cyanidation bottle roll test was conducted to determine free milling gold in the ore. Information on refractoriness of gold ore can be obtained from fire assay and cyanidation bottle roll test. Residues from cyanidation bottle roll test was also treated with fire assay to determine remaining of interlocked gold after extraction of free gold from ore. Concentration of gold was determined using Atomic Absorption Spectrometry (AAS) instrument.

Diagnostic leaching was carried out to study deportment of gold and the information retrieved can be utilized to improve recovery rate of the ore. Selective oxidative acid leaching was employed in diagnostic leaching to solubilize the least stable minerals associated with gold in the sample matrix before they were destroyed. This was followed by cyanidation to extract free gold from the minerals that had been

destroyed. All solutions obtained were sent for AAS analysis to determine gold concentration in the solution.

1.6 Thesis Outline

This thesis consists of five primary chapters and divided into a few subchapters to explain each work carried out in completing this study. The first chapter contains this research's background, problem statement in relation with this research, objective of this study, significance and scope of the research work.

In the following chapter, literature review, all relevant information for this research was sourced from journals, papers, and previous studies. Generally, covering gold ore types, gold geology and mineralogy, mineralogical analysis characterization methods, and diagnostic leaching experiments.

In chapter three, all methods that were applied for this research work is detailed out. The next chapter presented all data and findings obtained from this study. Experimental data were retrieved from mineral characterization, fire assay, cyanidation bottle roll test, aqua regia acid digestion and diagnostic leaching experiment.

Final chapter of this study will gives an overall conclusion and provides recommendations and suggestions for improvement that can be taken for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Gold is among the most valuable mineral on the planet. Its physical features, such as its bright yellow color and glittering surface, make it have attractional value to human being. Due to its demand, recovering and providing this mineral can be economically profitable. Gold is one of the most inert metals known to man, with a density of 19.32 grammes per cubic centimeter. Gold is also known as a 'noble' metal, which is an alchemistic terminology for metals that do not oxidize under normal conditions, such as silver (Ag) and platinum (Pt) (Pt). Gold is classified as a 'Transition Metal' because it is ductile, malleable, and good conductor of electricity and heat, according to the periodic table (Kirkemo et al., 1932). Due to its ductile and malleable qualities, gold can be formed into a variety of shapes and patterns. It can be pulled out into thin wire and joined with other metals via the alloying process. It can also be hammered into extremely thin sheets or leaves.

Treating gold, it does dissolve readily in aqua regia, but metallic gold is not chemically reactive, unaffected by oxygen, and inert to attack by a concentrated, hot mineral acid (Ishida and Orimo 1994, Ammen 1997, Cotton et al. 1999):

$$Au + 4H^+ + 4Cl^- + NO_3^- \rightarrow AuCl_4^- + 2H_2O + NO$$

In the presence of oxygen or hydrogen peroxide, gold also dissolves in alkali cyanide solutions to produce a cyano complex:

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

In comparison to other metals, the average concentration of gold in the world is less than 0.005 g/t (Marsden and House, 2006).). In contrast to silicates, gold tends to concentrate in subsequent metallic or sulphidic phases and residual hydrothermal fluids now disseminated. Rocks that are high in clays and low in carbonates are the best

sources of gold. If gold is present as a minor component in a base metal concentrate, it may be recovered as a byproduct during the manufacturing of the base metal.

2.2 Types of Gold

Gold ores usually divided into two major types which are free-milling and refractory types. These two varieties of gold are treated and recovered in different ways. Refractory type is quite difficult to treat and yields low recoveries or only acceptable recoveries with the use of more reagent or more complex processes, whereas free-milling ore is often straightforward to treat and can be recovered 90% with traditional cyanide leaching (Vaughan, 2004).

2.2.1 Free Milling Gold

Gold ores can be divided into two types - free milling (non-refractory) and refractory type. Free milling gold ores are easy to process. Free milling gold are those from which conventional cyanide leaching may recover more than 90% of the gold (Zhou et al., 2004).

