Assessment and Countermeasure of Acid Mine Drainage Generation with Characteristics of Potential Acid Forming Waste Rock in Open-pit Gold Mine, Myanmar

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July 2020

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Graduate School of Engineering

Kyushu University

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A DOCTORAL THESIS

Submitted to the Department of Earth Resources Engineering,
Graduate School of Engineering, Kyushu University,
as a partial fulfilment of the requirements of the degree of
Doctor of Engineering

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JAPAN
2020

ABSTRACT

Acid Mine Drainage (AMD) is caused by the reaction in water with oxygen and the sulfide minerals contained in excavated rocks in the mine. The dissolution of high concentrations of metal ions (iron, aluminum, manganese, zinc, copper, nickel, arsenic, cadmium) has an environmental impact on the rivers and the surrounding environment. AMD is a site-specific problem because the characteristics of AMD depend on the minerals contained in the rocks, climatic conditions, and the local hydrology. Currently, many open-cut mines are in operation in Myanmar. However, the research about AMD problems in Myanmar is limited, meaning that the sources and the potential of AMD generation are unclear though AMD generation has been reported to the government from some mines. Additionally, the countermeasures to mitigate AMD generation for the long term usually have to be discussed from the early stages of mine development with a source control strategy, i.e. dry cover method.

Hence, this study focuses on the identification of the source of rock to generate AMD and assesses the potential of AMD generation by investigating the Kyaupahto gold mine, which is the largest and oldest open-pit gold mine with the epithermal deposit in Myanmar. Additionally, the backfilling design of the proposed dry-cover system takes the geochemical characteristics of waste rocks into consideration. In order to achieve the objective of this study, the dissertation consists of six chapters as follows:

Chapter 1 presents the background of the current situation in the gold mines of Myanmar, the process of AMD generation within the open-pit mine, and the general countermeasures of AMD prevention. The requirements to discuss the application of the dry cover system in the gold mine and an outline of the dissertation are introduced in this chapter.

Chapter 2 describes the results of the field investigations in Kyaukpahto gold mine, which is the largest and oldest open-pit gold mine in Myanmar. The field investigations were carried out in order to identify the location that generates AMD and to examine the AMD characteristics, including the current countermeasures to mitigate AMD. As a result, AMD generation is confirmed in the open-pit and the low-grade ore dump and it

contains a high concentration of arsenic. Despite this, there is no water pollution in the surrounding environment while the current countermeasure is the addition of limestone to neutralize the acidic water. Considering that AMD has been identified at the mining site and the current countermeasure is just for temporary management, it is necessary to evaluate the potential of AMD pollution in the future and to discuss effective countermeasures for long term management.

Chapter 3 discussed the identification of the source of rock that generates AMD and assessed the potential of AMD generation by means of the geochemical analysis of rock samples from the open-pit and the waste rock dump in Kyaukpahto gold mine. The results show that the presence of potentially acid forming (PAF) which may form acidic water is confirmed in the open-pit and low-grade ore dump where AMD generation is identified. Additionally, AMD generation is clearly found from low-grade ore, which is the waste rock under the cut-off grade. On the other hand, the presence of non-acid forming (NAF) with the high acid neutralizing capacity due to the carbonate minerals has been found. Based on the results of X-ray diffraction, PAF contains pyrite and arsenopyrite as the major sulfide mineral and NAF contains calcite and dolomite as the carbonate mineral. The current risk of water pollution due to AMD generation is expected to be low because the volume of low-grade ore is quite small compared to that of waste rocks. Moreover, there is a possibility to adopt the dry cover system in this mine due to the high stripping ratio and the large volume of the waste rock with carbonate minerals, which have acid neutralizing capacity.

Chapter 4 describes the classification of PAF by investigating the elution behavior of the acidic water by means of the batch leaching test and column leaching test. From the results of the batch leaching test, it is revealed that a long-term metal elution is expected from the rocks which contain a lot of As regardless of pH. Additionally, the elution of metal ions is found not only in acidic conditions, but also neutral conditions due to the effect of acid buffering reaction. These facts mean that PAF can be classified with the sulfur content, ANC, and constituent metal elements. The results of column leaching test also show the same trend with those of the batch leaching test, meaning that the higher arsenic elution is confirmed by the end of the column leaching test from rock samples which contains a large volume of arsenic and the pH shows higher if the

samples have the high acid neutralizing capacity (ANC). Moreover, the oxidation and buffering reaction due to sulfide and carbonate minerals are well balanced in PAF, which shows the highest pH because the elution of sulfate and total cation are balanced. From these results, the different backfilling designs must be discussed for the different characteristics of PAF to achieve the efficient prevention method of AMD.

Chapter 5 discussed the backfilling design of waste rock as a dry cover system considering the characteristic of PAF. The same column leaching test was conducted with different cover scenarios by using the PAFs which have various characteristics and NAF which has a higher ANC. The results show that the pH of leachate improves as the layer thickness of NAF increases while the small amount of cover is enough to prevent AMD generation if PAF has a higher ANC. The ratio of NAF/PAF to minimize the AMD generation in terms of pH should be determined with net acid producing potential (NAPP) and ANC of the column. For the metal elution, the high concentration of the arsenic elution is confirmed from PAF containing a lot of arsenic even in the case of increasing the cover thickness, meaning that it is difficult to reduce the arsenic elution with only the upper layer cover from such PAFs. Therefore, the sandwich design to place NAF not only on the upper layer, but also as a bottom layer, is suggested to prevent metal elution efficiently. According to the results, the significant suppression of arsenic elution has been confirmed. This suppression is due to the co-precipitation of the arsenic with iron hydroxide (III) in the bottom layer. It is also confirmed that the elution of arsenic and iron reduces from leachate and these metals rises in the bottom layer from the results of SEM-EDX. Finally, the guideline for the application of the dry cover system in the epithermal gold mine of Myanmar is suggested in this chapter.

Chapter 6 summarizes the conclusions of each chapter, including the recommendations.

ACKNOWLEDGEMENTS

The success and final outcome of this research required a lot of guidance and assistance from many people and I am extremely privileged to have got this all along the completion of my research. All that I have done is only due to such supervision and assistance and I would not forget to thank them.

First and foremost, I wish to express sincere gratitude to Prof Dr. Hideki SHIMADA, as my supervisor, for all the support and guidance during the study at Laboratory of Rock Engineering and Mining Machinery, Department of Earth Resources Engineering, Kyushu University. His patience and support during the discussion, encourage me towards the completion of my research.

I would like to extend my gratitude and appreciation to Associate Professor Dr. Takashi SASAOKA, my co-supervisor, Laboratory of Rock Engineering and Mining Machinery of Kyushu University, for his kindly assistance and precious suggestions during my research. My sincere thanks also go to the member of my examination committee, Associate Prof. Dr. Naoko OKIBE, Department of Earth Resources Engineering, Kyushu University and Associate Professor Dr. Yoshinari HIROSHIRO, Department of Civil Engineering of Kyushu University, for his valuable comments and constructive suggestions.

My gratitude is especially delivered to Assistant Professor Dr. Akihiro HAMANAKA who kindly teaches and supports me through discussion during my research as well as her valuable comments and constructive suggestions to improve the results of this dissertation.

I would also like to thank Assistant Prof. Sugeng WAHYUDI and Assistant prof. Takahiro FUNATSU for their advice and assistance in keeping my progress on schedule. My grateful thanks are also extended to Fujita-sensei for his help in doing the preparation for experiments. I am thankful to and fortunate enough to get constant encouragement, support and guidance from all Teaching staffs of Earth Resources Engineering which helped me in successfully completing my studying in Kyushu University.

I heartily thank to Dr. Shinji Matsumoto, for valuable suggestions and kind help during this research work. I would like also to thank all of Rock Engineering member, Mr. Hiroto Yamazaki, Ms. Aya Harazawa, Dr. Sendy Dwiki, Ms Zara BUYANBAT, Kaito Murakami, and the rest of member for helping me in my experiment research.

My deep appreciation also goes to Associate Professor Dr. Myo Min Tun, Department of Geology, Kyaukse University, Myanmar, for his help and advice for my research, along with the endless support while I was studying in Kyushu University and also field research in Myanmar.

I would like to kind and strong supports from Director General and Staff Members of Department of Mines, Ministry of Natural Resources and Environmental Conservation, Myanmar for this research. I would like to express sincere thanks to

ETERNAL Mining Company Limited for permission to conduct the field works. Sincere thanks are also given to senior geologists and engineers from ETERNAL Mining Company Limited for their kind helps, providing information, data and samples for my research.

In addition, sincerely appreciation is also delivered to Japan International Cooperation Agency (JICA), for awarding the scholarship of KIZUNA program. I hope this program will be helpful to continue foster relationships between Myanmar and Japan mining industry.

Finally, I am deeply grateful thank to my parents, U San Win Maung and Daw Mya Moe Swe, and my lovely sisters, for their support and encouragement throughout my study and helping all of my life

Thant Swe Win

Fukuoka, Japan

July, 2020

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CHAPTER 1

Introduction

1.2 Background

Acid mine drainage (AMD), also known as acid rock drainage (ARD), causes environmental problems that affect many countries with historic or current mining activities. It has resulted from the exposure of sulfide ores and minerals to water and oxygen. When the ores are exposed to develop AMD, sulfate and heavy metals such as iron, copper, lead, nickel, manganese, cadmium, and zinc are also released contaminate into that water [1]. Metal-rich acidic waters can also be developed in spoil heaps, waste rocks and tailings, mainly by the similar biologically reactions as in mine adits, shafts, pit-walls and pit-floors. As acid-generating minerals are more disaggregated and concentrated in these waste materials, AMD which flows from them could be more aggressive than that which discharges from the source itself. Another important consideration is that of the potential long-term pollution problem, as AMD production may continue for several years after mines were shut and tailing dams were decommissioned [2].

Myanmar, one of the Southeast Asian nations, is highly endowed with various mineral resources, such as gold, silver, copper, and lead [3]. Kyaukpahto gold mine is the first open-pit gold mine excavated in Myanmar and located about 30 km east of the Kawlin and 250 km north of the Mandalay, in northern Myanmar Figure 1.1. Exploration works and calculations of ore reserves at in this mine have been conducted since 1982. By the 1990s, a total of more than 300 drill holes had been drilled and the reserve was estimated at approximately 6 million tons at an average grade of 3.0 g/t Au with a cut-off grade of 1.0 g/t [4, 5]. The important ore minerals of gold mineralization are pyrite, arsenopyrite and chalcopyrite with minor amounts of other sulfides. Gold can be observed as free particles and/or locked inside sulfides such as pyrite, arsenopyrite, chalcopyrite and tetrahedrite [5, 6]. When the sulphur content of the mine is within the range of 1-5% in the form of pyrite (FeS_2), there is a potential of AMD occurrence. AMD degrades the water quality in terms of lowering the pH of the surrounding water resources and increasing the level of dissolved heavy metals [7]. Currently, the water pollution due to AMD generation is not detected in the surrounding water monitoring points at Kyaukpahto gold mine based on the

environmental report from the currently operating mining company [8]. However, the risk of AMD generation from Kyaukpahto gold mine has to be evaluated to avoid the severe environmental impacts for the future.

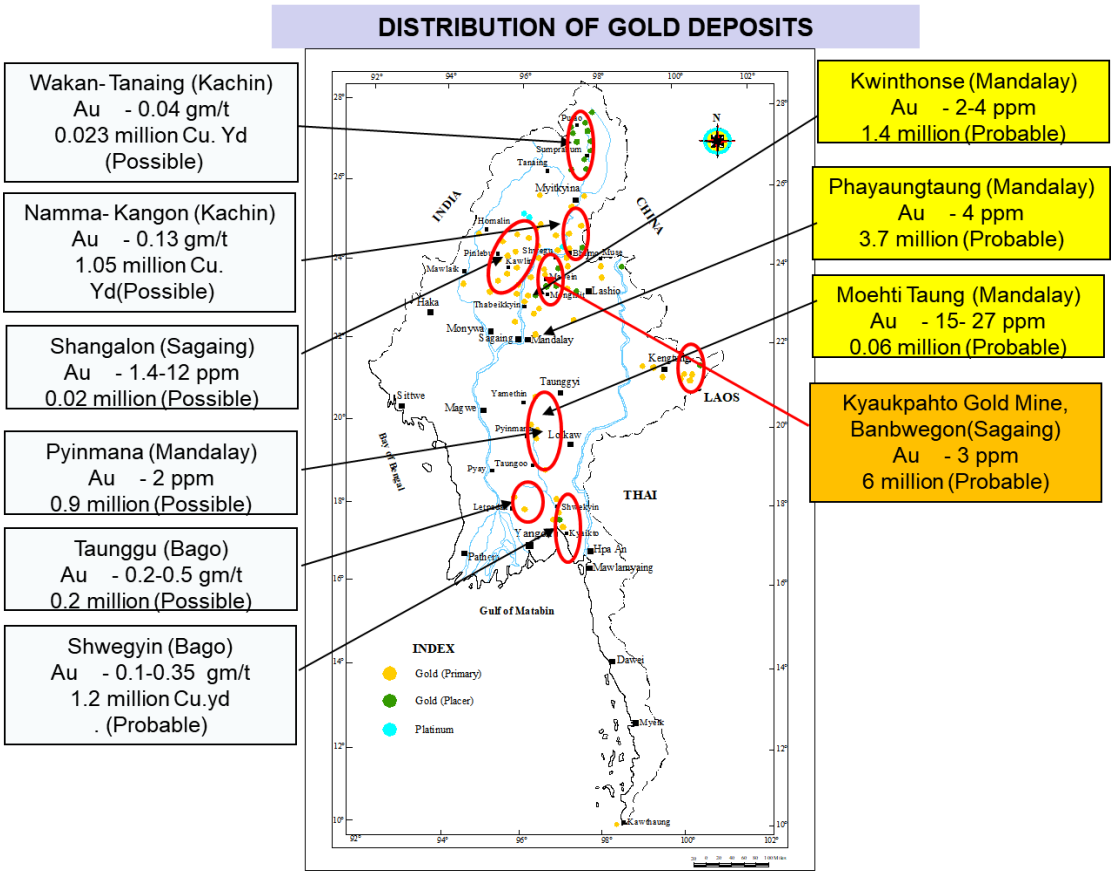

Figure 1.1 Distribution of Gold Deposits in Myanmar

In Kyaukpahto gold mine, gold ores exploited by open-pit mining method and waste rocks are disposed of as waste dumps near the mine site. A large number of waste rocks containing metal sulfides, such as pyrite and chalcopyrite, are exposed to the surface, favouring these sulfides in reaction with air and water, and produce acidic mine water. Potential generation of acidic miner water has been reported due to metal sulfide-bearing waste rocks in the open-pit backfilling at Monywa Copper deposit located to the south of Kyaukpahto gold mine [9]. Higher values of hardness and heavy metal concentrations are observed in this water which reduces the quality of water and creates potential harm to the nearby environment. Arsenopyrite is the source of arsenic in Kyaukpahto mining waste disposal. Based on the experiment on stream sediments and water samples, it was found that arsenic concentrations in the surface water and tailings are higher than WHO (World Health Organization) standard guidelines whereas groundwater samples are shown that arsenic and zinc

concentrations are below that guidelines [10]. Geochemical characteristics and the increase of the total reactive surface area of the sulphide-bearing waste rock due to weathering processes at waste dumping area have potential to boost the oxidation of sulphide minerals which are commonly present as pyrite (FeS_2), leading to AMD generation [11].

At present, measures are being taken to prevent the generation of AMD from closed mines mainly by adding a neutralizing agent as a collection and treatment method for wastewater [12]. Considering that this is a problem that occurs, it is considered that the wastewater collection method is economically disadvantageous. In other words, to prevent the generation of AMD even after the excavation, measures to control the source of AMD, such as the sulfide oxidation control method (Controls on Sulfide Oxidation), which is aimed at the early stage of mine development and for a long time after mine development is completed must be taken in advance. Besides, the characteristics of AMD generated in mines depend on the minerals contained in the rock, climatic conditions, hydraulic conditions, etc., so the characteristics vary depending on the mine site and are unique to the site [13, 14].

In this study, the long-term AMD measures in the Kyaukpahto gold mine in northern Myanmar is examined. To grasp the current situation and characteristics of AMD's occurrence at the mining site, field surveys and laboratory experiments were conducted. Furthermore, various studies were conducted on the application of an effective dry cover method in open-cut metal mines focusing on the characteristics of waste rock in this mine based on field surveys.

1.2 Acid Mine Drainage (AMD) generation and its impact to the environment

One of the problems related to the water quality is acid mine drainage (AMD) generation. AMD generation occurs when sulphidic materials are oxidized, through mining activities, by the oxygen and water, and the results of those processes are transported and discharged to the receiving environment.

The most common acid-generating sulfide minerals in the ore include pyrite/marcasite (FeS_2), pyrrhotite (FeS), chalcopyrite ($CuFeS_2$) and arsenopyrite (FeAsS). In general, pyrite, the common sulfide mineral of waste rocks and typical of many oxidation processes during weathering, is oxidized according to the following reactions [15]:

$$FeS_{2(s)} + \tfrac{7}{2}O_{2(g)} + H_2O_{(l)} \rightarrow Fe^{2+}{}_{(aq)} + 2SO_4{}^{2-}{}_{(aq)} + 2H^{+}{}_{(aq)} \quad (1)$$

If the surrounding environment is sufficiently oxidizing, much of the ferrous ion will oxidize to ferric ion:

$$Fe^{2+}{}_{(aq)} + \tfrac{1}{4}O_{2(g)} + H^{+}{}_{(aq)} \leftrightarrow Fe^{3+}{}_{(aq)} + \tfrac{1}{2}H_2O_{(l)} \quad (2)$$

At pH value from 2.3 to 3.5, the ferric iron will precipitate as $Fe(OH)_3$, leaving little Fe^{3+} in solution while lowering pH at the same time:

$$Fe^{3+}{}_{(aq)} + 3H_2O_{(l)} \leftrightarrow Fe(OH)_{3(s)} + 3H^{+}{}_{(aq)} \quad (3)$$

Any Fe^{3+} that does not precipitate from solution may be used to oxidize additional pyrite:

$$FeS_{2(s)} + 14Fe^{3+}{}_{(aq)} + 8H_2O_{(l)} \rightarrow 15Fe^{2+}{}_{(aq)} + 2SO_4{}^{2-}{}_{(aq)} + 16H^{+}{}_{(aq)} \quad (4)$$

Acid generation produces iron which is eventually precipitates as $Fe(OH)_3$ can be represented by a combination of reactions:

$$FeS_{2(s)} + \tfrac{15}{4}O_{2(g)} + \tfrac{7}{2}H_2O_{(l)} \rightarrow Fe(OH)_{3(s)} + 2SO_4{}^{2-}{}_{(aq)} + 4H^{+}{}_{(aq)} \quad (5)$$

The oxidation process could take place both in short-term and long-term periods, depending on many factors involved, and will release three main chemical parameters that could influence water quality: sulphate, acidity, and dissolved metals.

AMD can be prevented, and its prevention consists of several methods. Generally, the purpose of AMD prevention is the minimization of AMD factors. These factors include oxygen supply, water infiltration and leaching, sulfide minerals availability and bacteria (related to biogeochemical process). Moreover, in the prevention method, maximizing the availability of acid-neutralizing minerals or increasing the infiltrated water pH could be an option [16].

1.2.1 Dry cover system as a prevention method

Dry dump cover is a constructed layer over the sulphide material using a rock or soil material or alternative materials such as geosynthetic clay liner (GCL). The objective of the dry cover system is to minimize the influx of water and oxygen, as important factors in oxidation processes. Apart from these functions, the dry cover system is expected to be resistant to erosion and support the revegetation processes. The cover can be simple or complex, considering three key properties of the cover materials i.e. saturated hydraulic conductivity, soil-water characteristic curve (SWCC),

and the physical integrity of the cover system [17]. These key properties are affected by physical, chemical, and biological processes which will then influence the overall performance of the cover system. Long-term performance of the cover system should be evaluated to ensure that the objective of its construction can be achieved, that is the prevention of AMD generation. The summary of the processes affecting long-term cover performance is given in Figure 1.2.

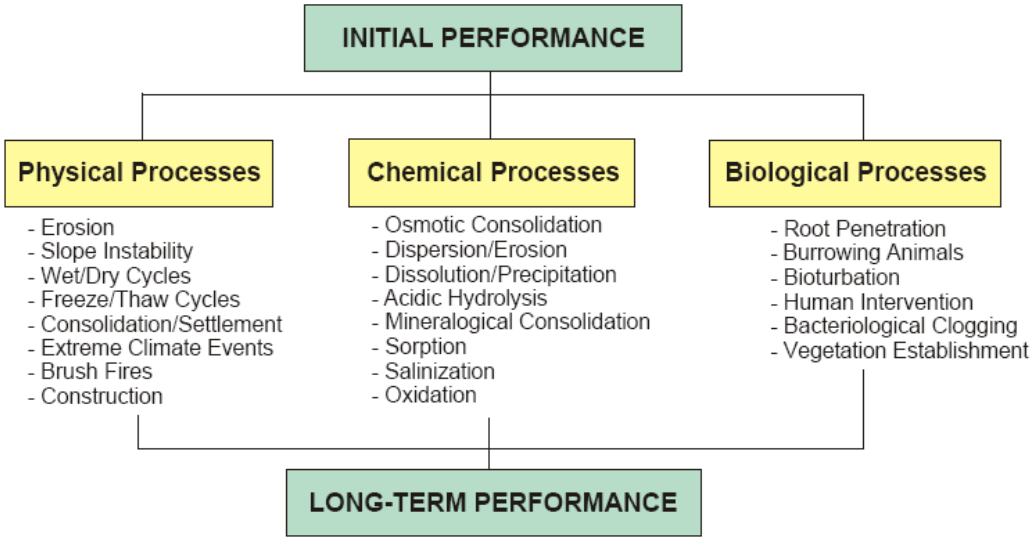

Figure 1.2 Summary of the processes affecting long-term cover performance [17]

1.2.2 AMD suppression method

Measures for the AMD problem can be broadly classified into source measures to control acid water from inside the mine and wastewater, and mineral wastewater treatment to treat acid water flowing out of the source by neutralization. The former includes a tunnel closure method to block a wellhead, an underground infiltration method to reduce mine water to the underground, an external cut-off method to prevent rainwater from penetrating the ore, and a dry cover method to cover mining sites and debris above ground, etc. In the latter case, a method of neutralization and precipitation treatment for neutralizing acidic wastewater and removing heavy metals mainly used.

As one of the dry cover methods, as shown in Figure 1.3, PAF (Potentially Acid Forming), which is a source of acidic water, is covered with waste rocks other than PAF such as clay and NAF (Non-Acid Forming). This method cuts off contact with oxygen and wastes rocks to suppress the generation of acidic water.

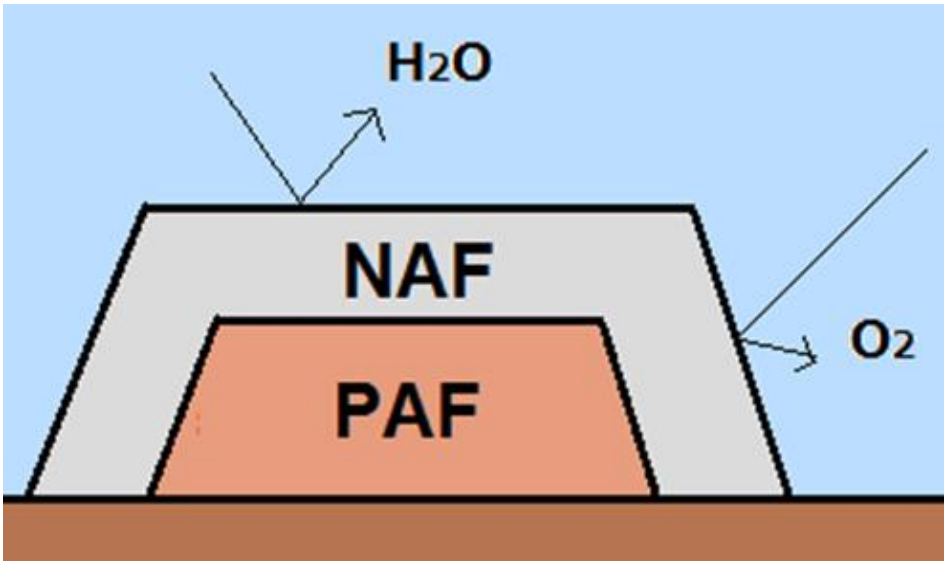

Figure 1.3 Conceptual diagram of AMD suppression

1.2.3 How to backfill waste rocks by NAG type

When waste rocks are used for rehabilitation, the backfilling method differs between PAF and NAF. For example, the Indonesian K mine employs the following three methods. In either case, the PAF, which can generate acidic water, is backfilled to the bottom so that it is not exposed to oxygen or water. Additionally, the NAF is backfilled above PAF to cover. PAF and NAF are distinguished by the NAG test, which will be described in detail in Chapter 3.

1). One Meter Compacted Clay Cover (DC01)

In this method, 1m of clay is compacted on top of the backfilled PAF layer,

After a 2 m NAF layer has been backfilled on top of it, the top is covered with 1m of clay (Figure 1.4).

2). Two Meter Compacted NAF Cover (DC02)

After the 2 m, NAF layer is backfilled on top of the PAF layer, it is compacted, followed by a 2 m NAF layer on top of it, and the top is covered with 1 m topsoil (Figure 1.5).

3). Loose NAF Cover (DC03)

After the 10-20 m, NAF layer is backfilled on top of the PAF layer, the top is 1 m topsoil (Figure 1.6).

The methods of 1) to 3) have advantages and disadvantages as shown in (Table 1.1), and are ultimately selected according to the amount and cost of NAF / PAF.

Table 1.1 Comparison of backfill methods for waste rock

OPTION	COMMENT
One Meter Compacted Clay Cover（DC01）	• Cost is related to consolidation time and depends on the volume and nature of the subsoil. • The soil layer is more susceptible to erosion and destruction. • Technical control with high technology is required.
Two Meter Compacted NAF Cover（DC02）	• Cost is related to adjustment and consolidation time and depends on the quantity and nature of the NAF. • The soil layer is more susceptible to erosion and destruction. • Engineering operation with high technology is required.
Loose NAF Cover （DC03）	• If there is a large amount of unsorted waste in the vicinity of the pit, it can be used with minimal cost. • The risk of erosion decreases as the cover layer becomes thinner. • There is no effect of sediment settlement. • Engineering operation with low technology is sufficient, but trust in waste stone evaluation and selective treatment are essential.

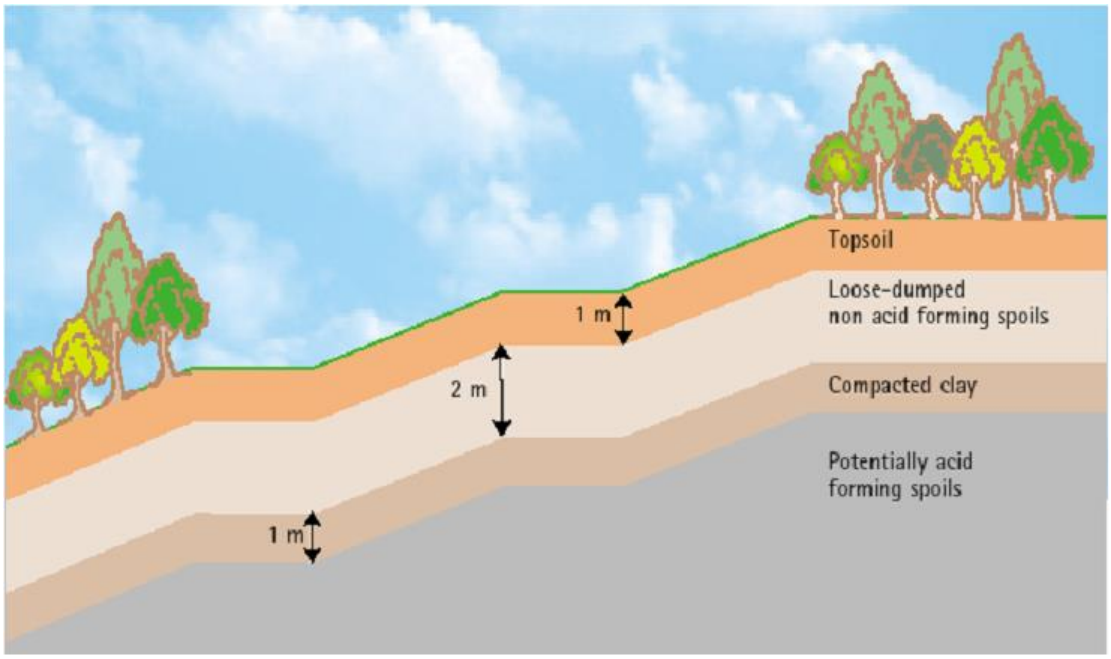

Figure 1.4 One Meter Compacted Clay Cover (DC01)

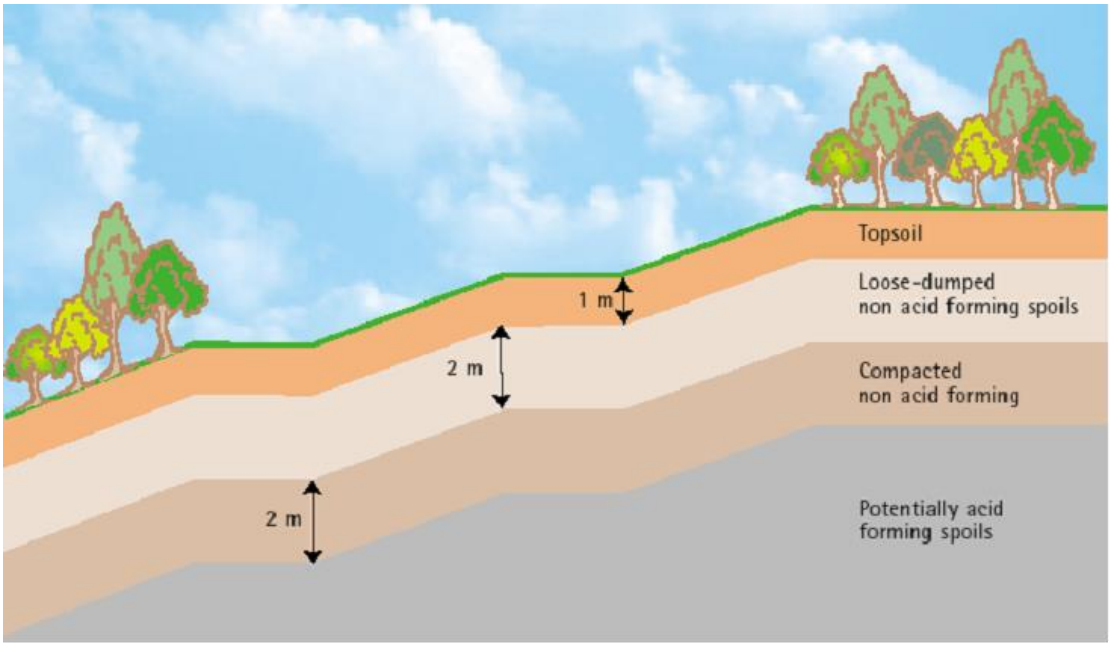

Figure 1.5 Two Meter Compacted NAF Cover (DC02)

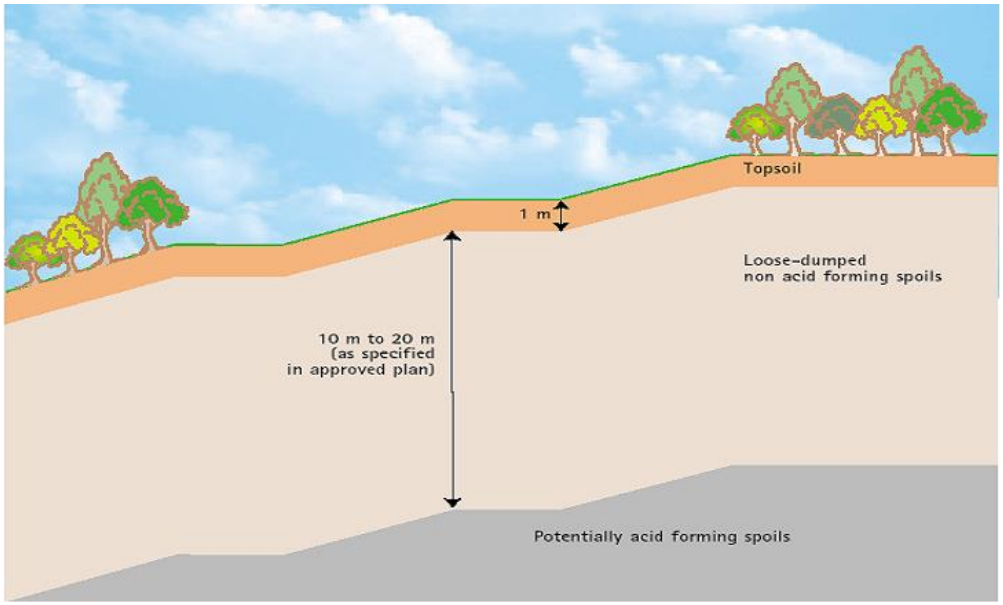

Figure 1.6 Loose NAF Cover (DC03)

1.3 Objective

Currently, many open-cut mines are operated in Myanmar. However, the research about AMD problem is limited in the mines of Myanmar, meaning that the sources and the potential of AMD generation are unclear though AMD generation is reported to the government from some mines. Additionally, the countermeasures to mitigate AMD generation for the long-term usually have to be discussed from the early stage of mine development with the source control strategy, i.e. dry cover method.

Hence, this study is focused on the identification of the source of rock to generate AMD and assesses the potential of AMD generation by investigating in Kyaukpahto gold mine which is the largest and the oldest open-pit gold mine with the epithermal deposit in Myanmar. Additionally, the backfilling design of the dry cover system is proposed considering the geochemical characteristics of waste rocks.

1.4 Study approach

In previous studies, various studies were conducted on the application of dry cover methods such as backfilling by NAG type, covering system with a mixed layer of NAF/PAF, and application of fly ash covering layer. However, most of them are studies in open-pit coal mines, and there is not enough knowledge on effective dry cover method in open-pit gold mine targeted in this study. Therefore, in the following

chapters, various studies will be made on the method of backfilling waste rock to control AMD at Kyaukpahto gold mine.

1.5 Dissertation structure

This dissertation consists of 6 (Six) chapters in which the contents are described as follow:

Chapter 1 presents the background of the current situation in Myanmar gold mines, the process of AMD generation within the open-pit mine, and the general countermeasures of AMD prevention. The requirements to discuss the application of the dry cover system in the gold mine, as well as an outline of the dissertation, are also introduced in this chapter.

Chapter 2 describes the results of the field investigations in Kyaukpahto gold mine, which is the largest and the oldest open-pit gold mine in Myanmar, selected as a case study. The field investigations were carried out to identify the place to generate AMD and examine the AMD characteristics including the current countermeasure to mitigate AMD.

Chapter 3 discusses the identification of the source of rock to generate AMD and assesses the potential of AMD generation using the geochemical analysis of rock samples from the open-pit and the waste rock dump in Kyaukpahto gold mine. Moreover, a possibility to adopt the dry cover system in this mine is discussed.

Chapter 4 describes the classification of PAF by investigating the elution behavior of the acidic water through the batch leaching test and column leaching test.

Chapter 5 discusses the backfilling design of waste rock as a dry cover system considering the characteristic of PAF. The same column leaching test was conducted with the different cover scenarios by using the PAFs which have different characteristics and NAF which has a higher ANC. Moreover, the guideline for the application of the dry cover system in the epithermal gold mine of Myanmar is suggested in this chapter.

Chapter 6 summarizes the conclusions of each chapter, including the recommendations.

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CHAPTER 2

Investigation of current status AMD issue in Kyaukpahto gold mine

2.1 Introduction

This chapter describes the current status and trends of AMD issues based on the water quality around the mine, the water quality inside the mine, and the geology inside the mine. The objective of this chapter is to investigate the problems of AMD generation in Kyaukpahto gold mine and to investigate the current countermeasure of AMD prevention operated by the mining company and its effect.

2.1.1 Background

The Kyaukpahto gold mine is located in the northern part of Myanmar. It was the first and the largest open-pit gold mine in Myanmar that began exploration in 1981 and has started mining in 1991 (Figure 2.1) [1]. The mineral amount at the beginning of the mine development was 3.71 million tons, and because of the epithermal vein, low-grade gold ore with an average grade of 2.11 ppm is mined with a cut-off grade of 0.3 ppm [2]. It has produced 5.0 tonnes of gold by 2017, and the current mining plan estimates that the remaining mine life will be 5-7 years [3]. There is only one pit in the mine, and the stripping ratio is 1:16, bench height of 10 m, bench wide of 10-20 m, bench inclination of 70 °, and average pit inclination of 45°. The maximum pit depth is 80 m. Waste rocks are transported to and deposited at three dumpsites (Low-grade ore dump, Waste dump 1, and Waste dump 2) in the mine as show in Figure 2.2.

Figure 2.1 Overview of the Kyaukpahto gold mine area

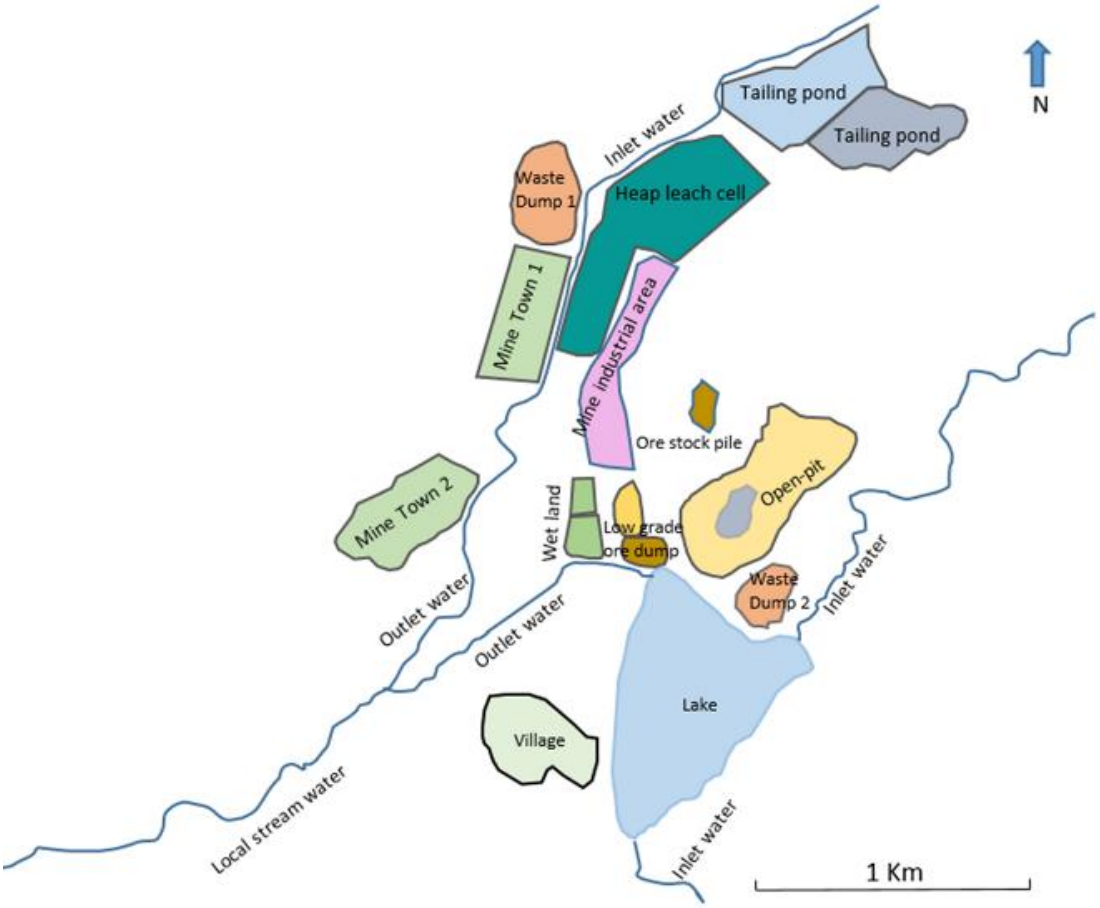

Figure 2.2 Map of Kyaukpahto Gold Mine

2.1.2 Kyaukpahto gold mine project

To extract pure gold in Kyaukpahto gold mine, metal ore are explored, crushed, and floatation is done and the metal concentrate is obtained. The metal concentrate is oxidised, and raw gold is extracted by the CIP (concentrate and Calcine Leach Residue) process. By refining raw gold by the wet digestion process, pure gold with gold concentration 99.99% is extracted [4]. Then the residual gold is extracted from low-grade oxidised metal ores and low-grade oxidised waste rocks using the wastewater from the plant which contains a slight concentration of the cyanide reagents. The steps in gold extraction procedures and the management of waste dump and wastewater in Kyaukpahto gold mine as shown in Figure 2.3 [3].

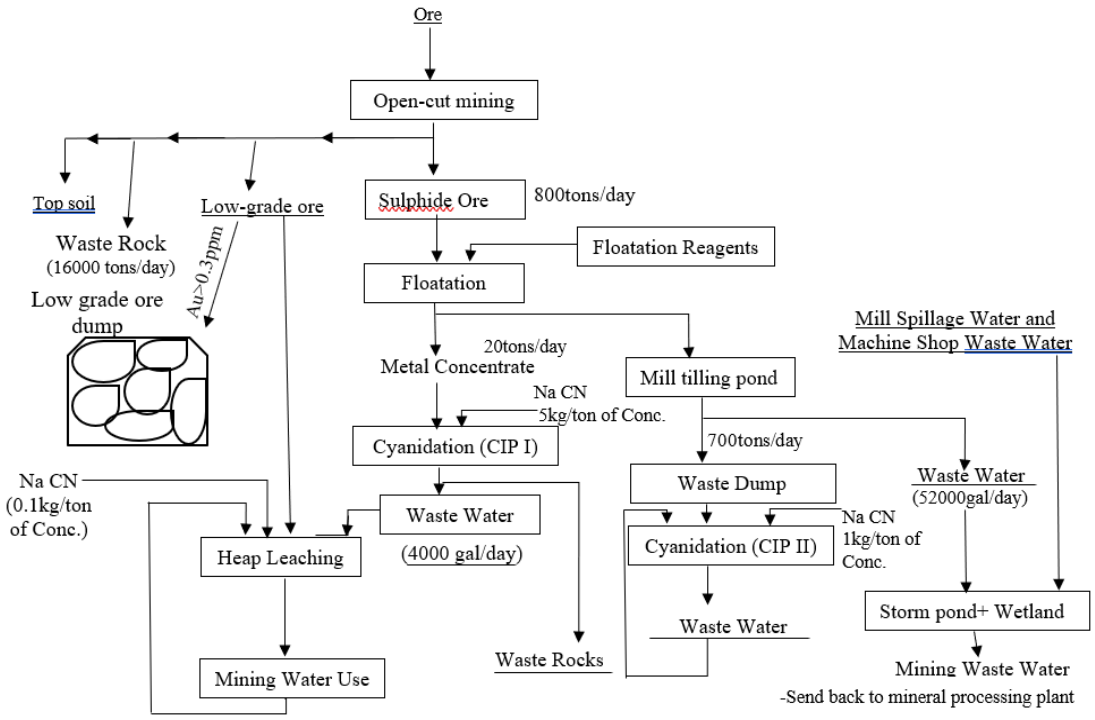

Figure 2.3 The steps in gold extraction procedures and the management of waste dump and wastewater in Kyaukpahto gold mine [3]

2.1.3 Management of mine wastewater to prevent environmental impact

Floatation process is applied to sulphide ores to obtain metal concentrate. Waste dumps and tailing ponds are systematically put in tailing ponds. The wastewater containing the reagents used in the floatation process is sent back to the floatation plant through Pump Station (PS-1) and reused. The water use of the plant is about 1 million gallons. The waste from CIP (concentrate and Calcine Leach Residue) is systematically kept in Leach Residue Ponds. To avoid water pollution above-ground and underground, the wastewater with lime and cyanide concentration is not discharged but reused in Heap Leaching of low-grade oxidised ores. The wastewater containing the reagents is also being reused in Heap Leach and CIP II. For increasing the percentage of wastewater reuse and reducing water use, passive treatment of the wastewater from CIP II is carried out using wetland. In Kyaukpahto gold mine, recycled water is used to prevent environmental impact as shown in Figure 2.4 [3].

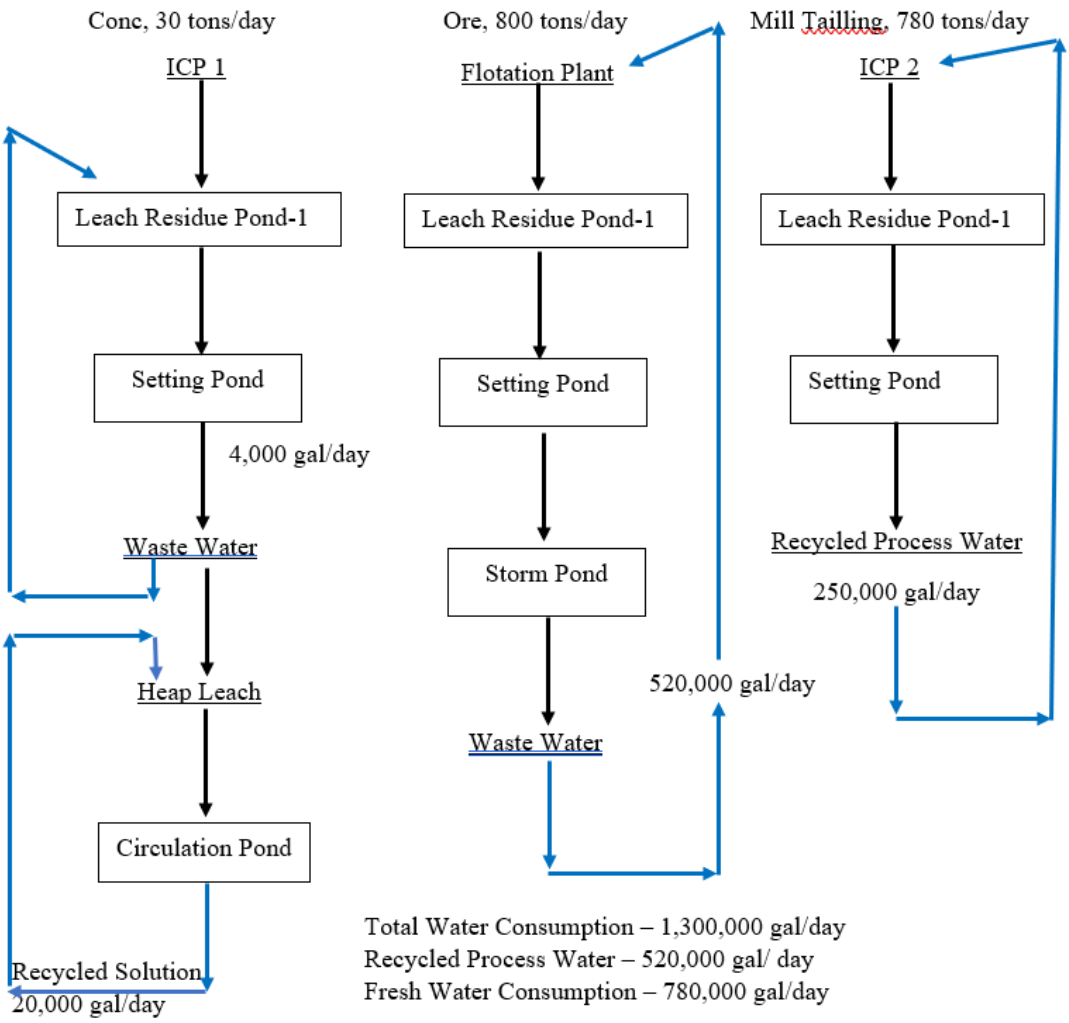

Figure 2.4 Water recycling uses in Kyaukpahto gold mine [3]

2.1.4 Water quality around Kyaukpahto Gold Mine

Table 2.1 shows the results of a water quality survey around the mine by a company currently developing this gold mine. The sampling points are as shown in Figure 2.5. According to the results in Table 2.1, no noticeable water pollution has been confirmed around the mine at present. However, the potential for future AMD should be considered, and the investigation is described in the next section. There is no water pollution in the surrounding environment while the current countermeasure is the addition of limestone to neutralize the acidic water as shown in Figure 2.6 [3]. Considering the AMD is identified in the mining site and the current countermeasure is just for the temporal management, it is needed to evaluate the potential of AMD pollution in the future and to discuss the effective countermeasure for long-term management.

Figure 2.5 Water sampling area around Kyaukpahto Gold Mine

Table 2.1 Water quality survey around Kyaukpahto Gold Mine (Unit; mg/L)[3]

	Standard	SW1	SW3		SW4		SW5		SW6-a		SW6-b		SW9	
		2015	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
pH	**6 – 9**	7.6	7.9	7.1	8.4	8.1	8.4	7.9	7.6	7.9	8.6	8.5	8.3	8.1
COD	**150**	32	32	64	32	32	32	32	32	32	32	32	32	32
BODs	**50**	10	8	18	6	10	4	8	12	10	8	10	4	8
Suspended Solid	**50**	38	126	78	72	50	42	20	70	12	80	36	62	22
SO_4^{2-}	**200**	12	92	110	36	81	28	18	22	28	52	28	35	96
Total CN	**1**	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	0.32	N.D	N.D	N.D	0.28
Fe	**2**	1.2	2.80	0.77	0.77	0.52	0.78	0.2	3.28	N.D	1.80	0.43	1.10	N.D
As	**0.1**	N.D	0.1	N.D	0.06	N.D	0.025	N.D	N.D	N.D	N.D	N.D	0.1	N.D
Cu	**0.3**	N.D	0.05	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D
Pb	**0.2**	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D
Zn	**0.5**	N.D	0.05	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	8.5	N.D	8.1

Figure 2.6 Adding limestone into the pit

2.2 Geology at Kyaukpahto Gold Mine

At Kyaukpahto area, the Male Formation consists mainly of sandstones, siltstones, mudstones and shales. The sandstones are medium to coarse-grained, massive to interbedded with minor shales with a consistent and repeated nature. Carbonised plant remains including leaf impressions are present in some parts of the altered Male Formation. A few Mollusca fossils (mainly gastropods) are also observed within the mineralised zone at Kyaukpahto [5].

Original host rock textures and compositions are almost completely obliterated by intense hydrothermal alteration (mainly silicification) along the eastern flank of the hill, which hosts the mineralisation. Surface observations indicate that the post-mineralisation fracturing (NW-SE trending cross-fault) took place within the mineralised zone. The southern part of the ore body has slipped down with a displacement of approximately 60 meters on a cross fault [2].

From the previous section, it was presumed that AMD of Kyaukpahtoe Gold Mine mainly occurred near the low-grade ore dump. The location of the Low-grade ore dump is as shown in (Figure 2.7). The rock existing in the area corresponds to the area indicated by Ore (Low grade; Au <0.3 ppm%) in the open-pit cross-section in Figure. 2.8. It may be backfilled in the area and cause AMD.