2.2.2 Refractory Gold

Refractory and complicated constitution of gold ores is one of the major obstacles to gold extraction. If gold recovery by cyanidation is less than 80%, the ore is referred to as refractory (Marsden and House, 2009; Zhou et al., 2004). In general, the following factors may contribute to the refractoriness of gold ores (Janse van Rensburg and Bazhko, 2015; Marsden and House, 2009) :

I. Physical encapsulation: gold is typically surrounded by sulphides and reactive gangue minerals, which prevents it from being freed even after fine grinding.

II. Chemical interference: gold is found in minerals like pyrrhotite, pyrite, marcasite, enargite, and arsenopyrite that consume large amounts of oxygen, cyanide, and lime.

III. Preg-robbing: gold leached during cyanidation process were adsorbed by organic carbon and carbonaceous materials present in the ore.

An oxidative pretreatment technique is often necessary to successfully process the refractory gold ores in order to oxidise the refractory minerals and make the gold susceptible to cyanide leaching.

2.3 Gold Mineralogy

2.3.1 Gold Properties

The mineralogy of the gold must be thoroughly investigated in order to process the ores effectively. This is done to avoid unnecessary processes from being taken when mining or processing ores. Physical and chemical properties of gold are shown in the Table 2.1 and Table 2.2 respectively.

Table 2.1 Physical properties of gold.

Properties	Observation
Color	Bright yellow
Luster	Metallic
Streak	Golden yellow
Hardness	2.5 – 3 (on Mohs Scale)
Cleavage	None
Fracture	Hackly
Specific gravity	19.3
Malleability	High
Ductility	High
Melting point	1060 ºC
Common associate minerals	Quartz, pyrite, arsenic, calaverite, sylvanite, sulphide mineral

Table 2.2 Chemical properties of gold.

Properties	Observation
Chemical Formula	Au
Activity	Chemically inactive and extremely resistant to chemical action
Reactivity with acids	Can be dissolved by Aqua regia, a mixture of nitric and hydrochloric acid
Isotopes	Has one stable isotope, $Au197$
Reactivity with Non-metals	Does not react with Non-metal except halogens which will produce halides
Alloys	Silver and platinum

The two primary types of deposits where gold can be found in the crust are disseminated in sulphide hydrothermal veins and placers, which can be either consolidated or unconsolidated. The latter are created from the former through weathering and erosional processes; gold is concentrated and separated from other minerals due to its high density and relative immunity to chemical and mechanical weathering.

The majority of gold that is hydrothermally formed is found in quartz veins, frequently in association with pyrite, other sulphides, gold-silver tellurides, scheelite, tourmaline, ferroan dolomite (also known as ankerite), sericite, or the green chromian sericite. Smaller quantities of gold are also present in large hydrothermal deposits that also contain pyrite, chalcopyrite, pyrrhotite, and sphalerite; in these deposits, gold is frequently extracted as a profitable by-product of base metal mining.

Gold occurs as spherical or flattened grains and nuggets along with other heavy resistant minerals in placer deposits (both current unconsolidated and older consolidated placers). Gold has been extracted mostly from unconsolidated placers from ancient times. Since the middle of the nineteenth century, the recovery of the metal has become more dependent on the mining of hydrothermal veins and solidified placers.

2.3.2 Gold Deposits

There are many different hydrothermal deposits where gold can be found. These deposits can then be eroded, have the gold concentrated by hydraulic processes in rivers and on beaches, and then be deposited as sedimentary placer deposits. Table 2.3 lists the many types of typical gold deposits

Table 2.3 Gold deposits (Gasparrini, 1993).

Deposit	Structural character	Age	Type locality	Main minerals	Assoc. minerals	Typical elements	Metals mined	% of world production
Gold-quartz lodes	Hydrothermal veins	Mostly precambrian	To be expected in precambrian rocks, such as the Canadian, Australian, Brazilian-Guayana and African-Arabian shields	Low-silver native Au	Quartz	Si	Au	20-25
Epithermal deposits	Hydrothermal veins	Tertiary	Emperor deposit (Fiji)	High-silver native Au, tellurides	Quartz, carbonate, barite, fluorite	Te, Bi, Pb, As, Sb, Hg, etc.	Au, Ag, some base metals	Very small
Young placers	Unconsolidated or semiconsolidated sands and gravels	Recent	River beds that assay for gold	Native Au	Minerals such as monazite, ilmenite, zircon, apatite, pyrochlore, etc	Ti, RE's, N	Au, Ti, RE's, Nb	5-10; 25 to 35 in the past
Fossil placers	Conglomerates consisting of quartz pebbles in matrix of pyrite and mica	Precambrian	Witwatersrand to be expected in the precambrian shields	Native Au	Heavy minerals including uraninite	U, PGE, etc	Au, U, PGE	More than 60
Disseminated gold	Silty carbonaceous dolomitic limestone	Mesozoic tertiary	Carlin, Cortez, Getchel, Gold Acres (Nevada type	Very fine native Au	Silicate, barite, pyrite and other sulfides	Fe, As, Sb, Hg, C,	Au	Has been increasing. Brought