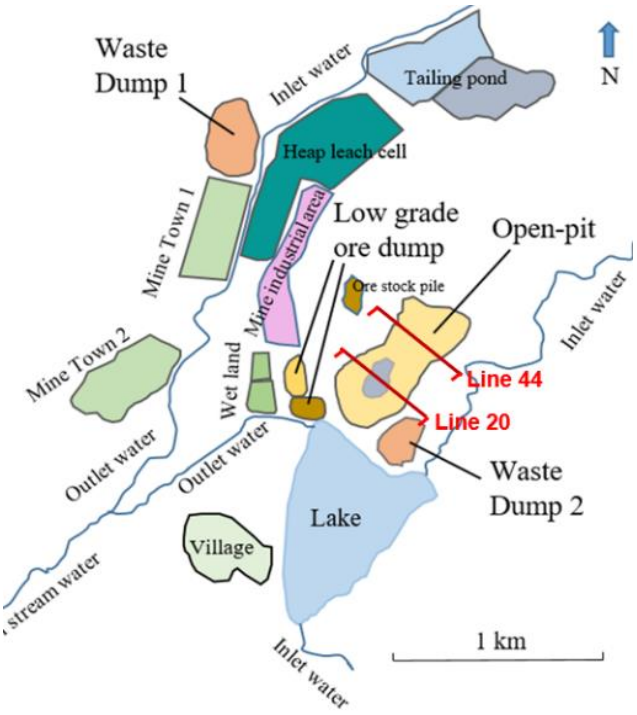

Figure 2.7 Cross section and location map areas

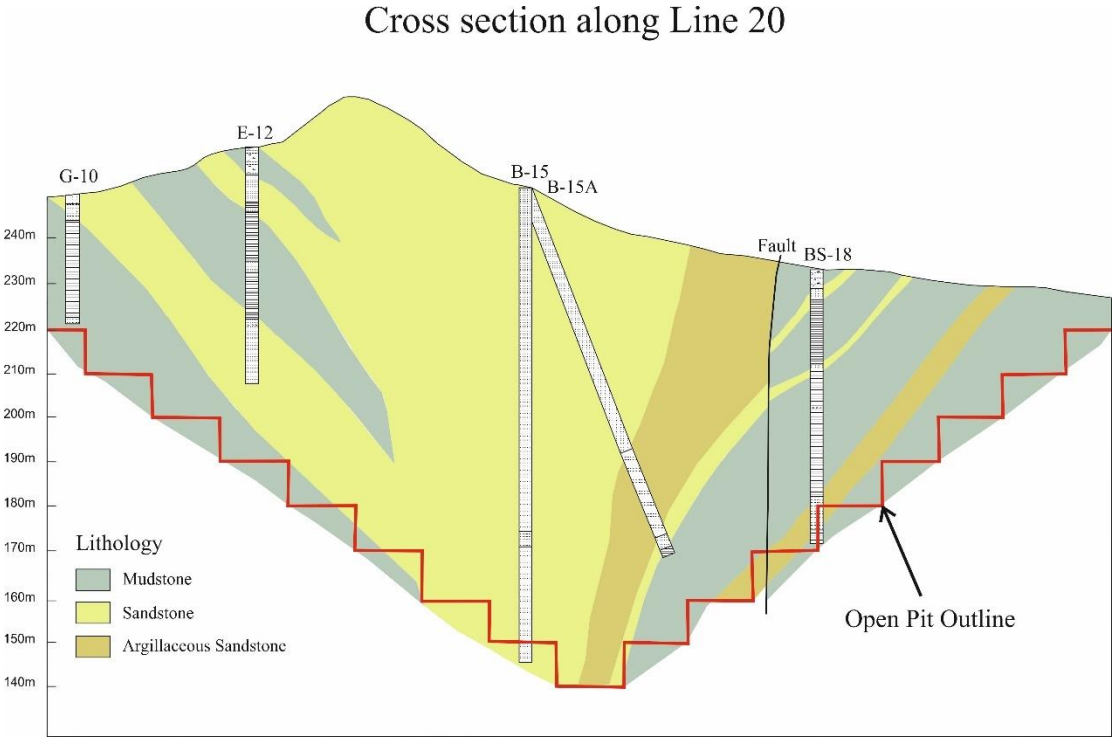

Figure 2.8 (a) Open-pit cross-section line 20 of Lithology

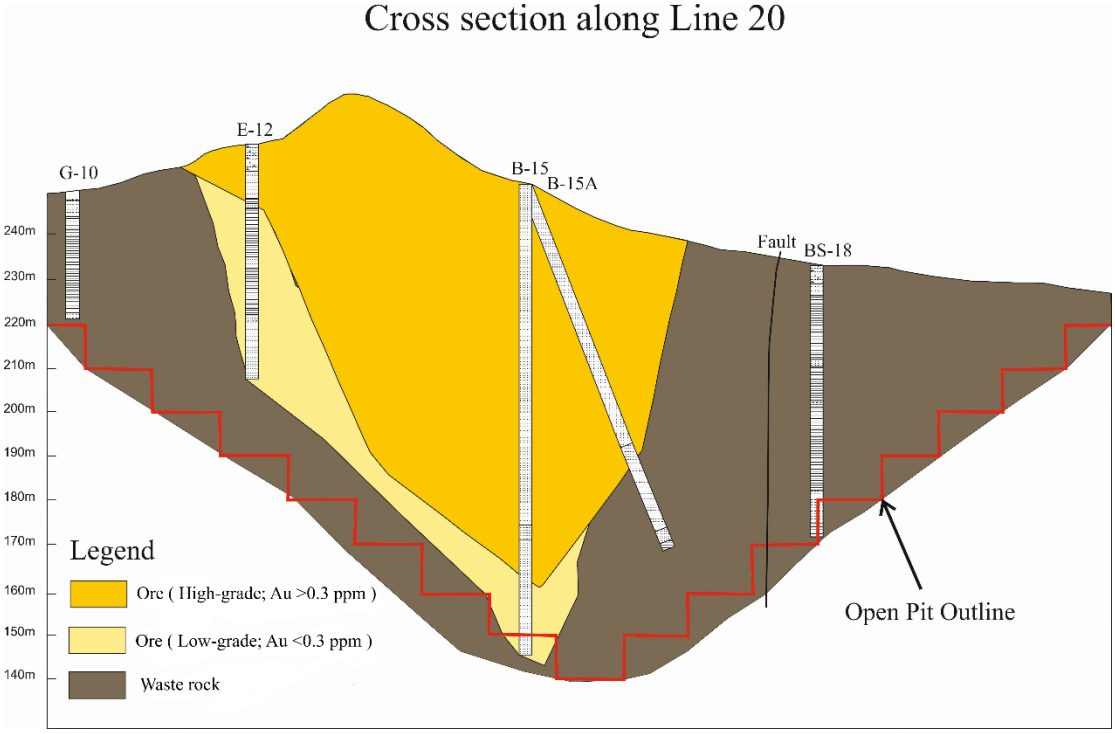

Figure 2.8 (b) Open-pit cross-section line 20 of Kyaukpahto Gold Mine

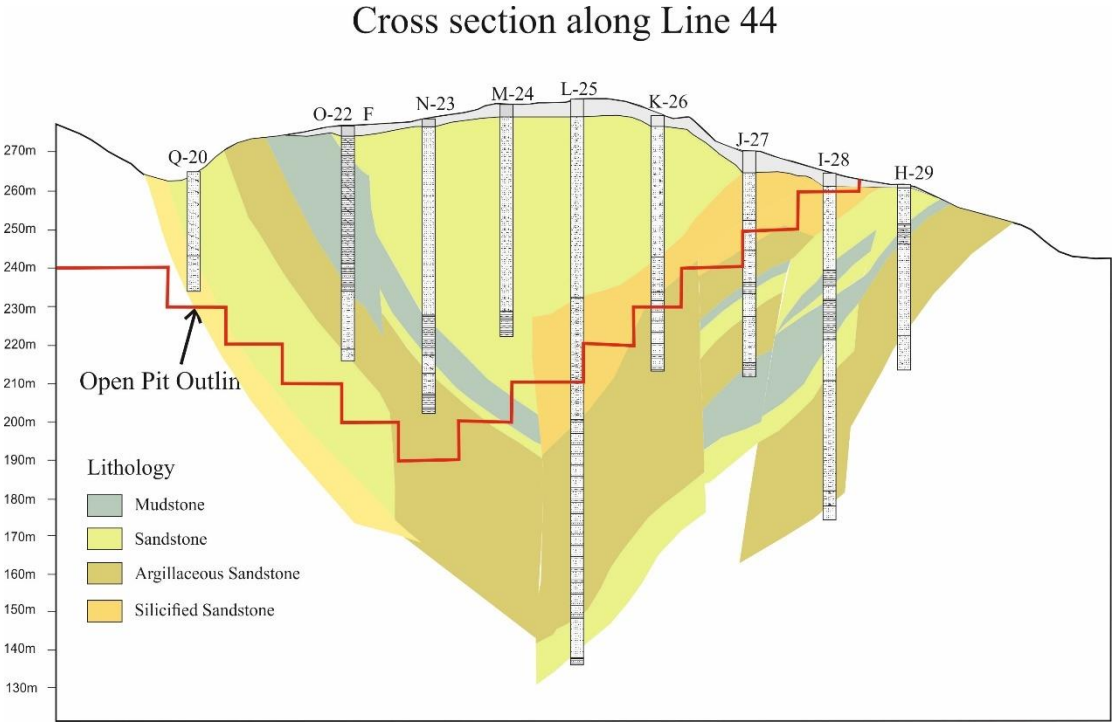

Figure 2.8 (c) Open-pit cross-section line 44 of Lithology

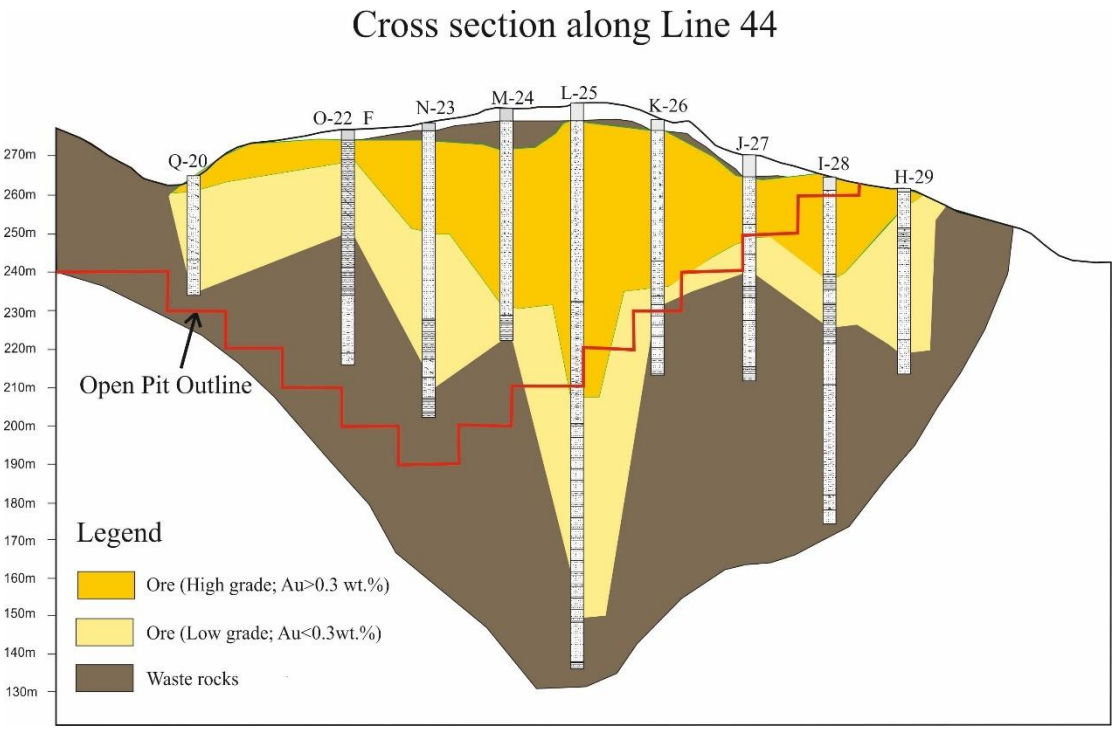

Figure 2.8 (d) Open-pit cross-section line 44 of Kyaukpahto Gold Mine

2.3 Current status of environmental pollution at Kyaukpahto Gold Mine

At present, water pollution inside the mine has been confirmed, but no noticeable water pollution has occurred in the surrounding environment. It can be said that there is no possibility of elution. At present, water pollution inside the mine is limited to a part of waste rocks and pits, but the pH is very low in the highly contaminated areas and several ten times more heavy metal is eluted than in other areas was confirmed.

In particular, in the case of low-grade ore dump, all collected mine wastewater shows strong acidity of pH 3 or less, and a large amount of characteristic heavy metals are eluted in gold mines such as Fe, Cu, As, etc. It showed high electrical conductivity.

Based on the above, we concluded that at locations where highly acidic water with a pH value exists, the surrounding geology may produce AMD by reacting with oxygen and water. By elucidating the elution characteristics from the extent of AMD and heavy metals eluting together, the geology causing the problem can be identified.

2.4 Field investigation of current AMD problems

A field survey was conducted to determine the current status of AMD at the Kyaukpahto gold mine. First, a survey of the open-pit confirmed the presence of red water presumed to be caused by the occurrence of AMD at the bottom of the open-pit and the water path inside the open-pit, as shown in Figures 2.9 and Figure 2.10. In the previous study, when examining the gold formation process at this mine, it was confirmed that pyrite (FeS_2), arsenopyrite (FeAsS), and chalcopyrite ($CuFeS_2$) were contained in the rock [1, 2, 5]. Besides, as shown in Figures 2.11 and Figure 2.12, red water was also observed in the water path around the waste rock accumulation site (Low-grade ore dump) as in the case of the open-pit. Therefore, red water was collected from the water near the open pit and low-grade ore dump, and the results of pH, EC, and eluted ion surveys are shown in Table 2.3. The sampling points are shown in Figure 2.13. According to the table, red water around open-pit and Low-grade ore dump show acidity of pH about 2~3, and Fe, Cu, Zn, and As, which greatly exceed the water quality standard in Myanmar [6], are eluted. It can be seen that Al and Mn, which are generally confirmed to be eluted when occurs, are also eluted. Also, considering that excess sulfate ions (SO_4^{2-}) are eluted in any red water, it is

presumed that these red waters are generated by the oxidation reaction of sulfide minerals contained in rocks. On the other hand, the pH of water samples collected around the waste dump, mine town underground water, and lake are neutral to weakly alkaline, and the generation of acidic water at the mine is limited. It is thought that the acidic water only originated from the waste rock from the pit. Considering that a large amount of the waste rock will be deposited and disposed of at the dumpsite due to further mine development, and considering the long-term water quality management after final excavation, the existing waste backfill design will be accompanied by the occurrence of AMD. Since there is a possibility of causing water pollution in the surrounding rivers, it is necessary to consider measures for the source of AMD in the future. Therefore, in the next chapter, laboratory experiments using rocks collected from the mine were conducted to examine the geochemical characteristics of the rocks.

Figure 2.9 Open-pit bottom

Figure 2.10 Water path in Open-pit

Figure 2.11 Red water near Low-grade ore dump

Figure 2.12 Water path near a Low-grade ore dump

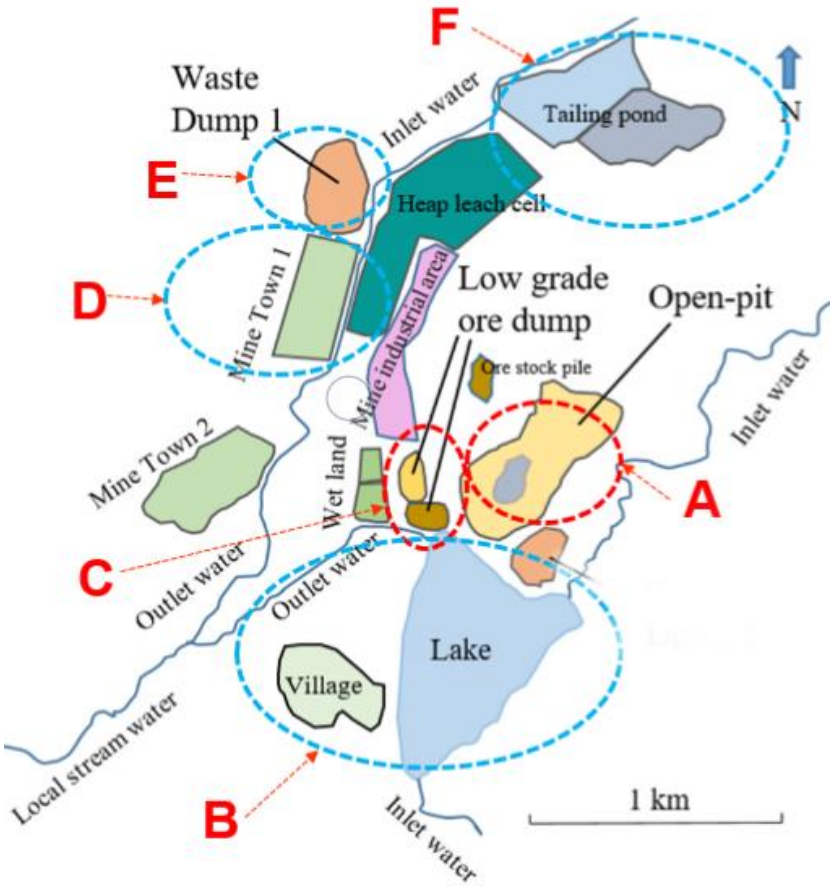

Figure 2.13 Water sampling location in the mine

Table 2.3 Field investigation results of pH, EC, and eluted ions

Location	Sample	pH	EC (mS/cm)	Al mg/L	Mn mg/L	Fe mg/L	Cu mg/L	Zn mg/L	As mg/L	SO_4^{2-} mg/L
Area – A	PW-1	2.61	3.80	370	19.1	9,519	14.3	23.3	373.4	6,201
(Open-pit)	PW-5	7.24	2.20	56.9	0.29	232.6	11.2	1.2	3.73	1,886
	PW-9	2.53	2.53	116	8.90	171.	15.6	36.6	0.50	9,652
Area- B	LW-1	7.63	0.49	3.61	0.05	1.99	0.49	2.0	0.03	10.80
(Lake)	LW-5	7.73	0.42	6.21	0.71	11.15	0.41	0.3	0.02	36.31
Area – C	LGW-1	2.57	6.50	163	72.6	298.7	29.7	16.0	0.16	17,646
(Low-grade	LGW-2	2.50	6.00	234	19.2	538.8	15.5	99.8	1.52	22,205
ore dump)	LGW-3	1.54	12.60	3622	71.4	13,964	296.8	671.6	331.2	86,510
Area- D	TW-2	8.25	0.59	2.61	0.02	1.12	0.52	2.2	0.01	1.23
(Mine town)	TW-3	8.35	0.67	2.55	0.05	1.84	0.32	2.8	0.01	7.09
Area- E	WW-1	7.67	1.67	160	4.98	99.4	37.	111.8	0.38	1,749
(Waste dump)	WW-5	8.18	1.31	23	0.49	12.7	3.6	21.7	0.04	1,262
Area- F	T-1	5	1.46	4	-	4	0.7	0	0	-
(Tailing pond)	T-2	4.87	1.48	5	-	2	0.6	0	0.1	-
MNEQ guideline	Standard	6-9	-	-	-	2	0.3	0.5	0.1	200

2.5 Conclusion

The problems of AMD generation in Kyaukpahto gold mine are considered to exist at active pits and low-grade ore dump. Concentrations of toxic chemical elements (e.g. Fe, As, Ni, Zn, etc.) are very high in the acidic mine waters from the pit and low-grade ore dump. The current countermeasure is the addition of limestone to neutralize the acidic water. There is no water pollution in the surrounding environment currently although AMD generation is confirmed in open-pit and low-grade ore dump in Kyaukpahto gold mine. It is needed to evaluate the potential of AMD pollution in the future and to discuss the effective countermeasure for long-term management.

2.7 References

[1] S. Maung, S. Myint, H. Kyaw, Y. Kyi and S. M. Swe, "Report on Ore Reserve Estimation of the Kyaukpahto Gold Deposit," DGSE, Myanmar, 1991.

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[6] Myanmar National Environmental Quality (emission) guidelines, (2015), pp.70-71.

CHAPTER 3

Identification of AMD source by geochemical analysis of the rock sample

3.1 Introduction

In the previous chapter, a site survey was conducted in the Kyaukpahto gold mine. As a result, it was confirmed that acidic water was generated from a part of the mine. Therefore, this chapter discusses the identification of the source of the rock that generates AMD and assesses the potential of AMD generation through the geochemical analysis of rock samples from the open-pit and the waste rock dump in Kyaukpahto gold mine.

3.2 Sampling

A field investigation was carried out in Kyaukpahto gold mine in order to understand the field conditions in the mining area concerning waste rocks. An environmental report from the mining company states that water pollution due to AMD is not currently detected at the wastewater quality monitoring point outside the mining area owing to the current water treatment producers. However, there are residential areas adjacent to the mining area, and so, assessment of the potential contamination risk from AMD from the Kyaukpahto gold mine is required to protect the health of the residents and enable the sustainable development of the gold. Acidic water with red-brick colour was found in the open-pit and the low-grade ore dump, and basically, the water flow is north to south.

Water samples for pH and electric conductivity (EC) measurements were collected from a total of 41 points in the areas A, B, C, D, E, and F, which are shown in Figure 3.1. These areas are respectively located in the tailing pond, a waste dump, the mining town, the low-grade ore dump, the open-pit, and downstream of the drainage from the mine area. The water samples were introduced into an Agilent 7500 Series Inductively Coupled Plasma-Mass Spectrometer (ICP-MS) after adding 0.1% of HNO_3 [1].

Waste rock samples were collected from three areas in the mine site as marked in (Figure 3.1): the open-pit (Area A), the low-grade ore dump (Area C), and the largest waste dump (Area E). These samples were named as OP-1, OP-2, OP-3, OP-4,

LG-1, LG-2, LG-3, LG-4, LG-5, WD-1, WD-2, WD-3, and WD-4. A paste pH, a net acid generation (NAG) test, acid-base accounting (ABA), and X-ray fluorescence (XRF) analysis were performed to characterize the geochemical characteristics of the waste rocks.

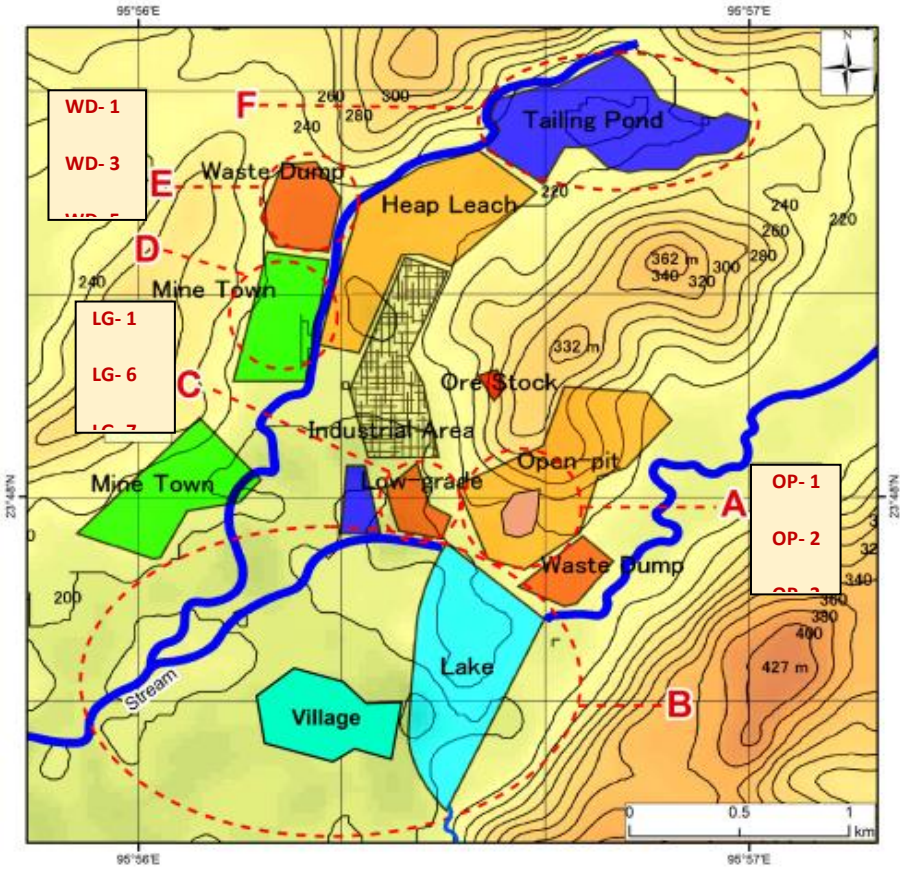


Figure 3.1 Location map of rocks samples in Kyaukpahto gold mine: red letters indicate water-sampling areas; the open-pit (OP), the Low-grade ore dump (LG), and the waste dump (WD) indicate waste rock sampling areas.

Table 3.1 summarizes the water quality results for surface water in areas A, B, C, D, E, and F locations are shown in Figure 3.1. The measured pH was less than 3.0, and the measured EC was more than 2.0 mS/cm in areas A and C. Furthermore, high concentrations of Fe, As, Al, Cu, and Zn were detected in the samples of these areas when compared with those of areas B, D, E, and F. These values exceed the Myanmar National Environmental Quality standards [2], which are pH=6-9, Fe < 2.0 mg/L, As < 0.1 mg/L, Al < 3 mg/L, Cu < 0.3 mg/L, Zn < 0.5 mg/L. Although both pH and the Fe and As concentrations also exceed standard levels at several points in B, D, E, and F, the very low pH values and extremely high Fe and As concentrations in areas A and C make these the main AMD source areas.

Table 3.1 Chemical concentrations (mg/L) in water samples from the research area. EC is in mS/cm

Area	No	pH	EC	Fe	As	Al	Cu	Zn
A (Open-pit)	1	2.61	3.8	9519	373	370	14	23
	2	7.23	0.93	359	10.7	7	0.9	1
	3	6.76	3.7	522	9.8	49	8.8	2.1
	4	2.59	2.7	170	1.6	78	14	5.1
	5	7.24	2.2	233	3.7	57	11	1.2
	6	2.68	2.7	114	0.7	64	9.7	5.3
	7	2.85	3.9	79	0.3	142	20	10.
	8	2.66	2.7	87	0.3	102	15	6.6
	9	2.53	4	171	0.5	116	16	37
B (Lake and stream)	10	7.63	0.49	2	0	4	0.5	2
	11	7.62	0.44	1	0	1	0.5	0.6
	12	7.6	0.39	1	0	1	0.4	1
	13	7.94	0.38	1	0	1	0.3	0.3
	14	7.73	0.42	11	0	6	0.4	0.3
	15	7.19	0.66	2	0.5	2	0.6	0.6
	16	7.98	0.59	0	0	1	0.4	0.2
	17	8.3	0.31	0	0	0	0.1	0.1
	18	8.41	0.36	0	0	0	0.1	0
C (Low-grade ore dump)	19	2.57	6.5	299	0.2	163	30	16
	20	2.5	6	539	1.5	234	15	99
	21	1.54	12.6	5586	132	1,449	119	269
D (Mine town)	22	8.64	0.64	1	0	2	0.3	0.8
	23	8.25	0.59	1	0	3	0.5	2.1
	24	8.2	0.67	2	0	3	0.3	2.8
	25	8.35	0.05	0	0	1	0.2	0.8
	26	8.59	2.7	55	0.4	69	17	78
	27	8.19	1.09	4	0.1	8	2.9	8
	28	8.31	0.85	2	0	3	1.6	2.6
	29	8.41	0.53	3	0.1	4	0.5	9.6
	30	8.89	0.64	3	0.1	4	1.7	5.4
	31	8.77	0.92	3	0	4	0.7	4.8
E (Waste dump)	32	7.67	1.67	99	0.4	161	37	12
	33	7.44	1.56	31	0.4	64	12	18
	34	7.92	1.64	41	0.4	38	7.5	21
	35	8	0.73	1	0	1	0.7	1
	36	8.18	1.31	13	0	24	3.6	22
	37	5.18	1.28	12	0.1	34	6.9	32
F (Tailing pond)	38	5	1.46	4	0	4	0.7	0
	39	4.87	1.48	2	0.1	5	0.6	0
	40	6.48	1.43	2	0.1	6	3.7	0.8
	41	6.58	2.04	21	0.2	18	4.7	6.6
MNEQ guideline		**6 -9**	**-**	**2**	**0.1**	**-**	**0.3**	**0.5**

3.3 Materials and methods

3.3.1 X-Ray Fluorescence analysis

X-Ray Fluorescence (XRF) is an analysis that irradiates a sample with X-rays, spectrographs the fluorescent X-rays generated from the sample, and qualitatively or quantitatively analyzes the elements according to the extraction angle and intensity. When an atom is irradiated with X-rays (primary X-rays), core electrons of some atoms are excited and emitted, and then the energy difference between these core electrons is determined by fluorescent X-rays Figure 3.2.

Here, each element has its spectrum of fluorescent X-rays, and the intensity of the spectrum is proportional to the element concentration. Separately, a standard sample with a composition similar to that of the sample is prepared and analyzed. In addition to the calibration curve method, there is an FP method that can calculate the effect of coexisting components. It is more qualitative and quantitative than the energy dispersive type and can analyze even light elements [3].