			ores); Bald Mountain			very little Ag		into prod. In 1935
Greenstones	Metamorphosed volcanic	Precambrian	Kalgoorlie, Hemlo, Timmins, Val D'Or Kirkland Lake	Native Au, calaverite	Tellurides of Au, Hg, Pb, Cu, Bi, compounds of gold with Hg, Sb, and other elements, native tellurium	Hg, Pb, Bi, Sb	Au	Has been increasing
Young greenstones	Metamorphosed volcanic	Mesozoic tertiary	Deposits in Southeastern Au California	Native Au	Pyrite, Fe oxides, various silicates	Fe, Si	Au	Has been increasing
Byproduct gold	-	-	Any gold bearing base metal deposit	Native Au, other gold minerals	Base metal minerals	Cu, Pb, Zn, As, Sb, Bi	Au, base metals	5-10
Gold in seawater	0.0011-0.05 ppb in solution	-	-	-	-	-	-	-

2.3.3 Geology of The Gold-Belt in East Malaysia

The four components of the gold-geology belt's include stratified rocks, volcanic and hypabyssal rock present at the same time as stratified rocks, intrusive plutonic rock, and recent alluvium. Examples of stratified rocks include limestone, calcareous shale, quartz, shale, and chert, which is also often referred to as calcareous slate.

Volcanic rock that found to be in connection with gold deposit in several places such as Pulai, Kelantan, Merapoh, near Kuala Nipis and Raub is grouped as Pahang Volcanic Series ranging from rhyolites to dolerites. This type of rock is known as muscovite-aplite because its grain is finer than that of typical aplite and it contains fine-grained intergrowths of quartz, feldspar, and muscovite. Granite, hornblende-granite, syenite, and diorite are the plutonic rocks.

This type of rock is known as muscovite-aplite because its grain is finer than that of typical aplite and it contains fine-grained intergrowths of quartz, feldspar, and muscovite. Granite, hornblende-granite, syenite, and diorite are the plutonic rocks. There have also been a few instances of cassiterite with gold being found close to Kuala Lipis and in the Benom Range, which is to the south of Kuala Lipis. The concentrations also contain ilmenite, zircon, and rutile.

2.4 Classification of Gold

Based on study, there are 11 different types of gold ores, all of which have their own unique mineralogical features that reflect extraction technique to be applied (Zhou *et al*., 2004). Classification of gold is shown in Table 2.4.

Table 2.4 Classification of gold (Zhou *et al*., 2004).

Ore type	Mode of occurrence of gold
Placer	Gold is easily liberated or has already been liberated prior to processing, and it usually ranges in size from 50-100 μm.
Quartz vein- lode ores	Mostly exist as native gold in quartz veins, lodes, or stockworks, some tellurides and occasionally aurostibite and maldonite. Typically found as liberated gold particles, and some disseminated gold may be present.
Oxidised ores	Commonly found freed or in the alteration products of sulphide minerals, and oxidation increases the degree of gold liberation.
Silver-rich ores	Although kustelite may be contained in some ores, gold is most usually found as electrum. It is possible that native silver is present.
Copper sulphide ores	Gold exists as coarse liberated particles and small particles is found locked in copper sulphides and pyrite.
Iron sulphide ores	Gold is found as liberated particles, attachments to and inclusions in sulphide minerals (most typically pyrite, but less commonly marcasite and pyrrhotite), and as sub microscopic gold in sulphide minerals.
Arsenic sulphide ores	Occurs as liberated particles and inclusions, and sub microscopic gold in arsenopyrite and oxidised products.
Antimony sulphide ores	Mainly found as native gold, with minor to moderate amount of aurostibite, either liberated or locked in sulphides.
Bismuth sulphide ores	Gold occurs as native gold, with minor to moderate amounts of maldonite. Sub microscopic gold could be present in sulphides.
Telluride ores	Occurs as native gold and gold tellurides, either liberated or locked in sulphides. Sub microscopic gold may be present.
Carbonaceous – sulfidic ores	Mainly exists as fine-grained gold particles and sub microscopic gold in sulphides. Surface gold adsorbed onto the surface of carbonaceous matter and FeOx.