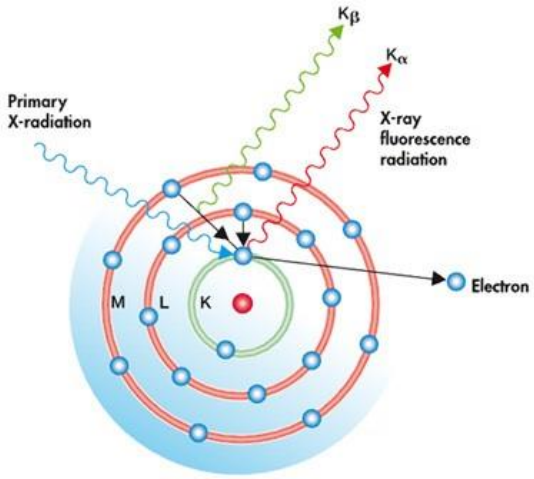


Figure 3.2 Core electron in an excited state

3.3.1.1 Analysis method

In this study, X-ray fluorescence analysis was performed to understand the elemental composition of each rock sample and calculate NAPP. A Rigaku RIX3100 was used for the measurement. Besides, since the ignition loss cannot be measured with a fluorescent X-ray analyzer, the measurement was performed in advance before the analysis. The measurement procedure is described below.

1. Each sample was ground by a vibrating mill TI-100 in an amount of about 10 g to fill the sample holder while preventing orientational orientation.
2. The weight of the crucible was recorded.
3. Approximately 1 g of the sample ground in step 1 was placed in a crucible, and the total weight was recorded.
4. The sample was heated in an oven at 110 ° C for about 90 minutes and dried.
5. After cooling the sample after heating at room temperature, the mass was measured, and the difference from the weight recorded in 3 was taken as the attached water.
6. The sample was heated in an oven at 1,000 ° C for about 4 hours to reduce the amount of structural water and carbon dioxide.
7. After cooling the sample after heating at room temperature, the mass was measured, and the difference from the weight recorded in 5 was reduced by ignition loss. The sample after the measurement was discarded.
8. About 5 g of the sample pulverized in step 1 was placed in a vinyl chloride ring, and the sample was pressurized with a pressure machine at a pressure of 20 tonnes.
9. The pressurized sample was fixed to a sample holder, and the measurement was performed with a fluorescent X-ray analyzer RIX3100 Figure 3.3.

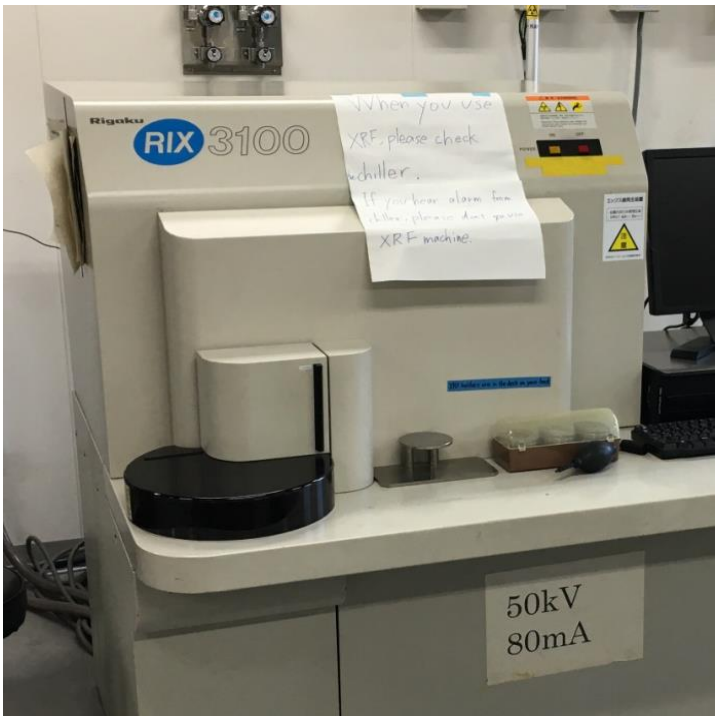


Figure 3.3 X-ray fluorescence analyzer RIX3100

3.3.2 Paste pH test

Paste pH is the pH indicated by the eluted water after adding deionized water to powdered crushed rock samples and leaving it to stand for 12 hours or overnight [4].

3.3.2.1 Test method

The measurement procedure is shown below。

1. 25 g of a sample having a particle size of -75 μm or less was placed in a beaker.
2. 50 g of deionized water was added to the beaker.
3. The sample was left overnight.
4. The pH of the elution water was measured, and the result was defined as Paste pH.

3.3.3 Net Acid Generation (NAG) Test

The NAG test is a test that indicates the possibility of acidification of water eluted from waste rock. This test alone can be used to determine PAF (a waste stone that is a source of acid water) or NAF (other waste stone). From the viewpoint that the reaction area increases as the specific surface area increases, the rock or mineral sample are finely pulverized, and the rock or mineral sample is completely oxidized by mixing hydrogen peroxide water into a part thereof. Hydrogen peroxide is a strong oxidizing agent, and the redox potential is E = 1.77 (V), which is higher than the redox potential (E = 0.77 (V)) of iron. Rocks identified as PAF are classified as potentially generating acid mine drainage and are backfilled deep underground without exposure to water or air.

3.3.3.1 Test method

The measurement procedure is shown as follows, [5],

1. 2.5 g of a sample having a particle size of -75 μm or less was placed in a 500 mL conical flask.
2. 250 mL of a 15% hydrogen peroxide solution was gradually added to the conical flask.
3. The watch glass was placed on the conical flask and allowed to stand overnight in a ventilated area.
4. Using a hot plate, the sample was heated with boiling water. The heating time was until no reaction was observed or for a minimum of 2 hours.

5. After heating, contents cooled at room temperature.
6. Deionized water was added to a total volume of 250 ml, and at the same time, the sample attached to the side of the flask was washed away.
7. The pH of the elution water was measured, and the result was defined as NAG pH.

3.3.4 Acid-Base Accounting（ABA）test

The ABA test is a generic term for a static test that determines the relative balance between the ability of minerals in a sample to generate and neutralize potential acids and to predict the potential for acid formation in rock samples. This method was proposed by Sobek in 1978 and has been used for many analyses [5]. The following parameters can be calculated by this test [6, 8].

- Maximum Potential Acidity（MPA）

Potential acid generation capacity based on sulfur analysis, determined by the following equation: In this study, we calculated the sulfur content from the results of XRF analysis and calculated the MPA.

$$\text{MPA} = \text{Sulfur content (\%)} \times 30.6 \quad (\text{kg}H_2SO_4/\text{t}) \tag{6}$$

- Acid Neutralizing Capacity（ANC）

The acid-neutralizing capacity is the ability to neutralize acids. The calculation method will be described later. ($\text{kg}H_2SO_4$ /t)

- Net Acid Producing Potential（NAPP）

The theoretical balance between the ability of the sample to generate acid and the ability to neutralize acid, and is given by the following equation:

$$\text{NAPP} (\text{kg}H_2SO_4/\text{t}) = \text{MPA} - \text{ANC} \tag{7}$$

In addition, rock samples can be classified as shown in (Figure 3.4) below from NAPP determined by the ABA test and NAGpH determined by the NAG test, as described in this chapter.

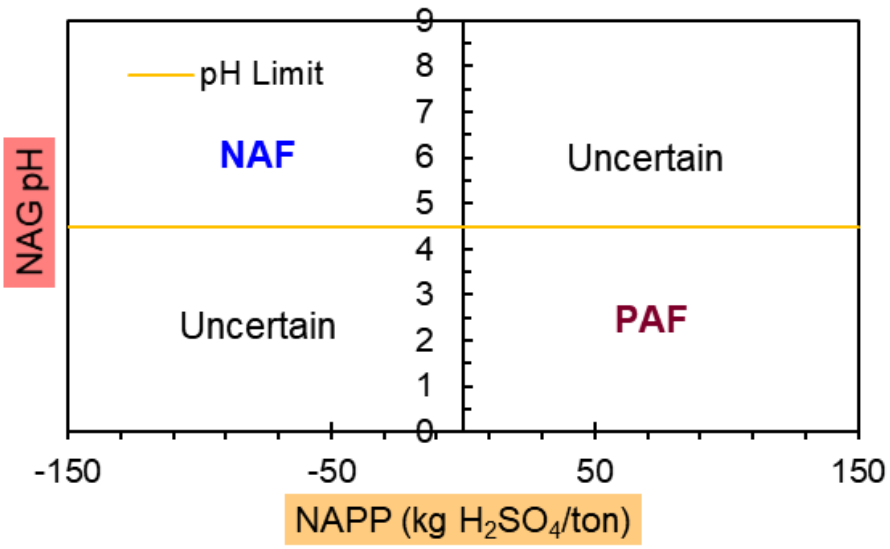


Figure 3.4 Classification of waste rocks by geochemical characteristics

3.3.5 Fizz test

To determine the amount and concentration of acid to be used in the analysis, the sample is given a "Fizz Rating". The Fizz test is a simple test for estimations of the amount of carbonate mineral in a sample. This test observes the reaction of a small sample with strong hydrochloric acid and is performed to determine the amount and molarity of hydrochloric acid needed to determine ANC. The test procedure of the Fizz test is shown below [4].

1. About 0.5 g of a sample having a particle diameter of 250 μm or less was placed in a glass.
2. 1-2 drops of 25% hydrochloric acid were added to the sample。
3. The state of foaming was observed, and the Fizz Rating was determined and recorded based in Table 3.2.

Table 3.2 Fizz Rating

Reaction	Fizz Rating
No reaction	0
Slight reaction	1
Moderate reaction	2
Strong reaction	3
Very strong reaction	4

3.3.6 Acid Neutralizing Capacity（ANC）test

Acid Neutralizing Capacity (ANC) is a quantification of the ability of a rock sample to neutralize acid calculated by oxidation of sulfur in minerals. The ANC measurement method is shown below [4, 5].

1. A 2.0 g sample was placed in a 250 mL conical flask.
2. According to the Fizz Rating, hydrochloric acid of the amount and concentration shown in Table 3.4 was added to the conical flask.
3. An additional 20 ml of deionized water was added.
4. A sample-free solution was prepared in another conical flask using the same concentration and amount of the hydrochloric acid as the Fizz Rating for measurement. This solution is used as a blank.
5. Using a hot plate, each solution was heated with water at 80 to 90° C. The heating time was until no reaction was observed or for a minimum of 2 hours.
6. After heating, cooling was performed at room temperature.
7. Deionized water was added to a total volume of 125 ml, and at the same time, the sample attached to the side of the flask was washed away.
8. According to the Fizz Rating, sodium hydroxide solutions having the amounts and concentrations shown in Table 3.3 were added little by little to the conical flask.
9. The measurement was terminated when the pH reached 7.0, and the amount of the added sodium hydroxide solution was recorded.
10. ANC was calculated and recorded. The calculation method will be described later.
11. If the ANC was out of the range shown in Table 3.3, it was an error in the Fizz Rating, so the measurement was performed again with the Fizz Rating changed.

Table 3.3 Test conditions for each Fizz Rating

Fizz Rating	HCl molarity(M)	HCl volume(mL)	NaOH molarity(M)	Range of ANC
0	0.5	4	0.1	0～10
1	0.5	8	0.1	10～40
2	0.5	20	0.5	40～100
3	0.5	40	0.5	100～200
4	1.0	40	0.5	200～400

3.3.7 ANC calculation method

The method of calculating ANC is described below.

$$ANC = [Y \times MHCl / wt] \times C \quad (8)$$

Where:

$$Y = (\text{Vol. of HCl added (mL)}) - (\text{Vol. of NaOH titrated (mL)} \times B) \quad (9)$$

$$B = (\text{Vol. of HCI in blank (mL)}) / (\text{Vol. of NaOH titrated in blank (mL)}) \quad (10)$$

MHCl = Molarity of HCl

wt = Sample weight in grams

C = Conversion factor

C = 49.0 (to calculate kg H_2SO_4/ton)

C = 5.0 (to calculate % CaCO3 equivalent)

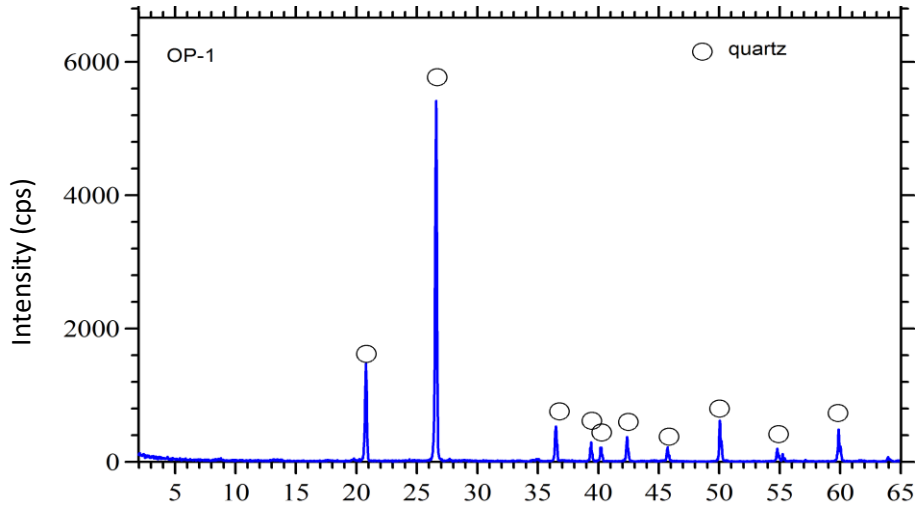
3.3.8 Result and Discussion of XRF analysis

The XRF analysis results of rock samples, as shown in Table 3.4, OP-1, OP-3, OP-6, LG-6, LG-9, and LG-12 in areas A and C showed a high concentration of the arsenic. This is consistent with the detection of a high arsenic concentration in surface water in areas A and C Table 3.2. The high concentration of Fe, Cu, As and S observed in areas A and C can be attributed to the common occurrence of pyrite, arsenopyrite, and chalcopyrite in the waste rocks, as geological investigations indicate the presence of these minerals in the rocks produced in the mine. Moreover, waste rocks in area E showed higher concentrations of Mg and Ca than in other areas. This suggests the presence of carbonate minerals, which will have contributed to the acid neutralization capacity informed in Table 3.2 for rocks from this area. Since the elution of As is a very important issue in water pollution, it is necessary to carefully consider this elution. Some of the samples contain a large number of carbonate minerals such as Ca and Mg. Considering that Ca and Mg have a buffering effect on acidic water, it is necessary to study the action of these ions on the suppression of acidic water. Table 3.4 shows the results of X-ray fluorescence analysis of each sample.

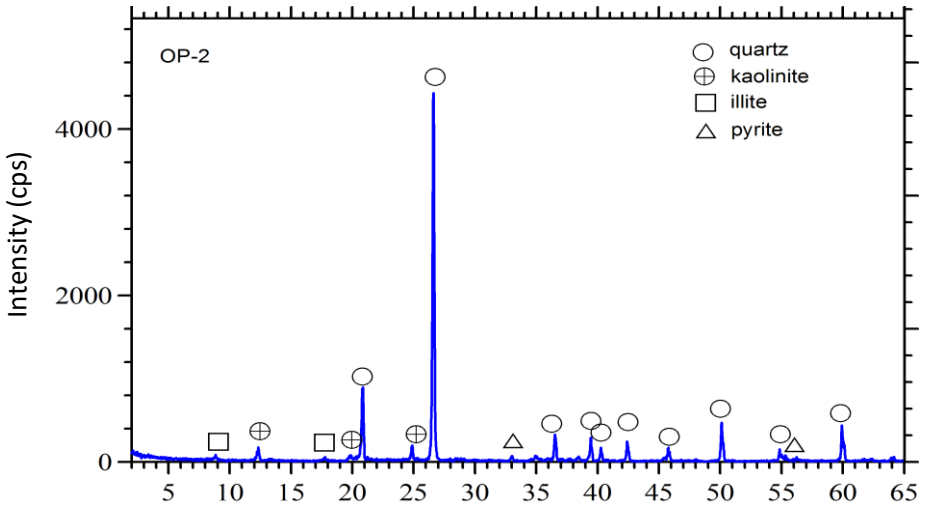
Table 3.4 The results of X-ray fluorescence analysis of samples

Location	Sp. ID	SiO_2 mass %	Al_2O_3 mass %	FeO mass %	MnO mass %	MgO mass %	CaO mass %	S mass %	Cu ppm	Zn ppm	Pb ppm	As ppm
Area A (Open-pit)	OP-1	93.40	2.86	0.85	0.00	0.12	0.02	0.39	8	8	0	5,691
	OP-2	78.78	10.06	2.32	0.00	0.35	0.03	1.82	69	81	0	852
	OP-3	73.96	9.51	4.62	0.00	0.43	0.01	2.59	8	24	88	23,524
	OP-5	59.97	17.55	5.65	0.09	3.25	0.83	0.63	0	0	0	95
	OP-6	80.02	9.49	1.94	0.02	0.71	0.12	0.87	0	0	0	2,967
Area C (Low grade ore dump)	LG-1	87.32	6.95	0.72	0.00	0.23	0.02	0.60	5	8	0	169
	LG-6	80.86	7.92	1.69	0.01	1.12	0.08	0.91	0	0	0	1,354
	LG-7	62.50	12.81	6.62	0.09	3.50	1.34	2.27	0	0	0	612
	LG-9	86.02	5.49	2.02	0.00	0.36	0.01	1.12	0	0	0	5,941
	LG-12	37.60	5.25	17.08	0.19	3.93	5.59	9.74	0	0	0	2,839
Area E (Waste dump)	WD-1	67.19	12.82	4.35	0.09	1.44	2.25	2.04	0	28	9	404
	WD-3	67.27	13.46	4.03	0.14	2.22	2.68	0.71	3	53	7	90
	WD-5	57.75	17.54	7.18	0.12	5.30	1.22	0.13	0	0	0	67
	WD-6	85.57	6.37	1.53	0.01	0.41	0.07	0.98	0	0	0	356
	WD-7	42.53	9.26	8.16	0.67	6.66	12.01	0.85	0	0	0	434

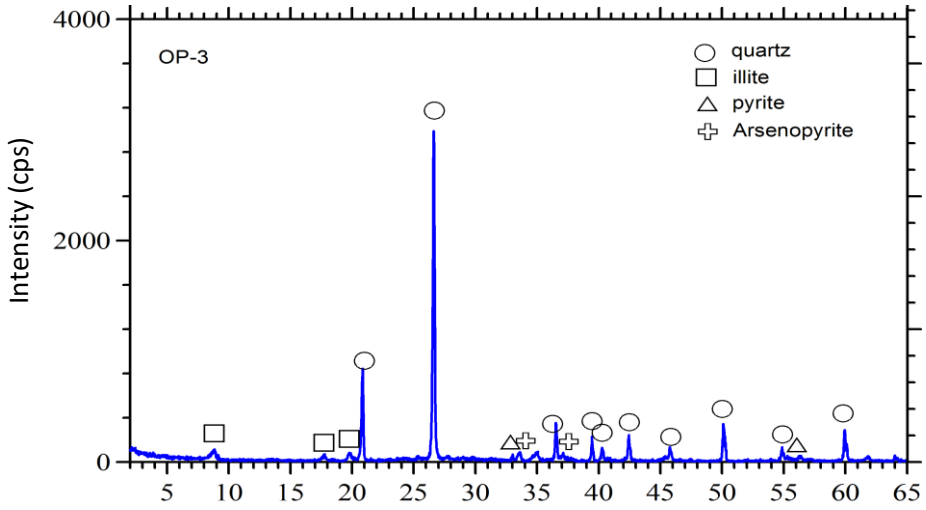
To support the result of mineral composition, XRD measurement is conducted [9]. The result of XRF measurement can be seen in Figure 3.5 and Table 3.5 provides the summary of XRD analysis measurement. The XRD result shows pyrite and arsenopyrite mineral is found in the areas A and areas C. Carbonate minerals such as dolomite and calcite are found in areas C and areas E. Carbonate minerals readily dissolve compared to sulfides causing the decrease of pH, resulting in the high paste pH. The large differences between paste pH and NAG pH indicated that the minerals having different dissolution rates were contained in the samples. Thus, the form of minerals in rocks significantly contributes to the change of pH, and the effect is not considered in the ABA test and NAG test.



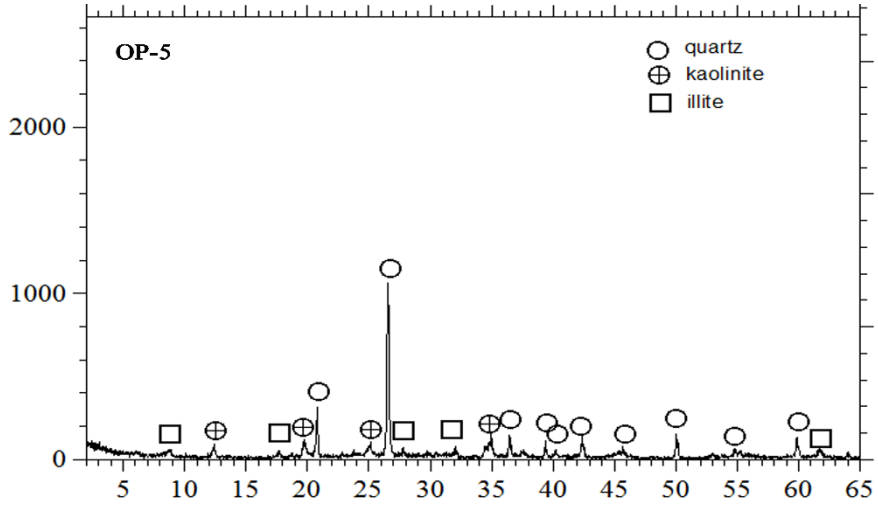
(a) OP-1 (Area A)



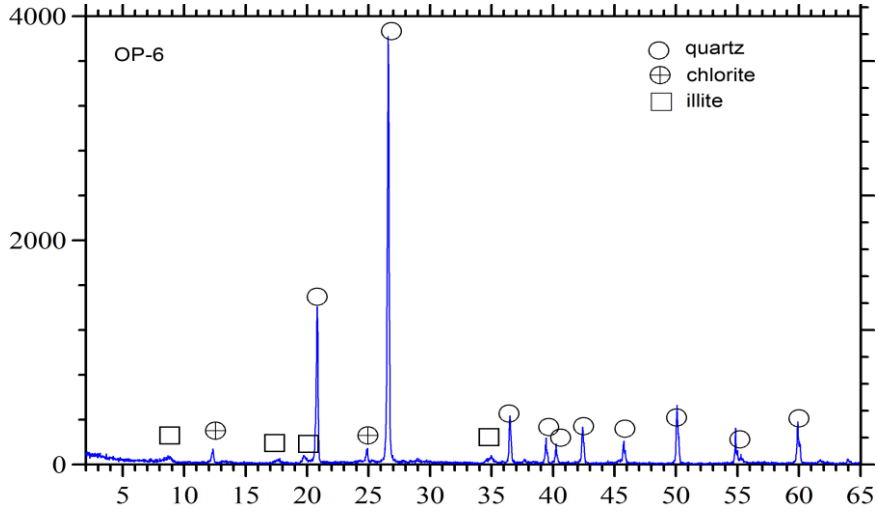
(b) OP-2 (Area A)



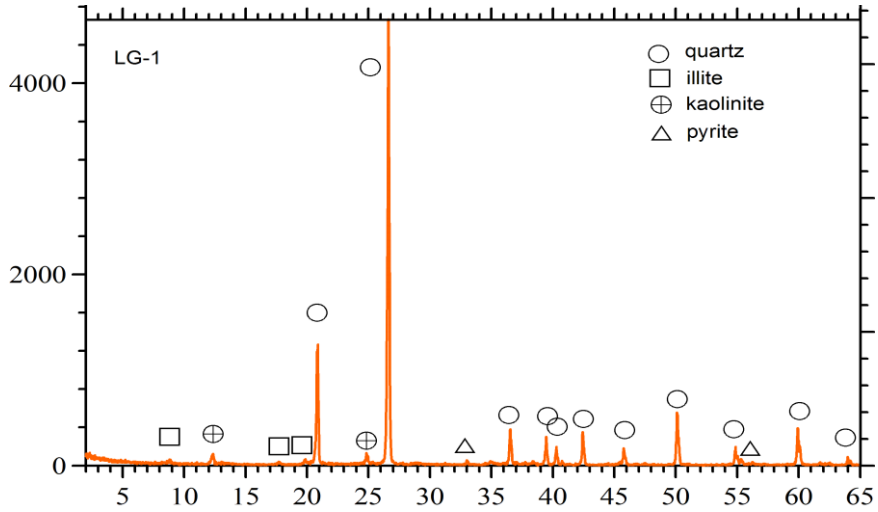
(c) OP-3 (Area A)



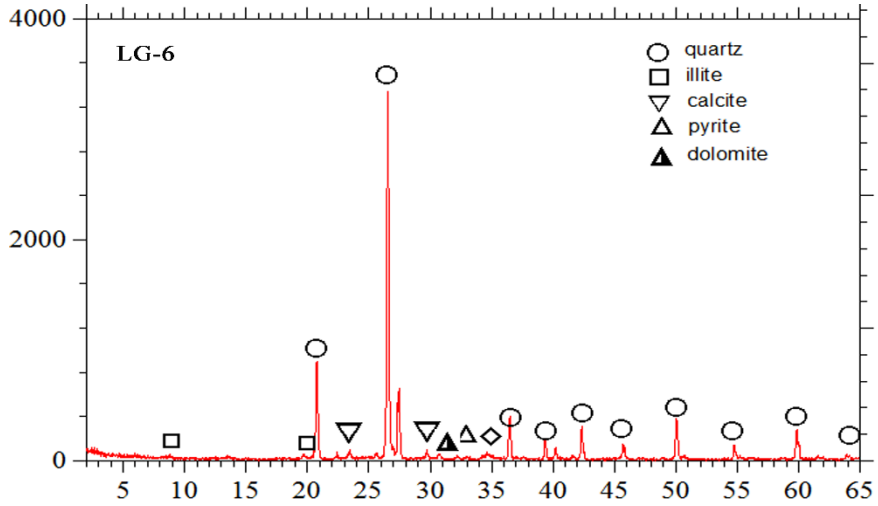
2 theta (degree)
(d) OP-5 (Area A)



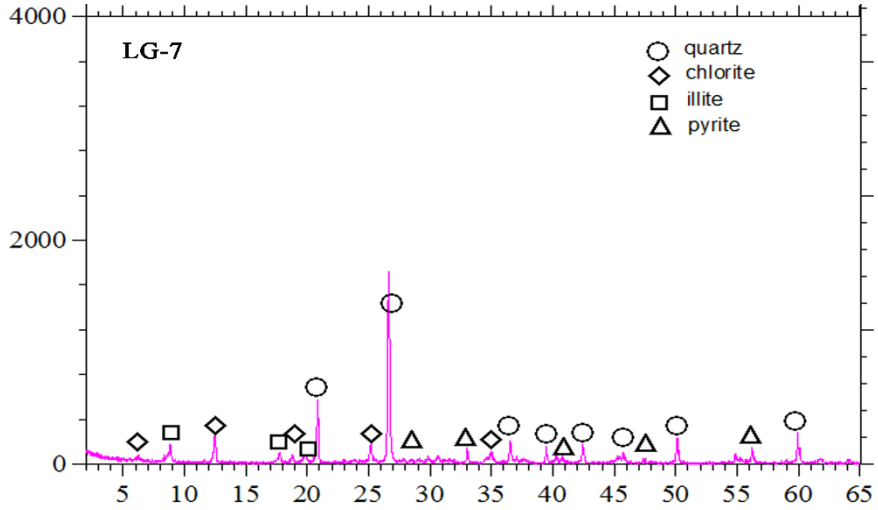
2 theta (degree)
(e) OP-6 (Area A)