In Malaysia, the majority of the gold ores are mined from placers, free-milling, oxidized, and carbonaceous materials. It is best to first determine the kind and nature of the gold ores before mining or processing them in order to achieve the optimum efficiency.

Based on the mode of occurrence, gold is divided into three classes: microscopic gold, submicroscopic gold, and surface gold. Gold carriers can be seen as gold minerals and minerals that contains merely trace amount of gold (Zhou *et al.*, 2004). Table 2.5 shows the classification of gold by form and carriers.

Table 2.5 Classification of Gold by Forms and Carriers (Zhou *et al.*, 2004).

Form	**Microscopic Gold**	**Submicroscopic Gold**	**Surface Gold**
Nature	Visible under microscope	Invisible under microscope	Invisible under microscope
Carrier	Arsenopyrite,Pyrite, Marcasite, Chalcopyrite, Enargite, Realgar, Loellingite, Acanthite FeOx, Clayminerals	Arsenopyrite,Pyrite, Marcasite, Chalcopyrite, Enargite, Realgar, Loellingite, Acanthite FeOx, Clayminerals	Carbonaceous matter, FeOx, Stained quartz, Activated carbon,Clay minerals, Wood chips, Pyrite, Arsenopyrite

2.5 Factors Golds in Extractive Metallurgy

Several factors that affect gold extraction process (Zhou et al., 2004):

2.5.1(a) Gold grain size

Gold with large particles may not be carried by flotation bubbles, may be stuck upstream of the cyanidation circuit, or may not be properly leached. Ultrafine gold recovery from cyanidation may be poor due to grain size <10μm and associated with sulphide minerals. One major reason for gold losses is the encapsulating of visible gold in sulphide and silicate minerals.

2.5.1(b) Sub microscopic gold

In gold solid-solution, often there is high concentration of fine grained sulphide minerals causing poor liberation of ultra-fine, gold hosted sulphide.

2.5.1(c) Coatings on the surface of the gold

Surface coatings on the gold will influence extraction of gold via flotation and cyanidation. Iron oxides or hydroxides (limonite or goethite), which occur as a result of oxidation, precipitation, or dissolution processes, may be present as these coatings. Additionally, insoluble aurous sulphide coatings form when gold and sulphide ions come together. Thioarsenite ions can cause the passivation layer to develop on gold.

2.5.1(d) Silver in gold minerals

Silver is typically found in gold ores, aside from when it takes the form of silver minerals, in electrum and kustelite. Silver-rich electrum and kustelite tarnish in the presence of sulphide ions, forming a coating of silver sulphide between 1-2 micrometres thick. It will limit the access of cyanide solution. If additional silver sulphate or silver oxide oxidation takes place, the silver coatings turn hydrophilic and impede gold flotation recovery.

2.5.1(e) Gold tellurides, aurostibite and maldonite

Gold tellurides, aurostibite, and maldonite are refractory minerals because of their slow dissolution in cyanide solutions.

2.5.1(f) Prescence of cyanide and oxygen consumers

Iron sulphides, arsenic, antimony, copper, tellurium, and zinc are interfering minerals in gold ores that slow down and lower the amount of gold leached. This occurs

as a result of the fact that some interfering minerals in cyanide solutions undergo a reaction that consumes oxygen, cyanide, or both.

2.6 Factors Affecting Gold in Dissolution

2.6.1(a) Temperature

When the activity and diffusion rate of reactive species increase at higher temperature, the rate of gold dissolution also increases. Figure 2.4 shows that the rate of dissolution rises by 20% with increasing temperature from 25ºC to 85ºC. However, this technique will only be used to leach high-grade materials.as it will increase the operating costs (Sarina Ramli and Osman, 2015).

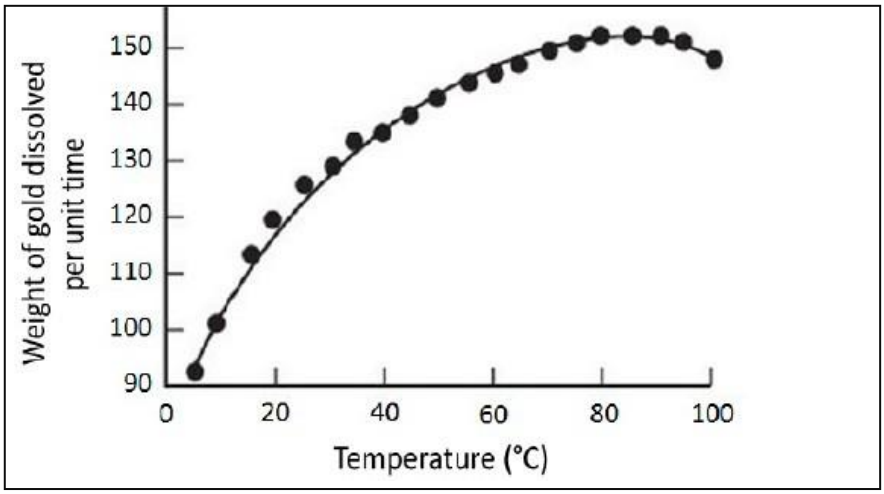


Figure 2.4 Effect of temperature on gold dissolution rate in aerated 0.25% KCN solution (Sarina Ramli and Osman, 2015)

2.6.1(b) pH

Gold cyanidation will always carried out at pH more than 10 and below 12. When Excess cyanide being used, it will be lost by hydrolysis and transformed into hazardous hydrogen cyanide gas, endangering both the environment and people. Depending on the nature of the process water and the mineralogy of the ore, most

facilities carried out gold leaching up to a pH of 11. Lime will be use to control the alkalinity of cyanide solution.

2.6.1(c) Degree of Agitation

The level of mixing provides a balance between the need for more energy-intensive mixing and the objective of accelerating gold decomposition. The rate of agitation determines the hydrodynamic boundary layer's thickness. Agitation, along with the concentration of diffusing species, regulates the diffusion of chemicals onto the gold surface. In working facilities, mechanical stirring or sparging air or oxygen through the slurry can both be utilised to speed up agitation (Rees, 2014).