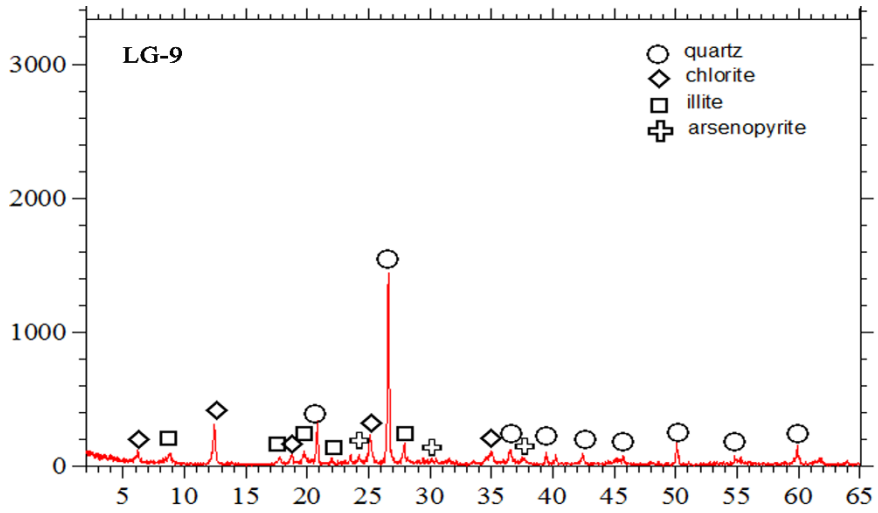
2 theta (degree)
(f) LG-1 (Area C)



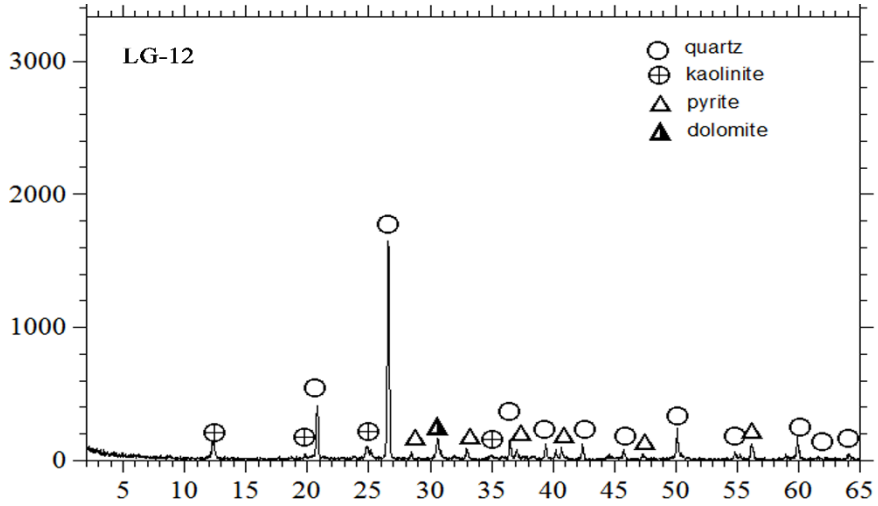
2 theta (degree)
(g) LG-6 (Area C)



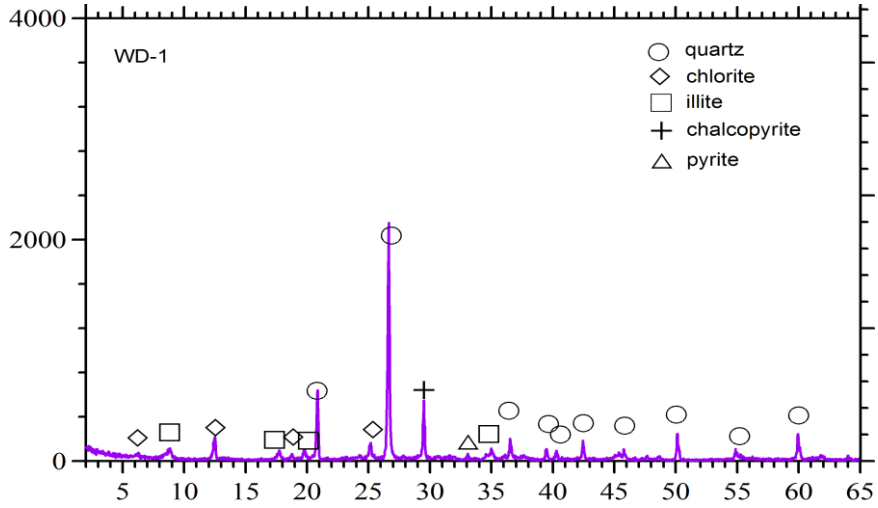
2 theta (degree)
(h) LG-7 (Area C)



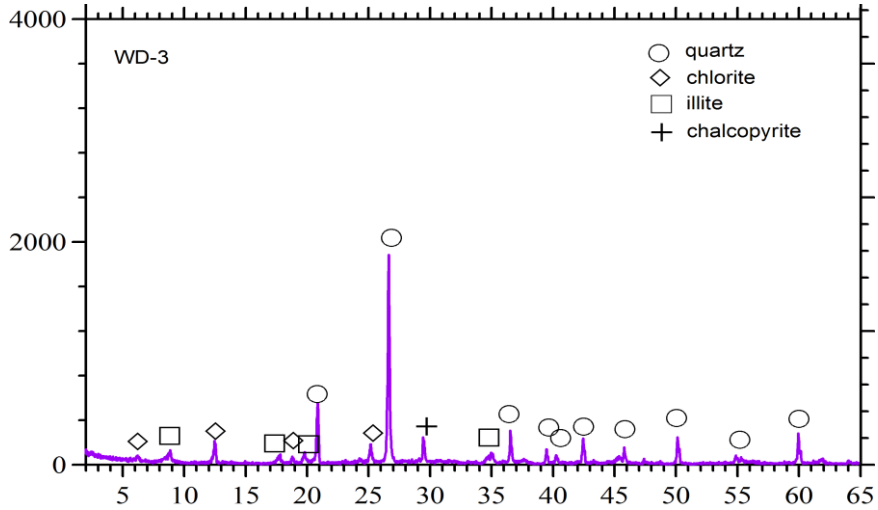
2 theta (degree)
(i) LG-9 (Area C)



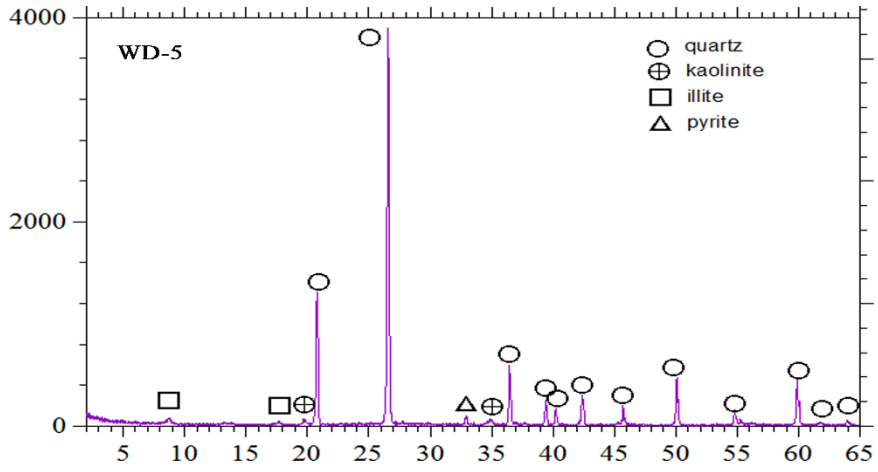
2 theta (degree)
(j) LG-12 (Area C)



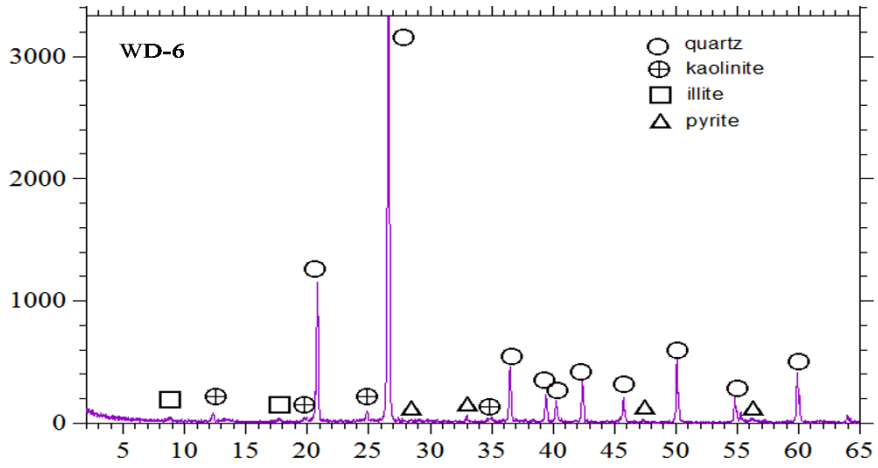
2 theta (degree)
(k) WD-1 (Area E)



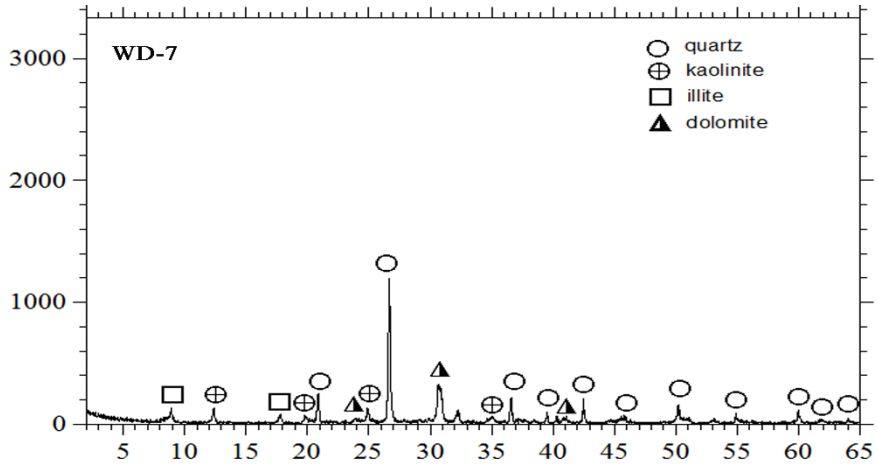
2 theta (degree)
(l) WD-3 (Area E)



2 theta (degree)
(m) WD-5 (Area E)



2 theta (degree)
(n) WD-6 (Area E)



2 theta (degree)
(o) WD-7 (Area E)

Figure 3.5 XRD results of rock samples are (a) to (e) from Area A, (f) to (j) from Area C, and (k) to (o) from Area E.

Table 3.5 XRD results of rock samples

Location	Sp. ID	Quartz	Pyrite	Arseno-pyrite	Chalco-pyrite	Illite	Kaolinite	Chlorite	Dolomite	Calcite
Area A (Open-pit)	OP-2	X	X			X	X			
	OP-3	X	X	X		X				
	OP-5	X				X	X			
	OP-6	X				X		X		
Area C (Low-grade ore dump)	LG-1	X	X			X	X			
	LG-6	X	X			X			X	X
	LG-7	X	X			X		X		
	LG-9	X		X		X		X		
	LG-12	X	X				X		X	
Area E (Waste dump)	WD-3	X			X	X		X		
	WD-5	X	X			X		X		
	WD-6	X	X			X	X			
	WD-7	X				X	X		X	

3.3.9 Geochemical test results

Table 3.6 shows the results of the Paste pH test, NAG test, and ABA test. The same table also shows the results of the classification of rock samples based on NAG pH and NAPP according to the AMIRA P387A Project ARD Test Handbook [4].

The geochemical properties of the waste rocks are summarized in Table 3.6. The geochemical classification of collected rock samples is seen in Figure 3.1. OP-1, OP-2, OP-3, OP-6 in the open-pit area and LG-1, LG-6, LG-7, LG-9, and LG-12 in the low-grade ore dump area were classified as PAF. The paste pH for all samples (except LG-2, LG-3, LG-4, and LG-5) ranged from 3.60 to 5.20, which exceeds the official standard value for pH. NAG pH ranged from 2.05 to 3.27, and NAPP showed positive values in the open-pit and low-grade ore dump areas. Thus, there is a potential risk of AMD in this area. This result is consistent with the findings from the water quality results that the major areas of AMD are located at areas A and C.

In area E, waste rocks have high carbonate minerals such as CaO and MgO can be produce neutralized in an absence of AMD in area E, where the measured pH of the wastewater can be seen to range from 4.30 to 8.7 in Table 3.1. The more positive NAPP values of rock indicate the higher capacity in producing acid while a more negative value informing that less capacity in producing acid and higher capacity in neutralizing the acidity within the system. NAG pH indicates acid potential after the

complete dissolution of the rock sample with H_2O_2, indicating that WD-6 is AMD contamination risk in the future, although there is currently no AMD in the area E.

Table 3.6 Summary of geochemical characteristics static test results from the Kyaukpahto gold mine area

Location	Sp. ID	Paste pH	Paste EC (ms/cm)	Total S %	MPA*	ANC*	NAPP*	NAG pH	Geochem Class
Area A (Open-pit)	OP-1	5.10	1.17	0.39	11.93	0.84	11.09	2.97	PAF
	OP-2	3.90	3.0	1.82	55.69	2.03	53.66	2.40	PAF
	OP-3	5.20	2.1	2.59	79.25	2.99	76.26	2.05	PAF
	OP-5	8.09	0.61	0.63	19.28	19.91	-0.63	6.65	NAF
	OP-6	6.17	1.20	0.87	26.62	26.53	0.09	3.01	PAF
Area C (Low grade ore dump)	LG-1	3.60	2.1	0.60	18.36	0.84	17.52	3.27	PAF
	LG-6	6.45	1.50	0.91	27.85	4.59	23.26	3.04	PAF
	LG-7	7.49	2.60	2.27	69.46	21.84	47.63	2.66	PAF
	LG-9	5.28	1.50	1.12	34.27	10.08	24.19	2.77	PAF
	LG-12	7.76	2.40	9.74	298.04	48.43	249.61	2.31	PAF
Area E (Waste dump)	WD-1	8.10	1.81	2.04	62.42	51.5	10.92	5.54	UC
	WD-3	8.70	1.08	0.71	21.73	55.56	-33.83	8.49	NAF
	WD-5	8.54	0.59	0.13	3.98	19.26	-15.28	7.79	NAF
	WD-6	4.30	1.70	0.98	29.99	-3.12	33.11	2.93	PAF
	WD-7	8.41	0.89	0.85	26.01	28.05	-2.04	8.28	NAF

The geological classification of collected rock samples can be seen in Figure 3.6. The results indicated that only one sample (sample WD-1 with NAG pH= 5.54, NAPP= 10.78 kg H_2SO_4/ ton) was identified as “UC” (uncertain) due to the conflict of NAG pH and NAPP values. However, the overall result in classification indicated that the NAG test was enough to classify most waste rocks as PAF for most waste

rocks (except one sample from area E). In general, the results indicated that area E contained both NAF and PAF materials, whereas areas A and C contained only PAF materials. The presence of PAF indicated the potency of AMD.

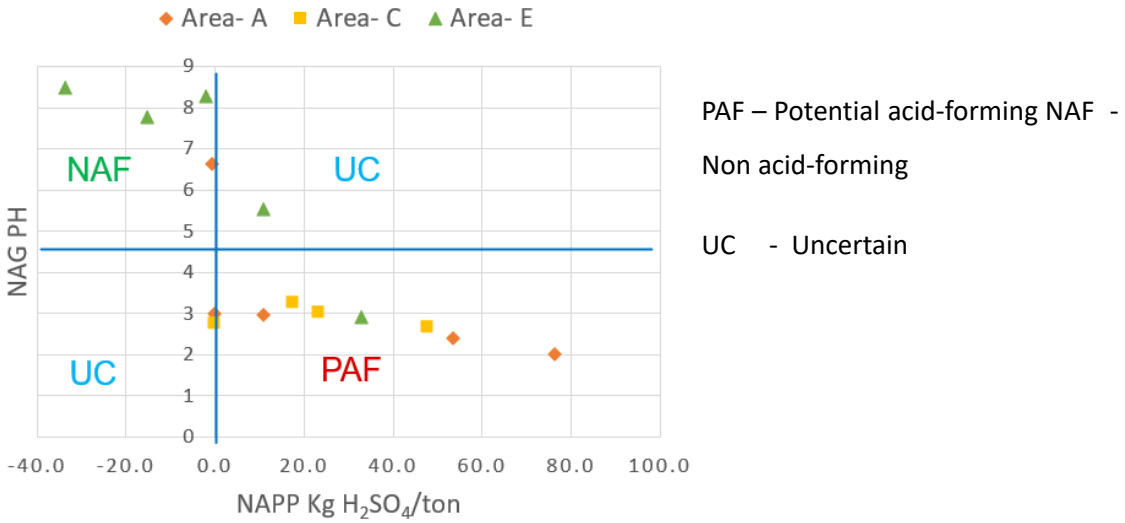


Figure 3.6 Geochemical classification of rock samples collected from Kyaukpahto gold mine

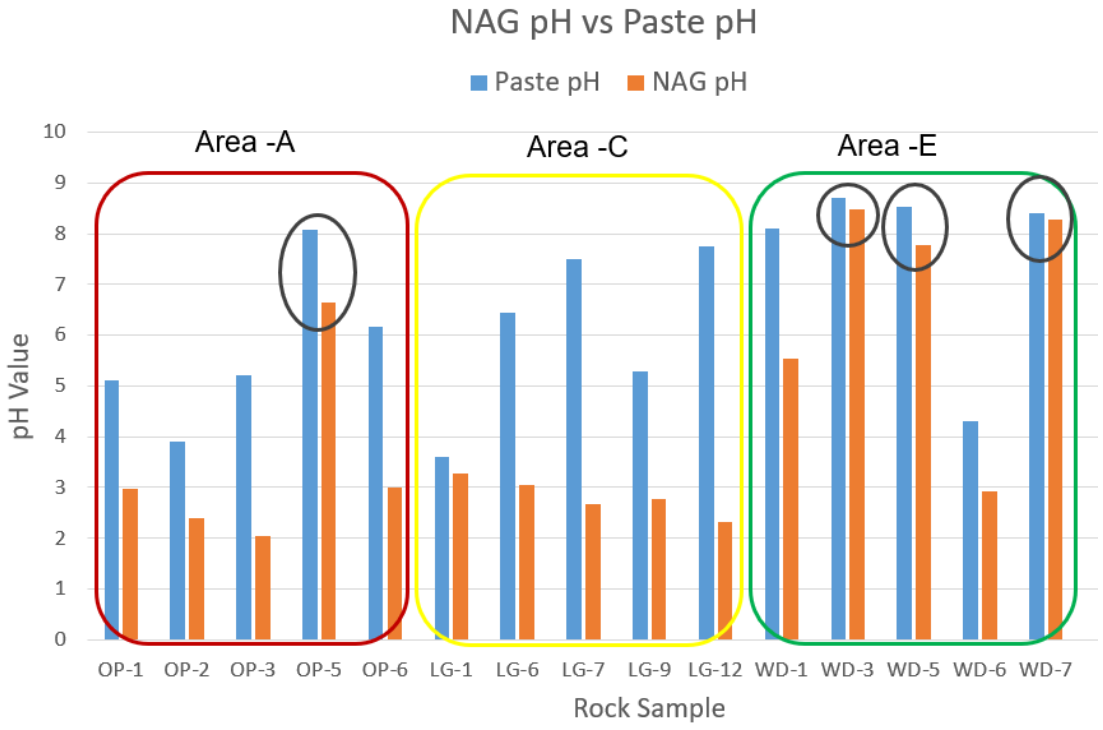


Figure 3.7 The relationship between NAG pH and Paste pH

The effectiveness of AMD generation can be observed from the relationship between NAG pH and Paste pH as shown in Figure 3.7. The relationship between NAG pH and Paste pH values offers an indication of relative reactivity of material.

Final pH value for rock sample (NAG pH) is measured after all sulfides available are oxidized using hydrogen peroxide (H_2O_2), whereas Paste pH shows the current pH value as the result of material reaction with water. The sample contains reactive sulfide minerals will be the most responsive in the Paste pH test [4]. As we can see in Figure 3.7, NAG pH value from the areas A and C are below 3.27. Therefore, it is possible that acid generation could be occurred in a future period. NAG pH value of WD-3 and WD-5 from area E reach above pH 5.54. Therefore, the possibility of acid generation is quite low. Moreover, they can create neutralization conditions due to the presence of carbonate minerals in the waste rock.

3.4 Applicability of dry cover system

The current risk of water pollution due to AMD generation is expected to be low because the volume of low-grade ore 0.208 M tons is quite small compared to that of waste rocks 15.7 M tons Figure 3.8. Moreover, there is a possibility to adopt the dry cover system in this mine due to the high stripping ratio of 1:16 and the large volume of the waste rock with carbonate minerals which have the acid-neutralizing capacity.

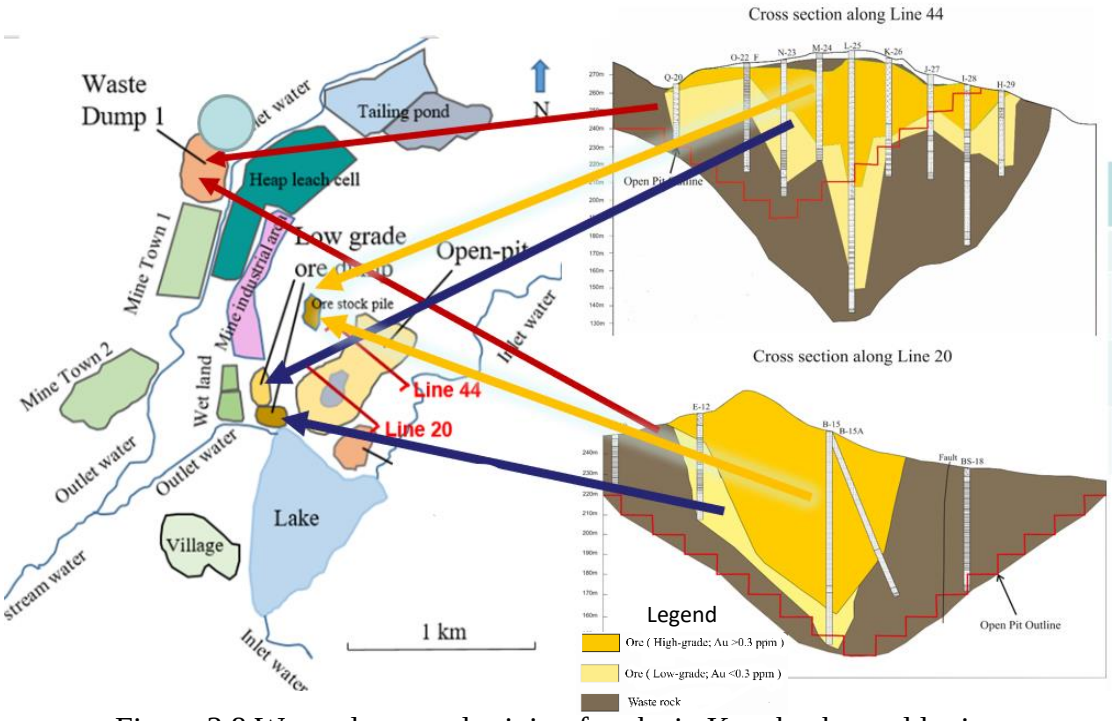


Figure 3.8 Waste dump and origin of rocks in Kyaukpahto gold mine

3.5 Conclusion

The results of the geochemical analysis of rock samples are consistent with the findings from the water quality results that the major areas of AMD are located at the open-pit and the low-grade ore dump. According to the NAG pH and Paste pH, some rocks have the potential to use dry cover material, if the value is no gap in the neutral pH. Paste pH indicates the pH at the time of reaction with water and is an index for predicting the current generation of acidic water due to the reaction of sulfide minerals contained in rock samples. This suggests the possibility of generating acidic water in the current open-pit and low-grade ore dump and is consistent with the results obtained in the field survey. The rock sample collected in the waste dump has a large ANC indicating the ability to neutralize acid compared to other rock samples, indicating that it is classified as NAF, which has a low possibility of generating acidic water. Arsenic and metal dissolutions should be considered in AMD prevention measures regardless of the evidence for AMD at present. There is a possibility to adopt the dry cover system in this mine due to the high stripping ratio and the large volume of the waste rocks with the presence of carbonate minerals which have the acid-neutralizing capacity.

3.6 References

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CHAPTER 4

Evaluation of acidic water elution characteristics of waste rock

4.1 Introduction

In this study, a two-step dissolution test was conducted to understand which waste rocks could generate AMD in the open-pit gold mine at the site, and the components were analyzed by ICP-MS and IC for the dissolution water.

In the previous chapter, it is pointed out that PAFs can be further classified among PAFs according to their constituent elements and geological characteristics. Therefore, by preparing an environment close to the actual site of the mine in a simulated manner, a column leaching test is performed to investigate what kinds of elution behaviour the classified PAF exhibit.

4.2 Materials methods

4.2.1 Two-step batch dissolution test (prEN 12457-3)

Geochemical analysis of rock samples revealed the acid generation potential of the samples. The two-stage batch test (prEN 12457-3) was performed to investigate metal ions eluted from these samples [1].

4.2.1.1 Material and method

The measurement procedure is shown below.

1. Crush rock samples to a particle size of -75 mm or less.
2. A 50 g of rock sample and 100 mL of deionized water were added to a 500 mL polyethylene container with has shaking width of 4 cm. Then, they were horizontally shaken at the speed of 200 rpm for 6 hours as shown in Figure 4.1.
3. After shaking, dissolve water was filtered with a 0.45 μm filter and separated into filtrate and residue, and the filtrate was used as the first-stage elution water as the L / S = 2 samples.
4. The pH and EC were measured for the filtrate of stage 3. ICP-MS and IC were performed to investigate dissolved metals.
5. The filtered residue from stage 3 was placed in a 1000 mL polyethylene container, and 200 mL of deionized water was added.

6. After shaking with a horizontal shaker, shaking width of 4 cm, for 18 hours, with 0.45 μm filter, use this as the L / S = 2~8 water samples.
7. The pH and EC were measured for the filtrate of stage 6. ICP-MS was performed to investigate dissolved metals.

Figure 4.1 Shaking equipment

4.2.2 ICP-MS inductively coupled plasma mass spectrometry

ICP-MS is an elemental analyzer that realizes highly sensitive multi-element analysis with high sample throughput. The plasma (ICP) is used as an ion source, and the generated ions are detected by a mass spectrometer (MS). Almost all elements on the table can be measured at the same time, and the measured elements can be measured at sub-mg / L (ppt) concentration levels, and qualitative, semi-quantitative, and quantitative analysis can be performed. Therefore, the isotope ratio measurement is also possible. For each sample, the concentrations of Fe, As, Cu, Zn, and Mn were measured by ICP-MS inductively coupled plasma mass spectrometry [2].