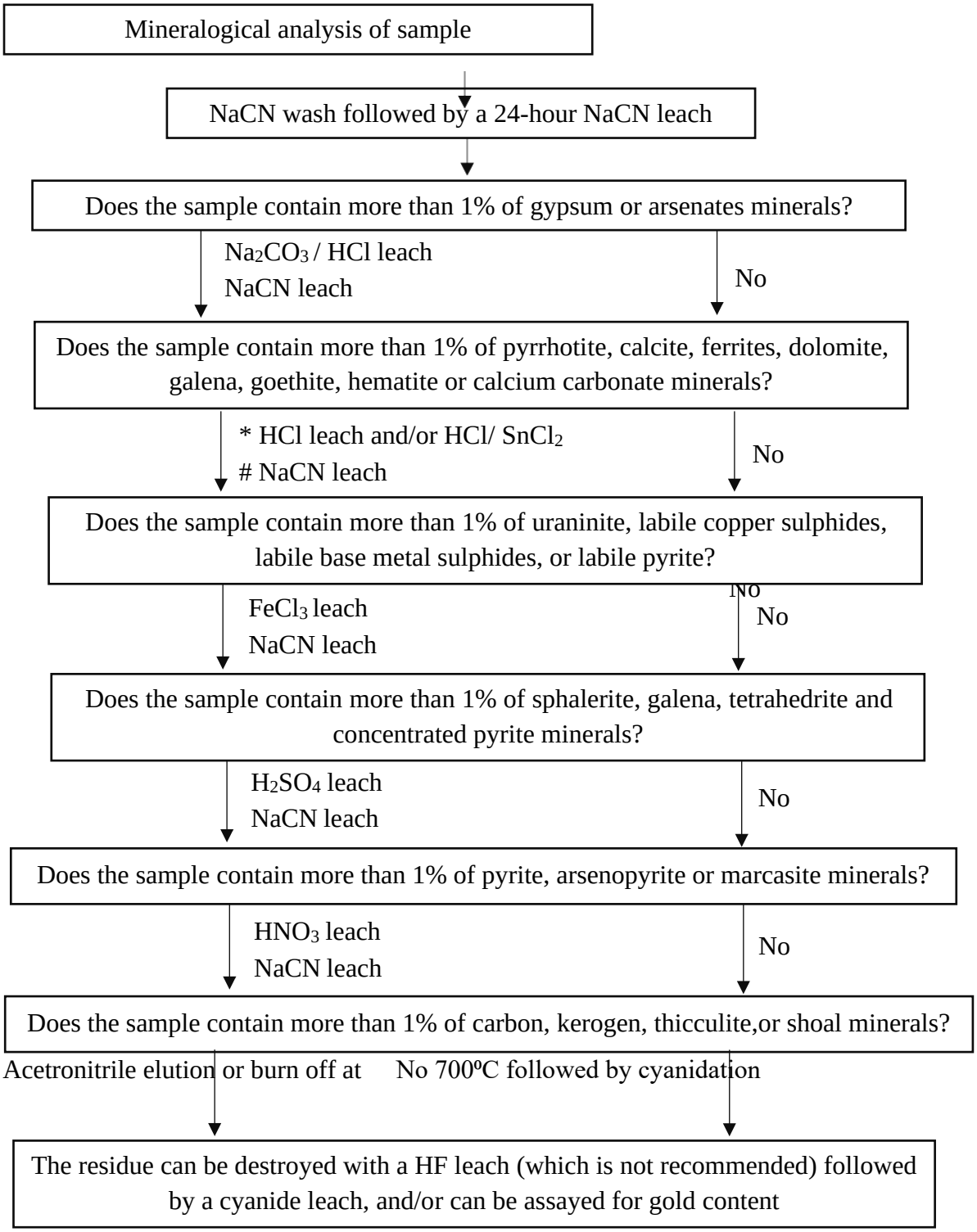
2.7 Diagnostic Leaching

Diagnostic leaching was created by Anglo American Research Laboratories to study the effects of gold-associated minerals on the chemicals used in extraction techniques like flotation, leaching, and roasting. Depending on the minerals present in the sample matrix, diagnostic leaching, which employs different acids, can be used to analyse the behaviour of gold in ore or any other type of plant product. Gold is a noble metal that can withstand all forms of acid attack except for aqua regia. To qualitatively determine how gold occurs in the ore and the degree to which it may be refractory, a diagnostic leach test can be very helpful. The general alteration of diagnostic leach tests involves sequentially leaching a gold ore sample with progressively stronger chemicals to produce a qualitative assessment of the gold deportment within the sample. Unique alteration of diagnostic leach tests relies on specific aims. From sequential selective oxidative leaching and interstage cyanidation, diagnostic leaching attempts to destroy the sample's least stable mineral in order to liberate the gold. The data acquired at the

end of the research will help the metallurgist construct a metallurgical flowsheet with the proper chemicals and process parameters, resolving the problems at the current facility (Lorenzen and Tumilty, 1992). Table 2.6 demonstrates the selective pre-treatment leach phases and the minerals that are expected to be destroyed at each stage. While, Figure 2.5 shows the detailed procedure of diagnostic leaching.

Table 2.6 Selective pre-treatment leach stages and the minerals destroyed (Lorenzen, 1995).

Pre – treatment stage	**Minerals likely to be destroyed**
NaCN washes	Precipitated gold
NaCN	Gold
Na_2CO_3	Gypsum and Arsenates
HCl	Pyrrhotite, Calcite, Dolomite, Galena, Goethite, Calcium Carbonate
HCl / $SnCl_2$	Calcite, Hematite, Ferrites
H_2SO_4	Uraninite, Sphalerite, Labile Copper Sulphides, Labile Base Metal Sulphides, Labile Pyrite
$FeCl_3$	Sphalerite, Galena, Labile Sulphides, Tetrahedrite, Sulphide Concentrates
HNO_3	Pyrite, Arsenopyrite, Marcasite
Oxalic Acid Washes	Oxide coatings
HF	Silicates
Acetonitrile elution	Gold adsorbed on Carbon, Kerogen



*Can be replaced with a HCl/SnCl2 leach if more than 5% calcite or hematite is present
#Can be replaced or followed by a FeCl3 leach if there is significant amount of sphalerite and tetrahedrites present with galena in the sample

Figure 2.5 The diagnostic leaching procedure (Lorenzen, 1995)

2.8 Fire Assay

Fire assay is the most precise technique for determining the concentration of gold, silver, and platinum-group metals (apart from osmium and ruthenium) in ores or concentrates. The fire assay mixes high heat (1900ºF) and dry reagents known as fluxes. Objective of the mixture is to combine the fluxing agents while separating the precious metals.

A sample containing silver or gold must first be soluble in molten metallic lead but insoluble in slag. Second, the specific gravities of the molten lead and slag are different. Due to the differences between them, it will separate the alloy containing the precious metal from the slag. In a porous receptacle known as a cupel, the precious metal can be separated using a controlled oxidising fusion. Finally, fire assay is possible since silver dissolves in nitric acid but gold does not.

The selection of fluxing reagents is determined by the acidic or basic nature of the rock. While basic rocks have a lot of oxides, carbonates, or other metals, acidic samples tend to have a lot of silicates, aluminates, or borates. Fluxes start a chemical reaction that causes the samples to break down and create a lead button with the valuable metals inside. The fluxes provide the metallic lead button, slag, and fluxing reagents like silicates and borates of metallic oxides that dissolve undesirable chemicals in the sample. An optimal slag with the proper bulk is essential to obtaining the best precious metal recovery. Basic, acidic, and neutral fluxes are the three types of fluxes (Michaud, 2016). Table 2.7 lists the components and purposes of each chemical reagent used in the flow.

Table 2.7 Composition and functions of chemical reagents used in flux (Michaud, 2016).

Classification of fluxes	Reagents	Functions
Basic	Sodium carbonate (Na2cO3) or soda ash	• Reacts with silica-based minerals to form a fusible sodium silicate • Na2CO3 + SiO2 = Na2SiO3 + CO2
	Sodium bicarbonate (NaHCO3) or baking soda	• Can replace soda ash, less commonly used.
	Litharge (PbO)	• Decompose silica to form fusible lead silicate. • Reacts with metallic oxide and silica to form slag. • Acts as an oxidising and desulfurising agent. • React with flour (reducing agent) which provides carbon to reduce litharge to lead. • 2PbO + C → 2Pb + CO2 • It supplies the lead to produce lead button that collects the precious metal

Basic	Hematite (iron oxide – Fe_2O_3)	• Sometimes used to replace litharge. Iron oxides act as oxidising agent by consuming carbon (flour). • A combination of a basic flux and an oxidising reagent. • Ferric oxide is difficult to fuse but during the process it is converted to ferrous state, which is easily fused. • It forms ferrous silicate when it reacts with silica.
	Lime (CaO)	• A base for fluxing the silica. • Limestone loses CO_2 and reacts with and produce a fusible silicate.
Acidic	Borax (sodium tetraborate – $Na_2B_4O_7$)	• Dissolving and fluxing the metallic oxides both acidic and basic.
		• It lowers the fusion temperature for the formation of slag. • Increases the fluidity of the slag
	Silica (SiO_2)	• Combines with metal oxides to form silicates, foundation of all slags.
Acidic	Fluorspar (calcium fluoride – CaF_2)	• Increase the fluidity of slag • It suspends the infusible particles without lowering the fluidity of the slag

Neutral		• Mainly used in fluxing ores containing calcium phosphate (bone ash), barites, gypsum, and infusible silicates.
Neutral	Salt (sodium chloride – NaCl)	• Protect the flux from air oxidation.
Neutral	Cryolite (AlNa3F6)	• Aid in the fluxing of high Al2O3 ores such as clays and occasionally in the melting of bullion