4.2.2.1 Sample preparation and measurement method

1. The first-step and second-step eluates obtained in the two-stage elution in the previous section were filtered with a syringe and a 0.45 μm filter, as shown in Figure 4.2.
2. It was diluted according to EC, referring to Table 4.1 below.
3. Nitric acid was added to a concentration of 1% concerning the diluent.

4. The component analysis was performed using the device shown in Figure 4.3.

Table 4.1. Dilution rate based on EC of ICP-MS sample solution

EC (mS/cm)	Dilution ratio
~0.0	×100
0~1.0	×500
1.0~1.5	×1,000
1.5~2.0	×5,000
2.0~	×10,000

Figure 4.2 A syringe and a 0.45 μm filter

Figure 4.3 Inductively coupled plasma mass spectrometer (Agilent 7500c)

4.2.3 Ion chromatography (IC)

For each sample, Mg, Na, Ca, SO_4^{2-} concentrations were determined by ion chromatography. The equipment used for ion chromatography was Dionex Ion Chromatograph-ICS-90 (Figure 4.5) [3].

4.2.3.1 Sample preparation and measurement method

1. The first-step and second-step eluates obtained in the two-stage elution in the previous section were filtered with a syringe and a 0.45 μm filter as shown in Figure 4.2.
2. It was diluted according to EC, referring to Table 4.2 below.
3. The diluent was placed in the dedicated cell shown in Figure 4.4, and the components were analyzed using the device shown in Figure 4.5.

Table 4.2 Dilution ratio of IC sample solution based on EC

EC (mS/cm)	Dilution ratio
~1.0	×10
1.0~1.5	×20
1.5~2.0	×100
2.0~	×500

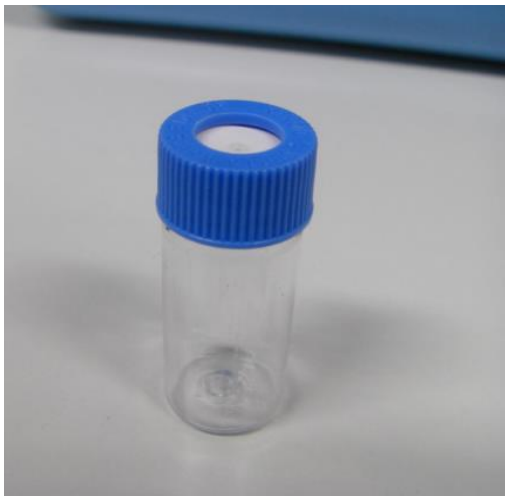


Figure 4.4. IC dedicated cell

Figure 4.5 Ion Chromatograph by Dionex-ICS-90

4.2.4 Results and discussions

The result of the two-step batch test, as shown in Table 4.3 and Table 4.4, the elution amount (mg/kg) of the element eluted per unit weight of the rock sample which is the analysis by ICP-MS and IC, and ANC is also shown as reference. In geochemical test results of rock, the PAF rocks classified both the first-step and the second-step, the acidic water around 4 of pH value generates for both first and second step from the rock samples of OP-2, LG-1, and WD-6 which are classified as PAF. A lot of metals and sulphate ions are dissolved under the acidic conditions in the first step: aluminum (1.7~98.7 mg/kg), manganese (1.0~14.1 mg/kg), iron (12.3~92.5 mg/kg), zinc (0.1~52.2 mg/kg), arsenic (0.2~52.2 mg/kg), sulphate ion (1,548~9,122 mg/kg) for OP-2, OP-3, LG-1, LG-9, and WD-6. These exceed the MNEQ guidelines [4]. The leached amount under the neutral conditions shows quite lower values compared to acidic conditions in the first step: aluminum (~1.7 mg/kg), manganese (0~7.3 mg/kg), iron (1.2~40.9 mg/kg), copper (0 ~8.7 mg/kg), zinc (0 ~82.7 mg/kg), arsenic (0.12~1.3 mg/kg), and sulphate ion (259 ~ 2,867 mg/kg) for OP-5, WD-3, WD-5 and WD-7. High As can be seen in OP-6 and LG-9 rock samples. The elution amount from the sample LG-9 containing a large amount of As in the rock is found to be the largest. Also, in Al, Fe, Cu, Zn which showed excessive elution in the acidic environment in the first-step, the elution amount in the second-step was largely reduced, but As eluted from LG-9 did not decrease in the second-step seen in Figure

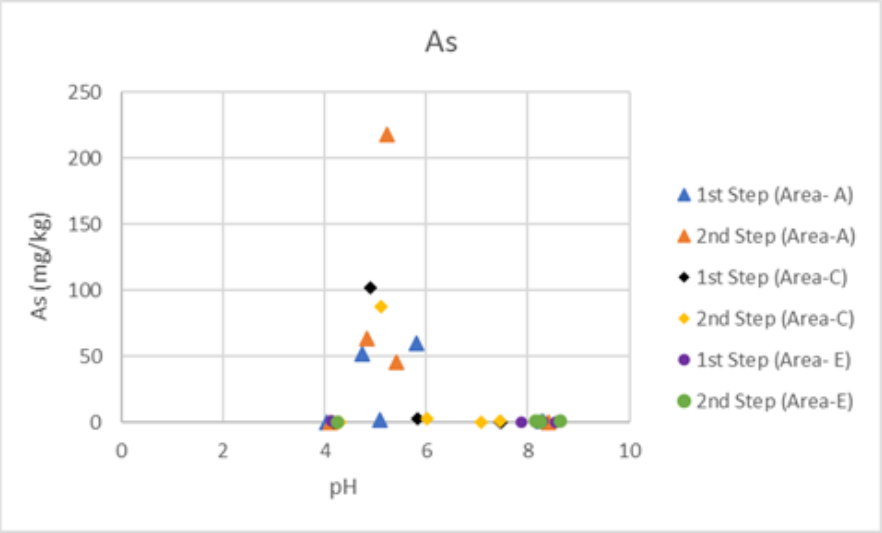
4.5. This indicates that As eluted from rocks containing a large amount of As such as OP-3, OP-6, and LG-9 may elute over a long-term compared to other metal ions. Therefore, the countermeasures to minimize AMD generation for long-term considering the dissolution behaviour of As have to be discussed in Kyaukpahto gold mine.

Table 4.3 Result of the first-step batch test (elution amount of element eluted per unit weight of rock sample, mg/kg).

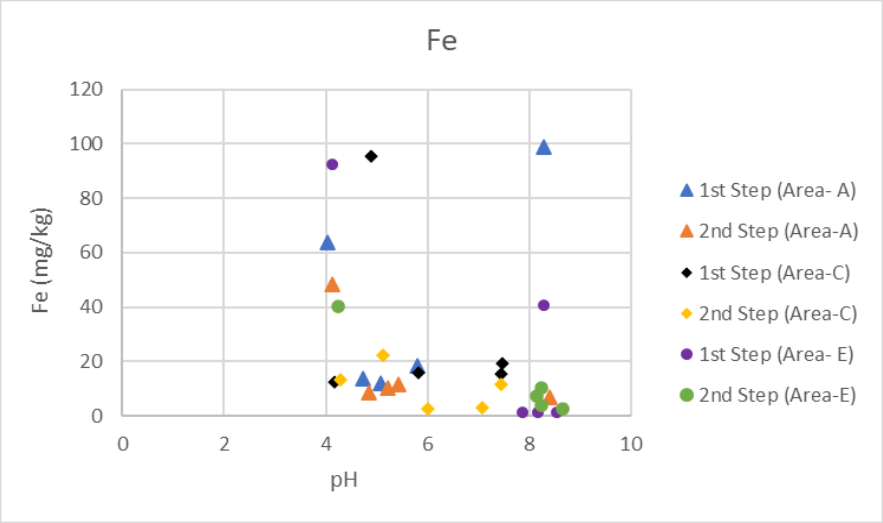
Location	Sp. ID	pH	EC (mS/cm)	ANC	Al	Mn	Fe	Cu	Zn	As	SO_4^{2-}
Area A (Open-pit)	P-1	5.08	0.93	0.84	2.3	1.5	12.2	0.2	2.7	2.3	977
	P-2	4.03	2	2.03	80.3	2	64	2.5	0.1	0.04	4,640
	P-3	4.73	2.1	2.99	1.7	1	13.5	0.1	52.2	52.2	2,409
	P-5	8.28	0.78	19.91	49.4	18.80	98.96	3.16	82.7	1.28	259
	P-6	5.81	1.62	26.53	0.0	7.34	18.52	8.66	1.7	59.74	3,244
Area C (Low-grade ore dump)	L-1	4.18	0.91	0.84	26.4	0.6	12.3	0.3	0.23	0.23	1,548
	L-6	5.82	1.94	4.59	13.0	7.30	16.02	10.66	35.5	3.10	5,477
	L-7	7.48	3.5	21.84	0.00	6.20	19.22	1.28	28.8	0.36	7,483
	L-9	4.9	2.3	10.08	0.0	6.06	95.44	3.96	23.0	101.78	6,611
	L-12	7.46	3.6	48.43	0.0	5.04	15.22	11.18	22.4	0.66	10,014
Area E (Waste dump)	D-1	7.87	1.83	51.5	1.4	0.1	1.1	0.2	0.21	0.21	2,769
	D-3	8.18	0.92	55.56	1.3	0	1.2	0.2	0.12	0.12	619
	D-5	8.54	0.49	19.26	1.7	0.29	1.388	0.624	1.9	0.15	63
	D-6	4.13	2.3	-3.12	98.7	14.06	92.46	0	27.2	0.70	9,122
	D-7	8.28	1.25	28.05	0.0	2.56	40.86	0	0.0	1.14	2,867

Table 4.4 Result of the second-step batch test (elution amount of element eluted per unit weight of rock sample).

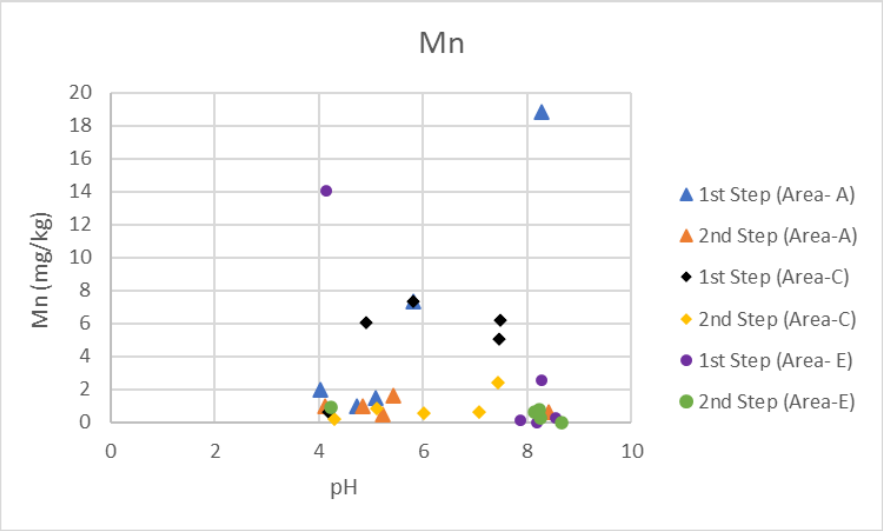
Location	Sp. ID	pH	EC (mS/cm)	ANC	Al	Mn	Fe	Cu	Zn	As	SO_4^{2-}
Area A (Open-pit)	P-1	5.42	0.2	0.84	18.80	1.6	11.40	0.40	1.70	45.62	523
	P-2	4.12	0.57	2.03	75.90	1	48.60	2.80	5.30	0.1	3,109
	P-3	5.23	0.63	2.99	2.70	0.5	10.20	0.30	0.00	217.8	1,747
	P-5	8.41	0.3	19.91	7.64	0.64	6.66	1.01	4.12	0.21	201
	P-6	4.84	0.31	26.53	7.38	1.01	8.71	1.10	11.57	63.93	1,109
Area C (Low-grade ore dump)	L-1	4.29	0.28	0.84	31.70	0.2	13.20	0.40	0.00	0.28	1,138
	L-6	6.02	0.37	4.59	1.42	0.57	2.66	0.00	15.49	3.11	1,164
	L-7	7.08	0.79	21.84	3.15	0.62	3.19	1.09	17.09	0.13	2,799
	L-9	5.12	0.39	34.34	0.62	0.87	22.27	0.00	7.64	87.24	1,152
	L-12	7.45	1.1	48.43	6.02	2.42	11.77	5.36	13.22	0.69	4,475
Area E (Waste dump)	D-1	8.15	0.58	51.5	5.00	0.6	7.20	0.60	3.50	1.17	1,703
	D-3	8.65	0.35	55.56	4.00	0	2.60	0.50	2.10	0.91	421
	D-5	8.25	0.192	19.26	5.15	0.30	3.84	0.05	32.77	0.60	136
	D-6	4.24	0.49	-3.12	26.02	0.92	40.43	0.00	21.12	0.06	2,701
	D-7	8.24	0.46	28.05	8.84	0.75	10.18	5.54	17.11	1.03	417



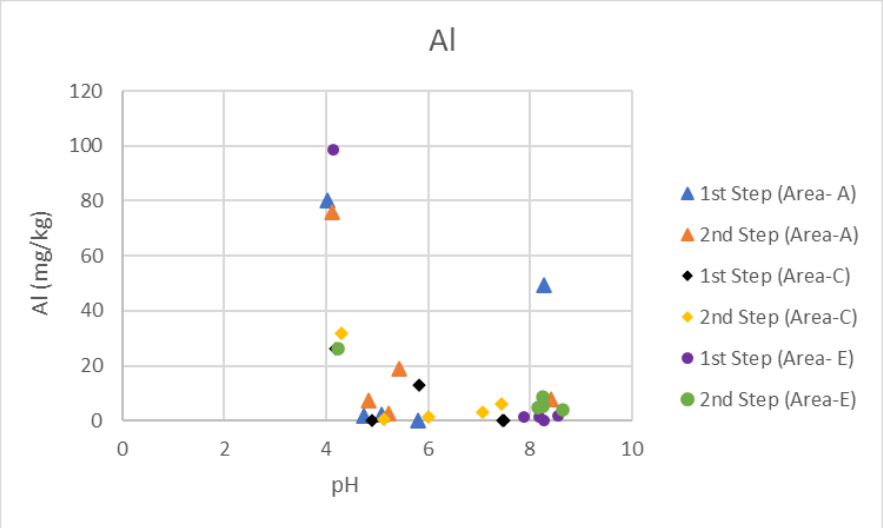
(a) Arsenic elution in the first- and second-steps



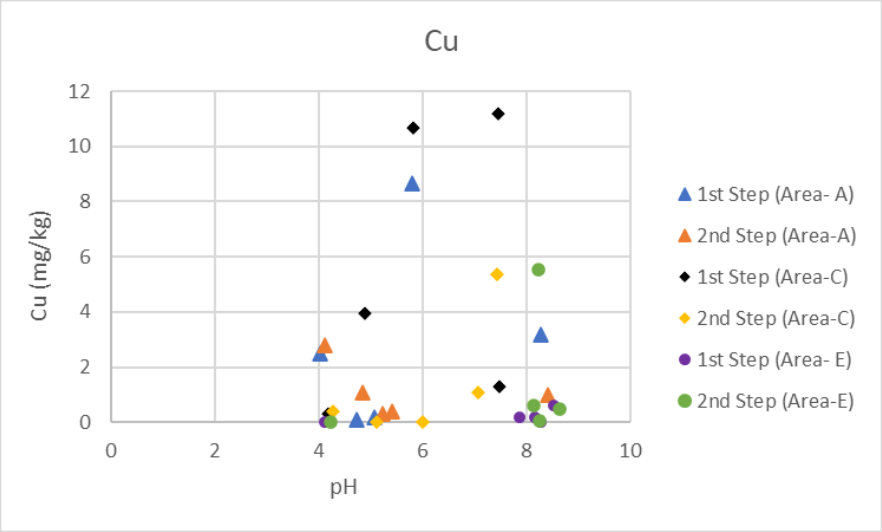
(b) Fe elution in the first- and second-steps



(c) Mn elution in the first- and second-steps



(d) Al elution in the first- and second-steps

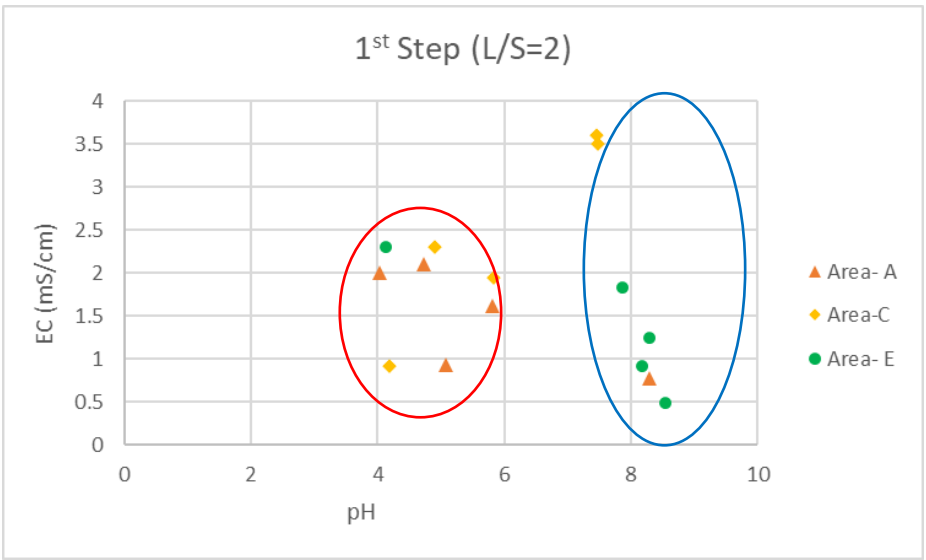


(e) Cu elution in the first- and second-steps

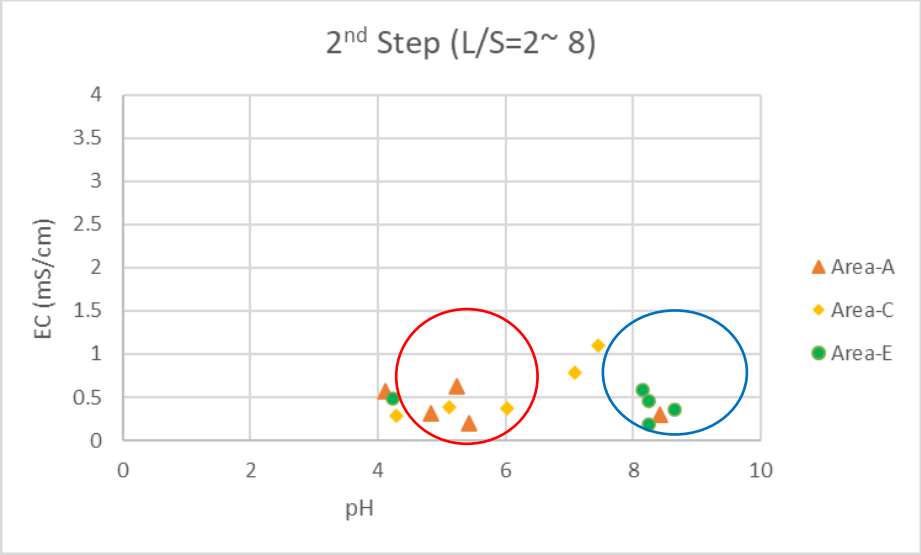
Figure 4.6 The metal elution of (a) As, (b) Fe, (c) Mn (d) Al and (e) Cu compared with the first- and second-steps based on pH value.

4.2.4.1 Relationship between pH and EC

The relationship between pH and EC in the two-step dissolution test shown in Figure 4.7. The elution of metal ions under the acidic condition because of the lower the pH is, the more metal ions elute. Meanwhile, the elution of metal ions due to the acid-neutralizing because some may be due to the presence of carbonate minerals that have a neutralizing effect on acidic water.



(a) First-step of dissolution test (L / S = 2)

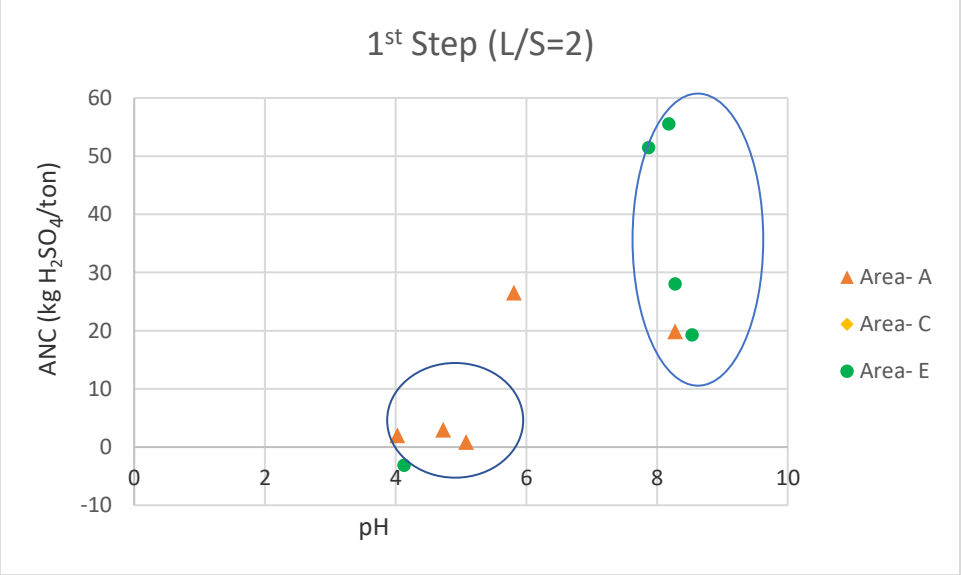


(b) Second-step of dissolution test (L / S = 2~8)

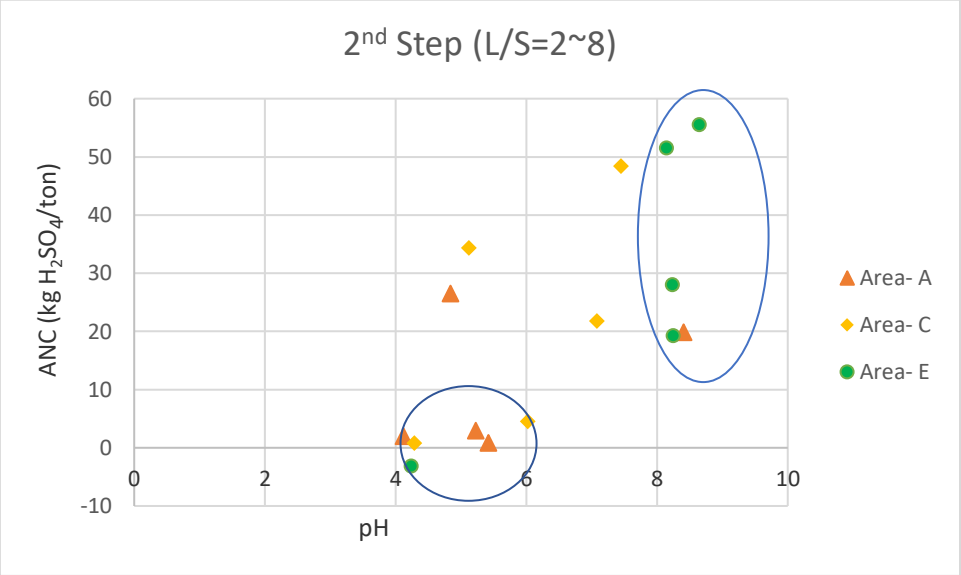
Figure 4.7 Relationship between pH and EC by a two-step dissolution test (a), (b).

4.2.4.2 Relationship between pH and ANC

The relationship between ANC obtained by geochemical analysis and pH measured by a two-step dissolution test is shown in Figure 4.8. It was found that the more neutral the pH, is the higher the ANC because of this kind of rock sample has acid neutralization capacity. The generation of acid water may be suppressed by minerals having an acid buffering action, such as carbonate minerals. It is presumed that as a result of ions derived from minerals having an acid buffering action being eluted due to a neutralizing action on the acidified water, EC exhibited a large value. Besides, in the results of the on-site water quality survey shown in Table 3.1 in the previous Chapter 3, a part of the water samples collected from the open-pit and waste dump showed a similar tendency. It is thought that the generation of acidic water may be restricted by the neutralizing action of minerals having an acid buffering action, such as carbonate minerals.



(a) First-step of dissolution test (L / S = 2)



(b) Second-step of dissolution test (L / S = 2~8)

Figure 4.8 Relationship between pH and ANC by a two-step dissolution test (a), (b).

4.3 Classification of PAF

From the discussion in the previous section, it was found that various types of rocks have low pH and are classified as PAF from the viewpoints of ANC and Paste pH. It can be divided into three types and can be characterized, as shown in Table 4.5 below. The ANC item indicates whether the value is larger or smaller than the average value of the ANC of the sample classified as PAF (about 15 kg H_2SO_4/ton) in this experiment. These PAFs generate AMD and lead to pollution inside the mine, as

shown in Chapter 3. It is necessary to confirm what kind of dissolution behaviour the rock samples.

Table 4.5 Classification of PAF

Classification	pH	ANC	Metal elution
PAF-1	Acidic (pH < 6)	Low (<12)	High
PAF-2	Acidic (pH < 6)	Medium (12 <)	High
PAF-3	Neutral (6 < pH < 9)	High (12 <)	High

4.4 Column Leaching Test

In the previous section, PAFs can be further classified among PAFs according to their constituent elements and geological characteristics. Therefore, by preparing an environment close to the actual mine site in a simulated manner, a column leaching test is performed to investigate what kind of elution behaviour of the classified PAFs.

4.4.1 Materials and methods

In the previous section, PAFs with different elution characteristics, which were collected from Kyaukpahtoe Gold Mine at Low-grade ore dump and the waste dump, were defined as PAF-1, PAF-2, and PAF-3. The rock samples were crushed and separated to adjust the particle size to 1 mm to 2 mm. The rock samples whose grain sizes have been adjusted after crushing are shown in Figures 4.9 (a), (b), and (c). The geochemical characteristics and constituent elements of each PAF are shown in Table 4.6 and Table 4.7. The rock which the sulfur content is relatively high are classified as PAF. The PAF-3 rock sample has an acid buffering action because it contains a lot of MgO and CaO, which are related to acid neutralizing. And also, the PAF- 2 and PAF-3 contain a lot of arsenic.

(a) PAF-1

(b) PAF-2

(c) PAF-3

Figure 4.9 PAF rock types

Table 4.6 Geochemical characteristics of each PAF

Sample	Paste pH	Paste EC (ms/cm)	Total S %	MPA*	ANC*	NAPP*	NAG pH	ANC type
PAF-1	4.30	1.70	0.98	29.99	-3.12	33.11	2.93	Low
PAF-2	5.28	1.50	1.12	34.27	10.08	24.19	2.77	Medium
PAF-3	7.76	2.40	9.74	298.04	48.43	249.61	2.31	High

Note. * in kg H_2SO_4/ton
MPA: Maximum Potential Acidity
ANC : Acid Neutralizing Capacity
NAPP: Net -Acid Potential Production
NAG : Net- Acid Generation

Calculation:
MPA= Total S% * 30.6
NAPP = MPA – ANC

Classification:
PAF : NAG pH < 4.5; NAPP > 0
PAF: Potentially Acid Forming

Table 4.7 Constituent elements of each PAFs from XRF results

Sample	pH	SiO_2 (%)	Al_2O_3 (%)	FeO (%)	MnO (%)	MgO (%)	CaO (%)	S (%)	Cu (ppm)	Zn (ppm)	As (ppm)
PAF 1	4.13	85.57	6.37	1.53	0.01	0.41	0.07	0.98	10	29	356
PAF 2	4.90	86.02	5.49	2.02	0.00	0.36	0.01	1.12	6	34	5,941
PAF 3	7.46	37.60	5.25	17.08	0.19	3.93	5.59	9.74	58	163	2,839

The test procedure of the column leaching test and the method of filling the sample are shown below.

1. The size of the column device was about 52 mm in diameter and about 150 mm in height, and the sample 30 mm was packed by changing the type of sample, as shown in Figure 4.10.
2. The glass beads having a diameter of about 10 mm were placed at the bottom of the column.
3. Each column was filled with a rock sample at a thickness of 30 mm (Figure 4.11) and a porosity of about 60%.
4. 150 mL of deionized water was passed through the top of the column at a water flow rate of about 2.5 minutes, and the leached water was collected from the bottom of the column.

5. After passing the water, drying with sunlight and lump at about 35°C was performed for 48 hours.
6. Steps 4 and 5 were defined as one cycle, and this was repeated in 10 cycles.
7. Eluted water in each leaching cycle was analyzed for pH, EC, and water quality by ICP-MS and IC.
8. After completion of the measurement, the sample used in the column water leaching test was observed.

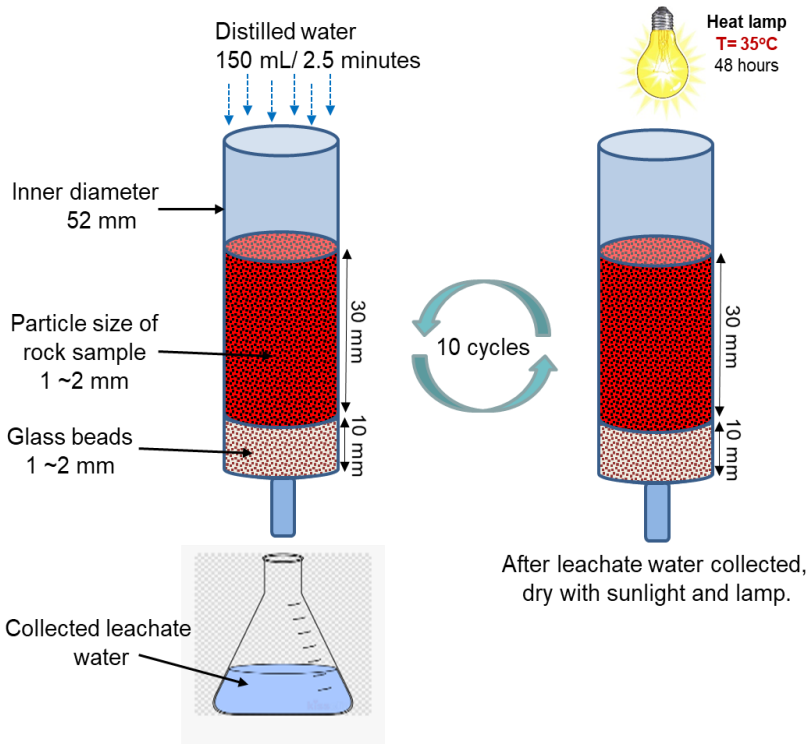


Figure 4.10 Outline of column leaching test

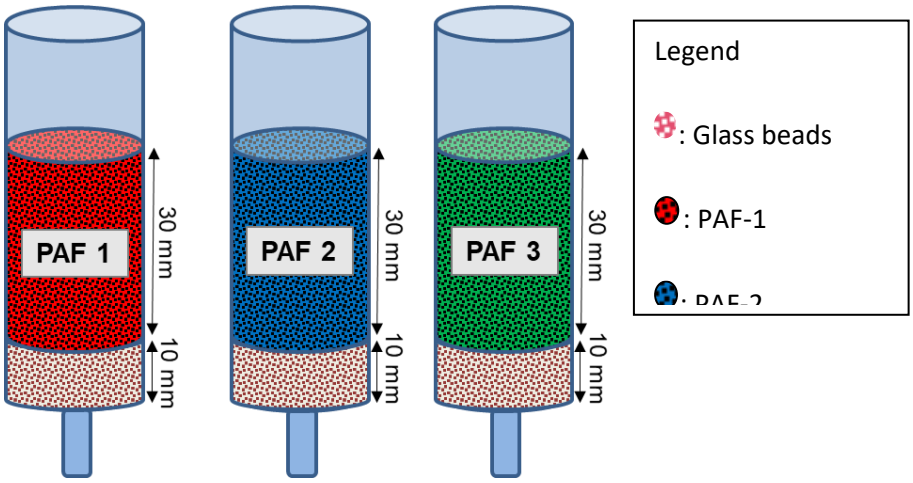
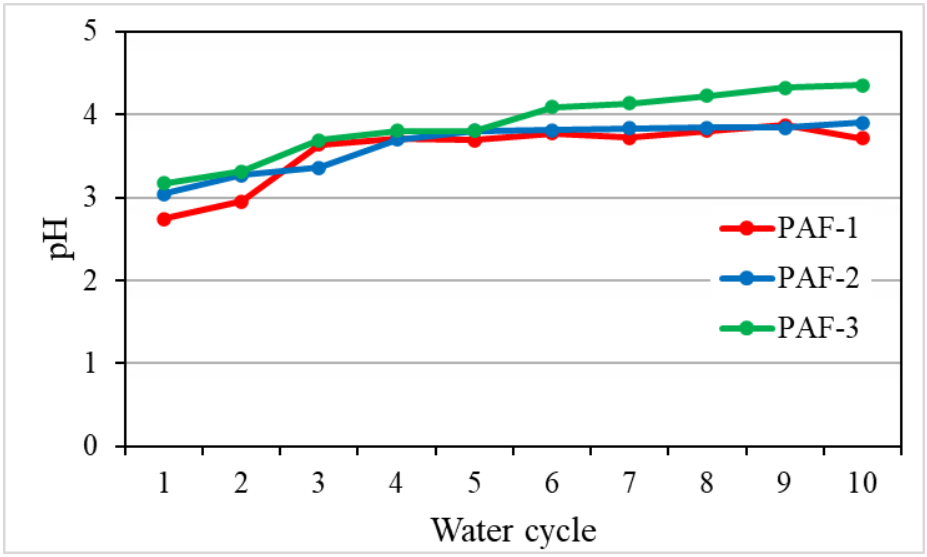


Figure 4.11 Column design

4.4.2 Results and discussion

4.4.2.1. Eluent water pH and EC for each PAF

pH and EC of the elution water cycle in each PAF are shown in Figure 4.12. The pH increases with increasing the number of water cycles, but the acidic still remains at the end of the water cycle. The EC drops dramatically until the third pass while a certain metal ion is eluted by the end of the test. The pH of PAF-3 sample has higher pH value than the other PAFs rock samples because of it have carbonate minerals such as MgO and CaO content.



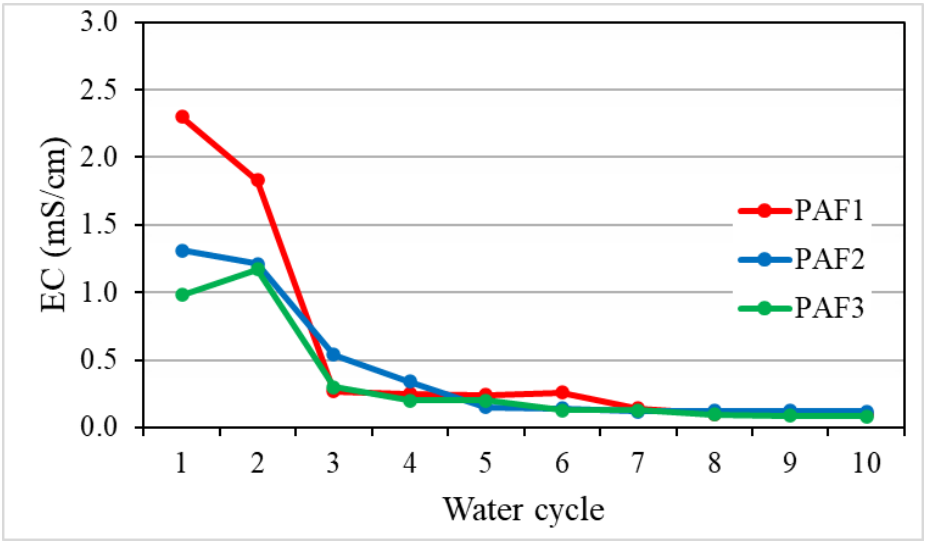


Figure 4.12 Elution water cycle of pH and EC

4.4.2.2 Metal concentration in elution water in each PAF

The concentrations of Fe, Pb, As, and Cu in the eluate in each PAFs water cycles shown in Table 4.8 and Figure 4.13. Although the initial elution amount of PAF-1 is large, the elution amount of PAF-2 and PAF-3 consistently exceeds the elution amount of PAF-1 after the third water cycle. In all the PAFs, the elution amount of Fe did not fall below the reference value (2 ppm). A relatively large amount of As is eluted from PAF-2. From the fourth water cycle, the amount of elution in the entire sample sharply decreased but exceeded the reference value (0.1 ppm). PAF-3 has a substantially constant elution amount after the third water cycle. The initial elution amount of PAF-1 was large, and the elution amount of Pb from all PAFs was lower than the reference value after the fourth water cycle. A relatively large amount of Cu is eluted from PAF-1 and PAF-3. With each repetition of the water cycle, the amount of elution in the entire sample decreased and was substantially below the reference value (0.3 ppm) after the fifth water cycle.

Table 4.8 Heavy metal elution amount in PAF water from column leaching test

Fe Unit: ppm Standard value: 2 ppm

sample	Number of water cycle										total
	1	2	3	4	5	6	7	8	9	10	-
PAF1	380.7	339.0	6.46	5.48	4.64	4.03	2.65	2.00	2.04	1.97	749.0
PAF2	125.7	101.6	92.9	31.1	20.8	15.8	14.5	13.5	17.4	14.3	447.7
PAF3	61.81	144.4	17.9	15.1	17.7	14.7	3.48	11.3	30.4	10.7	327.7

As Unit: ppm Standard value: 0.1ppm

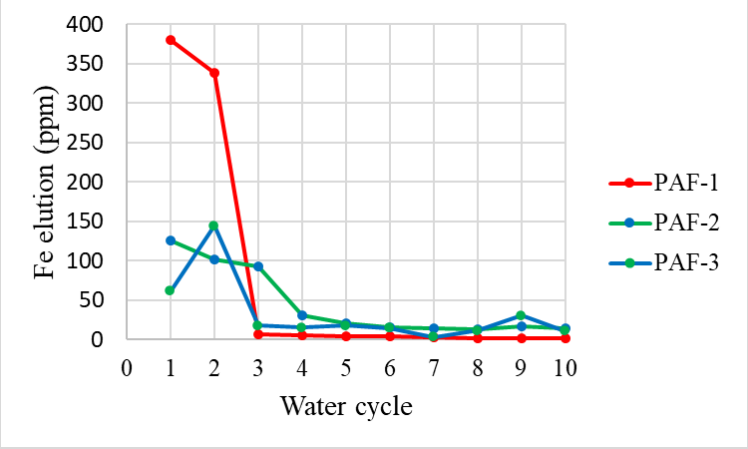
sample	Number of water cycle										total
	1	2	3	4	5	6	7	8	9	10	-
PAF-1	19.92	15.69	5.07	3.53	2.04	1.88	1.65	1.90	1.97	1.77	55.4
PAF-2	41.34	19.44	18.54	3.61	3.28	4.05	4.07	3.94	4.14	4.11	106.5
PAF-3	20.75	6.31	4.38	4.45	4.23	4.68	4.72	4.54	4.75	4.34	63.2

Pb Unit : ppm Standard value : 0.2 ppm

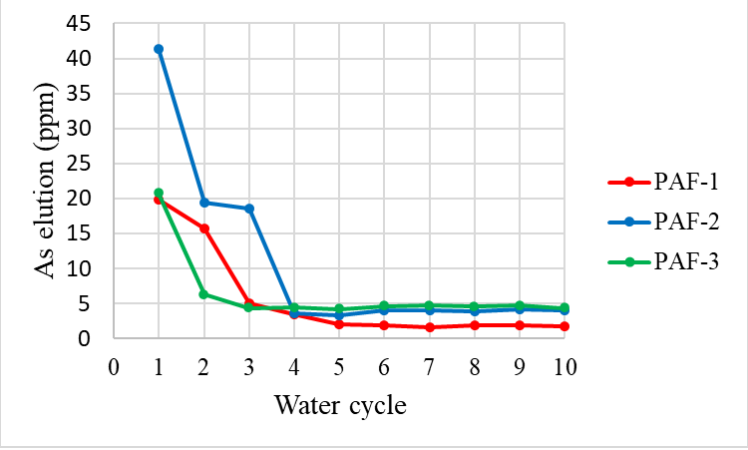
sample	Number of water cycle										total
	1	2	3	4	5	6	7	8	9	10	-
PAF1	0.13	0.85	0.42	0.09	0.08	0.09	0.09	0.01	0.09	0.09	1.93
PAF2	0.04	0.07	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.17
PAF3	0.43	0.18	0.08	0.09	0.09	0.09	0.02	0.09	0.09	0.09	1.25

Cu Unit: ppm Standard value : 0.3 ppm

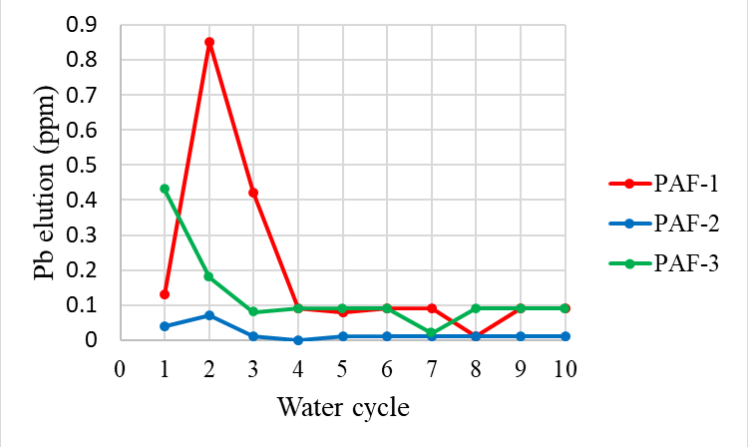
sample	Number of water cycle										total
	1	2	3	4	5	6	7	8	9	10	-
PAF-1	1.75	2.23	1.30	0.45	0.26	0.22	0.25	0.08	0.30	0.22	7.07
PAF-2	0.08	0.12	0.15	0.02	0.00	0.01	0.02	0.01	0.02	0.02	0.43
PAF-3	1.51	4.83	0.42	0.37	0.27	0.25	0.09	0.22	0.22	0.24	8.43



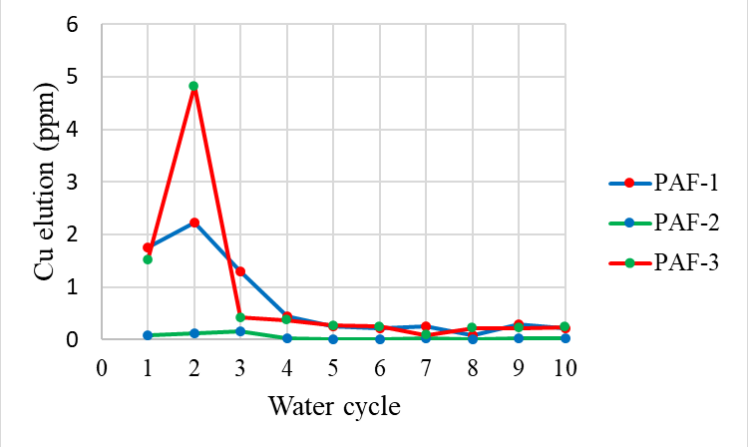
(a) Elution of Fe in each PAFs



(b) Elution of As in each PAFs



(c) Elution of Pb in each PAFs

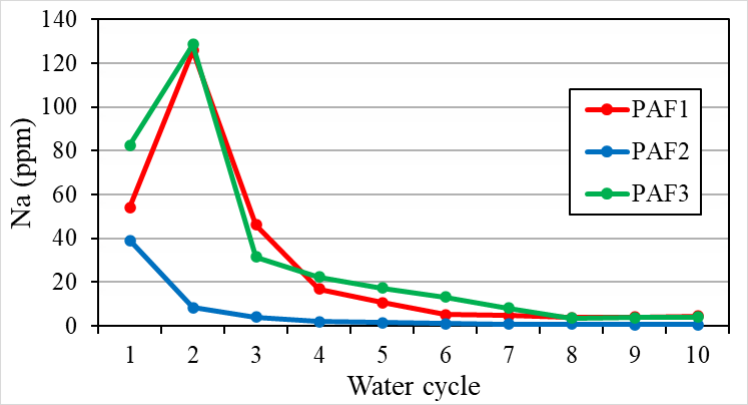


(d) Elution of Cu in each PAFs

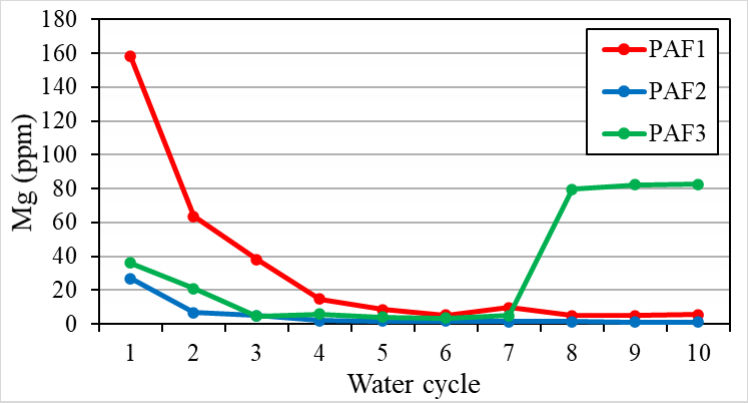
Figure 4.13 Concentration of (a) Fe, (b) As, (c) Pb, and (d) Cu in elution water of each water cycles

4.4.2.3 Eluted element concentrations in buffering mineral reactions

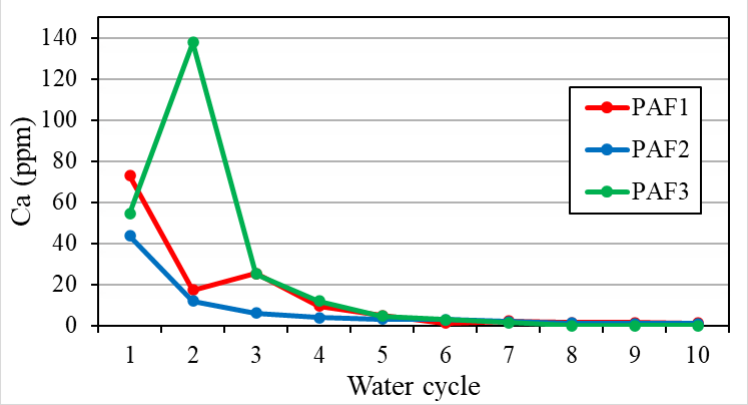
Figure 4.14 shows the Na, Mg, and Ca, concentrations of eluate in each PAF. In the elution of Na, Mg and Ca, PAF-3 is higher than PAF-1 and PAF-2 due to higher ANC and higher carbonate mineral. The carbonate minerals are contained in all of three PAFs. The content of these carbonate minerals causes acid buffering mineral reactions. The carbonate minerals contents remain until ten times of water cycle, causing acid buffering mineral reactions.



(a) Na elution in water cycle



(b) Mg elution in water cycle



(c) Ca elution in water cycle

Figure 4.14 (a) Na, (b) Mg and (c) Ca concentration of elution water

4.4.2.4 The elution behaviour of SO_4^{2-} and (Na, Mg, Ca)

Figure 4.15 shows the total amount of potassium, magnesium and calcium, (Na+Mg+Ca) and SO_4^{2-} concentration of elution water. The higher concentrations of SO_4^{2-} are confirmed in PAF-1, which pH shows the most acidic while it shows the lower concentration in PAF-2 and PAF-3. The higher concentrations of cation are confirmed in PAF-3. Therefore, the elution of metal ions is found not only in acidic conditions but also neutral condition due to the effect of acid buffering reaction. These facts mean that PAF can be classified with the sulfur content, ANC, and constituent metal elements.

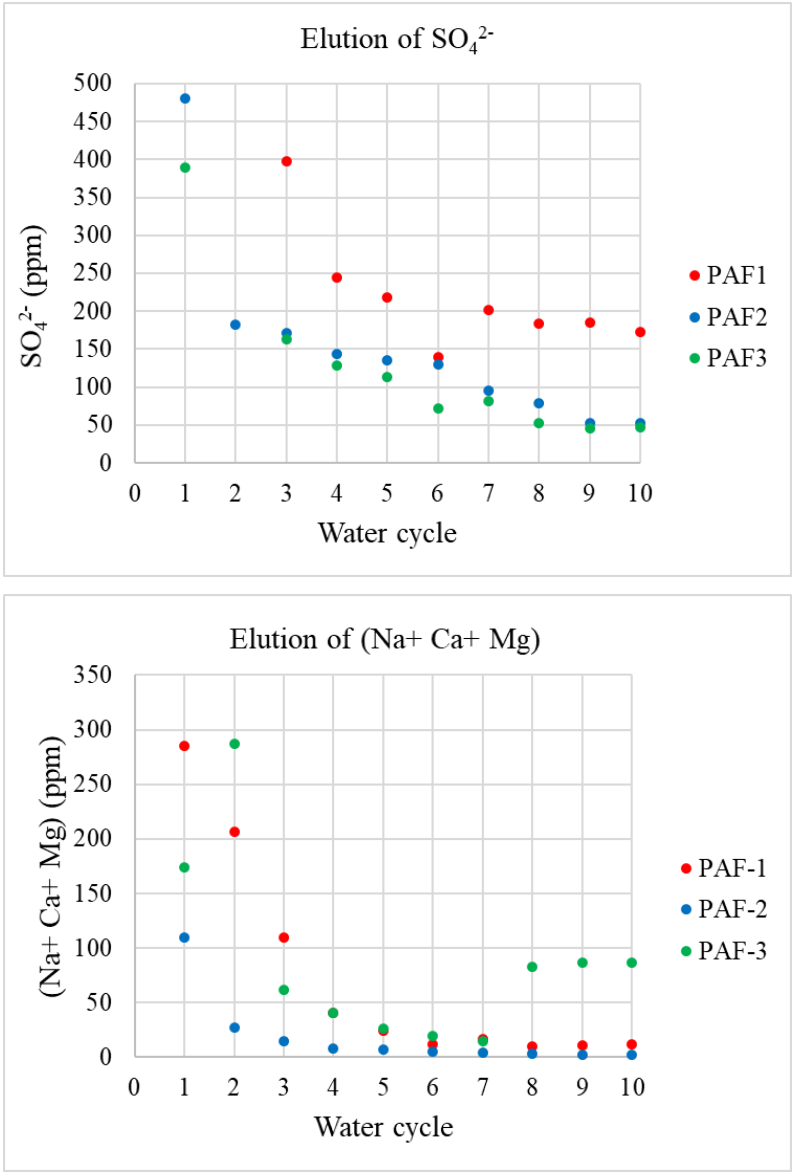


Figure 4.15 the total amount of potassium, magnesium and calcium, (Na+Mg+Ca) and SO_4^{2-} concentration of elution water

4.4.2.5 Evaluating the relative rates of oxidation and buffering

The resulting average pH values over column test for PAF-1, PAF-2 and PAF-3 are 3.4, 3.6 and 3.9, respectively. The PAF-1 shows the most acidic pH due to the higher oxidation reaction (SO_4^{2-} is higher). The PAF-2 shows a moderate pH due to the lower oxidation reaction (SO_4^{2-} is lower). The PAF-3 shows the highest pH due to the well-balanced oxidation and buffering reaction (SO_4^{2-} and cation are balanced) shows in Figure 4.16. The water quality of leachate from PAF is affected by the presence of sulfur content and carbonate minerals which attributes to neutralize the acidity. The oxidation and buffering reaction due to sulfide and carbonate minerals are well balanced in PAF, which shows the highest pH because the elution of sulfate and total cation are balanced. The pH of PAF-3 is higher than that of the other two due to its higher ANC carbonate.

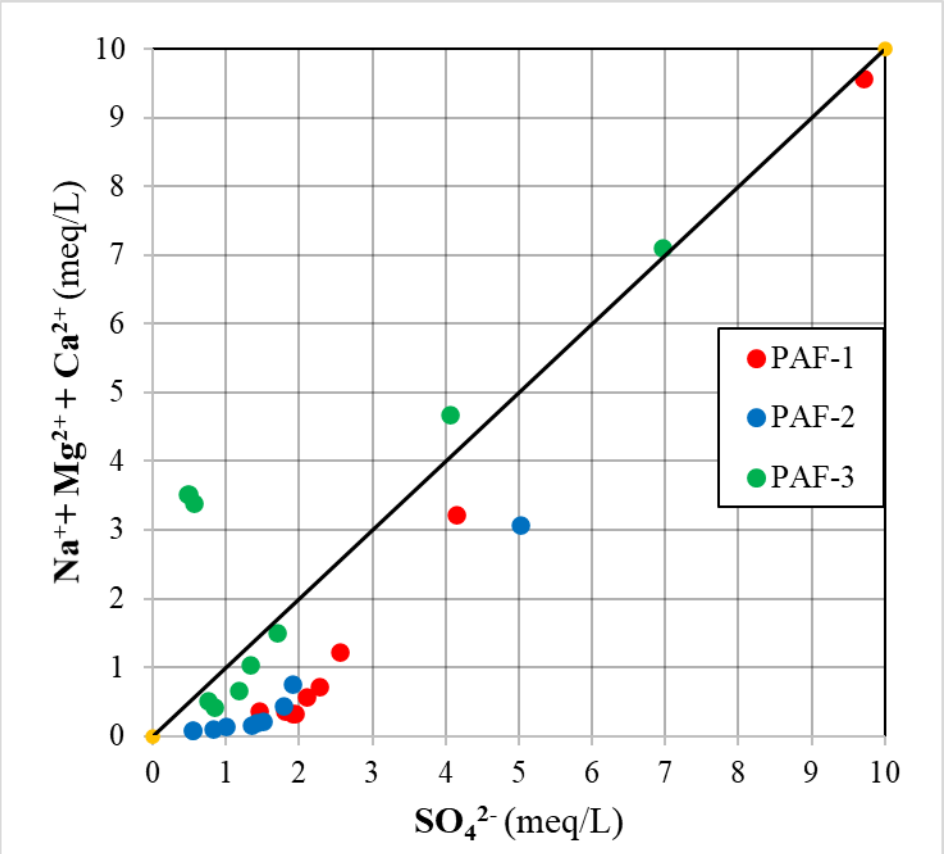


Figure 4.16 SO_4^{2-} and cation balance

4.5 Considerations related to Kyaukpahto Gold Mine

The PAFs exist in the mine waste rock field. It is assumed that PAF-1, PAF-2, and PAF-3 are mixed and that they are present separately.

In the former case, the elution behaviour, as shown in this experiment, is expected to be shown at each location. Alternatively, it is imaginable that the initial elution of PAF-3 may be slightly accelerated by the acidity of PAF-2 slightly stronger than PAF-3.

In the case, heavy metal elution due to the generation of AMD is mainly due to PAF-1, which should lead to the following situations. Due to the generation of relatively acidic AMD from PAF-1, a phenomenon is expected in which more heavy metals are eluted in a short period.

4.6 Conclusion

In this study, the classification of PAF by investigating the elution behaviour of the acidic water using the batch leaching test and column leaching test. From the results of the batch leaching test, it is revealed that the long-term metal elution is expected from the rocks which contain a lot of As regardless of pH. Additionally, the elution of metal ions is found not only in acidic conditions but also neutral condition due to the effect of acid buffering reaction. These facts mean that PAF can be classified with the sulfur content, ANC, and constituent metal elements. The results of column leaching test also show the same trend with those of the batch leaching test, meaning that the higher arsenic elution is confirmed by the end of the column leaching test from rock samples which contains a lot of arsenic and the pH shows higher if the samples have the high acid-neutralizing capacity (ANC). Moreover, the oxidation and buffering reaction due to sulfide and carbonate minerals are well balanced in PAF, which shows the highest pH because the elution of sulfate and total cation are balanced. From these results, the different backfilling design has to be discussed for the different characteristics of PAF to achieve the efficient prevention method of AMD. Therefore, in the next chapter, the application of an effective dry covering method in consideration of the characteristics of waste rock is examined.

4.7 References

[10] Bernd G. Lottemoser: Mine Wastes Characterization Treatment and Environmental Impacts, Springer, 2010

[11] Agilent Technologies, Inc: Principles of ICP-MS (http://www.chem-agilent.com/contents.php?id=35074)

[12] JAIMA Japan Analytical Instruments Manufacturers Association: Principles and Applications of Ion Chromatography, (https://www.jaima.or.jp/jp/analytical/basic/chromatograph/ion-chromatography/)

[13] Myanmar National Environmental Quality (emission) guidelines, (2015), pp.70-71

CHAPTER 5

Backfilling design of waste rock considering the characteristic of PAF

5.1 Introduction

In this chapter, the geochemical characteristics of rock samples analyzed in Chapter 3 are used. To study the generation behaviour of acid water at the actual site where the dry cover method is applied, a column water leaching test is performed with simulating the site conditions of temperature and rainfall. To study effective control of AMD generation with countermeasures by the dry cover system. To evaluate the future risk of AMD generation and the behaviour of metal ions elution with AMD suppression effect in epithermal type gold deposits.

5.2 Study sample from Kyaukpahto Gold Mine

As PAFs, two kinds of samples with different geochemical properties, PAF-1 and PAF-2, collected from the Kyaukpahto gold mine in Myanmar were used. A sample collected from the same gold mine was used as NAF for covering material. The geochemical characteristics and composition elements of each sample are as shown in Tables 5.1 and 5.2 [1, 2]. PAF-1 is different from PAF-2 in that the acid-generating ability NAPP is higher, and PAF-2 is medium in acid-neutralizing ability ANC than PAF-1. Further, since PAF-2 contains a large amount of As, harmful ions may be eluted in a large amount for a long period. NAF has carbonate minerals such as Mg and Ca, which are expected to have acid-neutralizing action.

Table 5.1 Composition elements of PAF-1, PAF-2, and NAF from XRF results

Sample	SiO_2 (%)	Al_2O_3 (%)	FeO (%)	MnO (%)	MgO (%)	CaO (%)	S (%)	Cu (ppm)	Zn (ppm)	As (ppm)
PAF-1	85.6	6.37	1.53	0.01	0.41	0.07	0.98	10	29	356
PAF-2	86.0	5.49	2.02	0.00	0.36	0.01	1.12	6	34	5,941
NAF	42.5	9.26	8.16	0.67	6.66	12.01	0.85	92	82	434

Table 5.2 Geochemical properties of PAF-1, PAF-2 and NAF

Sample	Paste pH	Paste EC (mS/cm)	NAG pH	Total S mass %	MPA*	ANC*	NAPP*	ANC Types
PAF-1	4.30	1.70	1.70	0.98	29.99	-3.12	33.11	Low
PAF-2	5.28	1.50	2.77	1.12	34.27	10.68	23.59	Medium
NAF	8.41	0.89	8.28	0.85	26.01	28.05	-2.04	High

Note. * in kg H_2SO_4/ton
MPA: Maximum Potential Acidity
ANC: Acid Neutralizing Capacity
NAPP: Net-Acid Potential Production
NAG: Net-Acid Generation

Calculation:
MPA= Total S% * 30.6
NAPP = MPA - ANC

Classification:
PAF: NAG pH < 4.5; NAPP > 0
NAF: NAG pH > 4.5; NAPP < 0
PAF: Potentially Acid Forming
NAF: Non-Acid Forming

5.3 Materials and methods of Column leaching test

The outline of the column leaching test is shown below. The column device was designed and used as shown in Figure 5.1, and the sample was packed by changing the type and thickness of the sample as shown in Figure 5.2. The column with column number 1 is referred to as Column C-1, and the other columns are similarly referred to as Column C-2 and Column C-3.

1. The wet filter paper was placed at the bottom of the column, and glass beads having a diameter of about 10 mm were placed thereon as a buffer.
2. A single layer of PAF-1, PAF-2, and NAF was filled as a control with a layer thickness of 30 mm. (Column C-1, Column C-2, Column C-3).
3. NAF was filled into the upper part of PAF-1 by changing the layer thickness to 15 mm, 30 mm, 45 mm (Column C-4, Column C-5, Column C-6).
4. The top of PAF-2 was filled with NAF with changing layer thickness to 15 mm, 30 mm, 45 mm (Column C-7, Column C-8, Column C-9).
5. 150 mL of deionized water was passed 2.5 minutes through the top of the column and, and the leachate water was collected from the bottom of the column.
6. After the passage of water, drying was performed for 48 hours in sunlight and lamp temperature with 35°C.
7. Steps 5 and 6 were defined as one cycle, and this was repeated ten cycles.

8. Eluted water in each flow cycle was analyzed for water quality by pH, EC, ICP-MS, and IC.
9. At the end of the measurement, the sample used in the column water flow test was observed.

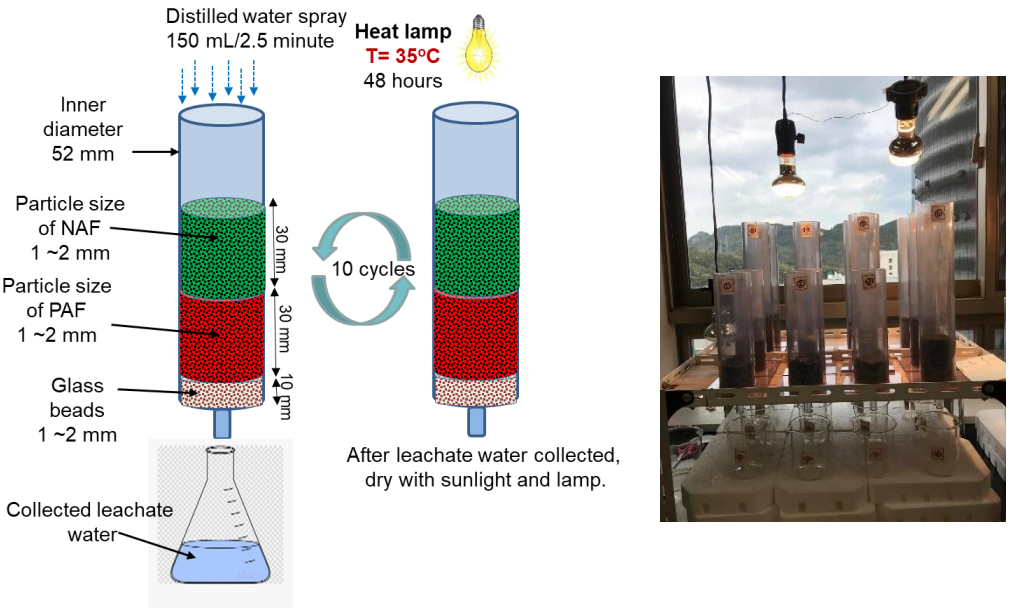


Figure 5.1 Outline of design for Column leaching test

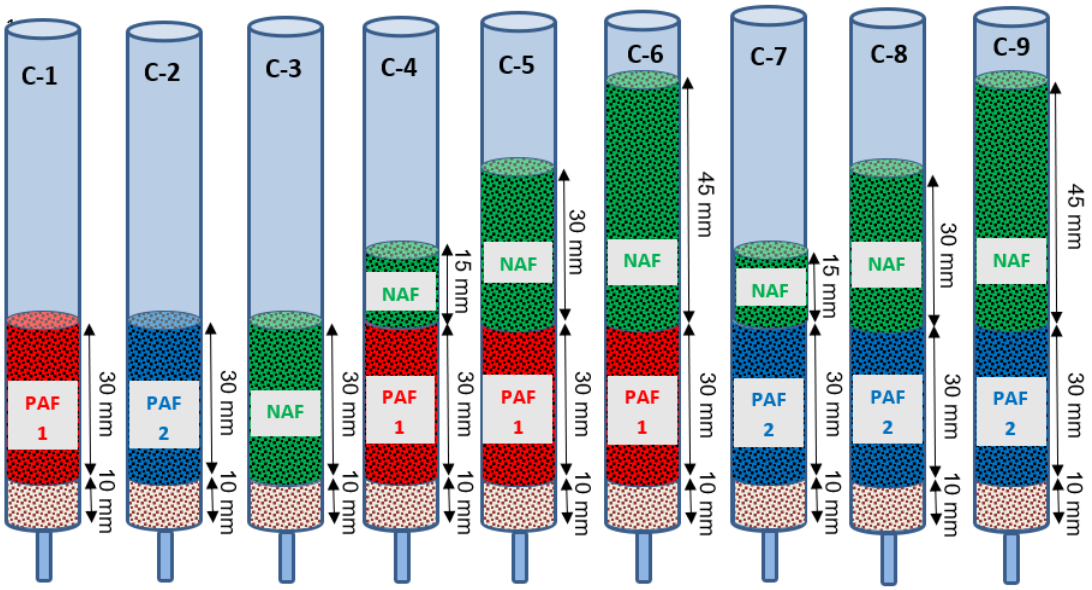


Figure 5.2 Column design conditions

5.3.1 NAPP and ANC for each column

The NAPP and ANC fot each column are ashown in Table 5.3.

Table 5.3 NAPP and ANC value of each Columns

	Column No	C-1	C-3	C-4	C-5	C-6
PAF-1	**NAPP**	33.11	-2.04	21.39	15.54	12.02
	ANC	-3.12	28.05	7.27	12.47	15.58
	Column No	**C-2**	**C-3**	**C-7**	**C-8**	**C-9**
PAF-2	**NAPP**	23.59	-2.04	15.05	10.78	8.21
	ANC	10.68	28.05	16.47	19.37	21.10

5.3.2 pH and EC of each column

Tables 5.4 and 5.5 show the results of the pH and EC of Column leaching test. The pH changes of PAF-1 and PAF-2 are shown in Figures 5.3 and 5.4.

Table 5.4 Column leaching test results of pH

	Number of water cycle									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
C-1	2.74	2.95	3.64	3.71	3.69	3.77	3.72	3.80	3.87	3.71
C-2	3.04	3.27	3.36	3.70	3.80	3.81	3.83	3.84	3.84	3.90
C-3	7.12	6.46	6.58	7.05	7.23	6.96	6.69	6.54	6.60	6.75
C-4	3.06	4.79	4.24	4.69	3.82	4.09	4.05	4.30	4.31	4.18
C-5	3.52	4.89	5.25	5.75	4.01	4.44	4.10	4.90	5.04	4.33
C-6	3.72	5.79	5.95	6.51	4.28	5.14	4.79	5.60	5.65	5.27
C-7	5.08	5.40	5.69	5.92	6.09	6.06	6.10	6.15	6.13	6.20
C-8	5.28	5.98	5.83	6.28	5.87	6.00	6.15	6.17	6.19	6.25
C-9	5.38	6.18	6.28	6.44	6.67	6.50	6.35	6.45	6.80	6.82

Table 5.5 Column leaching test results of EC

	Number of water cycle									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
C-1	2.30	1.83	0.27	0.25	0.24	0.26	0.14	0.10	0.10	0.10
C-2	1.31	1.21	0.54	0.34	0.15	0.14	0.12	0.12	0.12	0.12
C-3	0.49	1.86	0.27	0.30	0.17	0.14	0.07	0.06	0.06	0.06
C-4	1.14	1.79	0.30	0.34	0.36	0.31	0.19	0.16	0.15	0.15
C-5	1.00	2.20	0.51	0.45	0.42	0.36	0.24	0.24	0.25	0.24
C-6	1.06	2.50	0.51	0.47	0.37	0.33	0.15	0.26	0.26	0.24
C-7	0.71	1.15	0.41	0.23	0.16	0.15	0.13	0.13	0.13	0.13
C-8	0.72	1.17	0.60	0.37	0.19	0.20	0.18	0.17	0.17	0.17
C-9	0.86	0.93	0.49	0.42	0.18	0.18	0.15	0.15	0.15	0.14

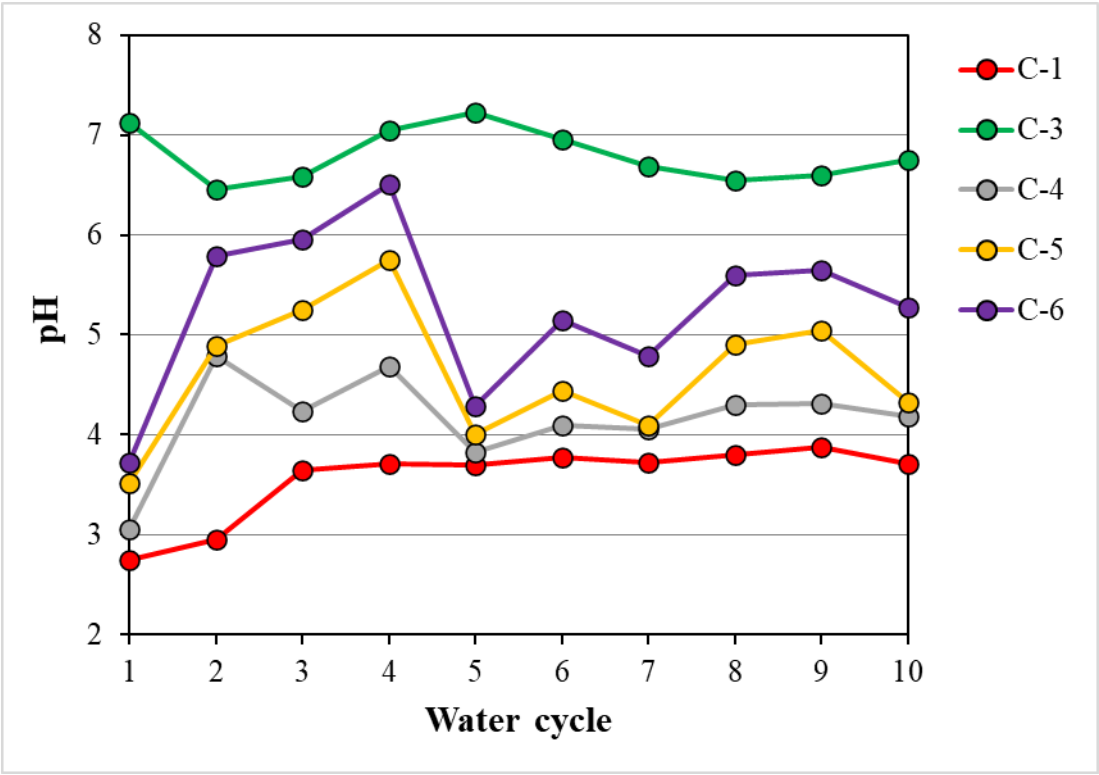


Figure 5.3 pH value of PAF-1

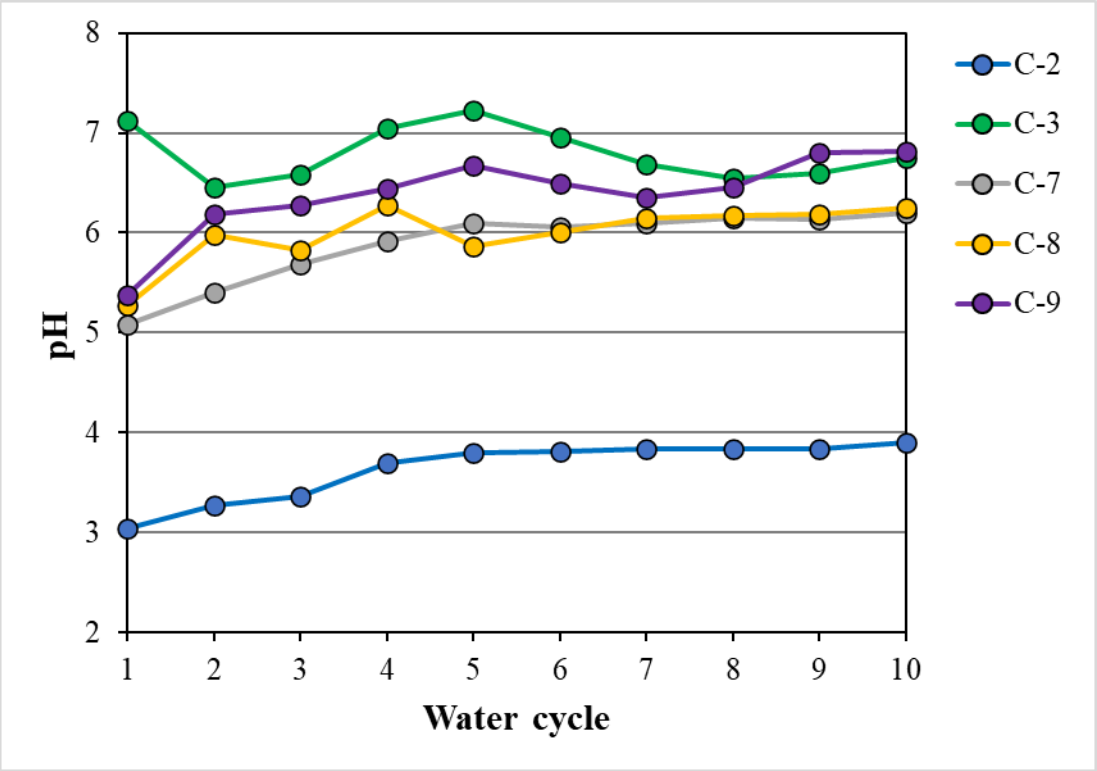


Figure 5.4 pH value of PAF-2

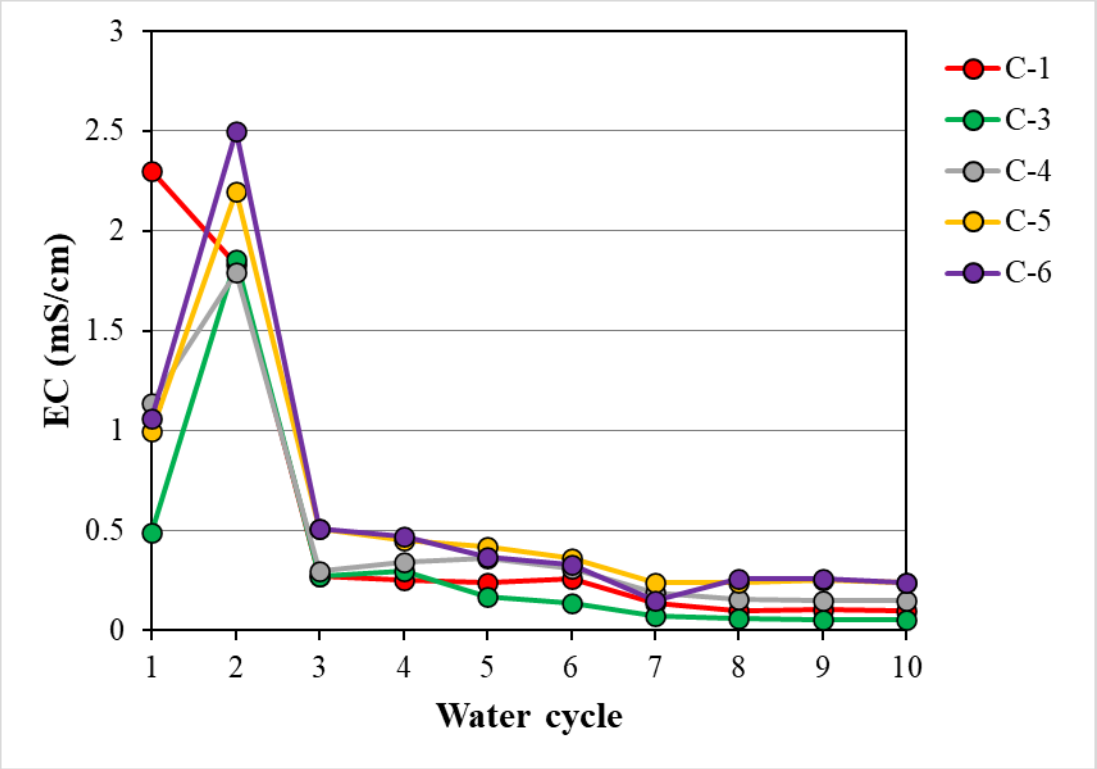


Figure 5.5 EC value of PAF-1

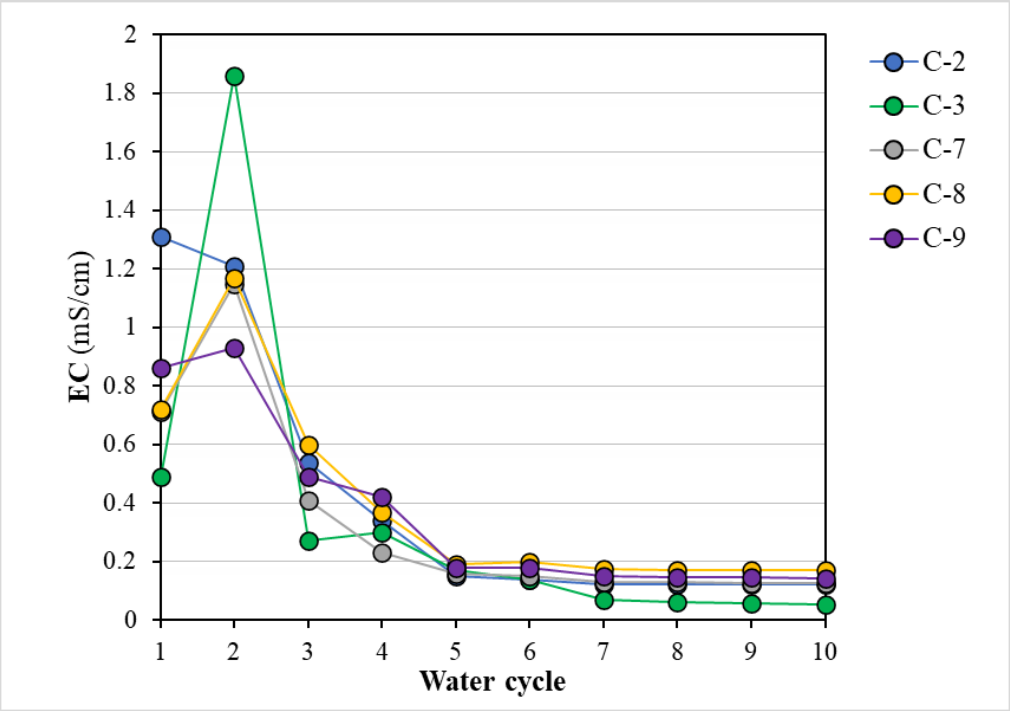


Figure 5.6 EC value of PAF-2

5.3.3 Elution of metal ions

The specific metal eluted ions, the measurement was performed using ICP-MS [3] and ion chromatography [4] used in Chapter 4. The results of metal eluted ions shown in Table 5.6 to Table 5.11 and Figure 5.8.

Table 5.6 Eluted ions As (ppm) , MNEQ Standard Value : 0.1 ppm

	Number of water cycle									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
C-1	19.920	15.685	5.065	3.534	2.038	1.881	1.654	1.903	1.972	1.767
C-2	41.344	19.440	18.536	3.613	3.283	4.050	4.074	3.942	4.141	4.110
C-3	1.022	0.878	0.099	0.038	0.097	0.088	0.027	0.017	0.013	0.021
C-4	9.673	4.775	0.127	0.031	0.094	0.084	0.028	0.075	0.037	0.029
C-5	6.462	1.140	0.140	0.045	0.459	0.102	0.053	0.021	0.124	0.033
C-6	1.043	1.061	0.155	0.040	0.493	0.107	0.024	0.023	0.060	0.030
C-7	4.978	3.750	3.701	3.195	2.622	1.618	1.230	1.628	1.635	1.393
C-8	5.093	1.597	1.969	1.136	0.731	1.233	1.971	1.563	1.646	1.259
C-9	3.884	2.971	1.845	1.447	1.280	0.955	0.840	0.927	1.162	1.046

Table 5.7 Eluted ions Fe (ppm) , MNEQ Standard Value : 2 ppm

	Number of water cycle									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
C-1	380.72	339.04	6.46	5.48	4.64	4.03	2.65	2.00	2.04	1.97
C-2	125.73	101.61	92.96	31.11	20.82	15.76	14.51	13.54	17.36	14.25
C-3	9.36	8.95	1.04	0.20	0.79	0.49	0.83	0.19	0.19	0.17
C-4	75.18	72.24	13.95	1.95	3.76	4.76	5.06	12.75	9.85	4.95
C-5	76.19	19.19	9.96	0.96	5.68	3.96	11.33	4.82	4.82	6.36
C-6	44.75	11.41	1.61	0.36	3.93	2.96	3.20	1.89	3.26	5.93
C-7	49.21	51.17	52.66	3.06	5.47	5.19	0.37	1.77	2.65	3.12
C-8	60.39	4.27	2.47	8.89	1.38	1.18	4.77	4.06	0.42	0.33
C-9	31.53	19.67	13.13	0.38	0.86	0.85	0.34	0.43	0.19	0.21

Table 5.8 Eluted ions Al (ppm)

	Number of water cycle									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
C-1	50.66	47.53	2.15	0.57	0.41	0.33	0.20	0.12	0.12	0.12
C-2	38.53	11.37	13.17	3.82	1.62	1.05	1.06	1.49	1.23	1.13
C-3	2.21	0.86	0.53	0.16	0.04	0.08	0.10	0.10	0.07	0.04
C-4	35.25	5.09	1.50	0.25	0.15	0.17	0.25	3.31	1.07	0.11
C-5	26.30	3.97	3.96	0.32	0.60	0.26	1.48	0.53	0.33	0.24
C-6	10.24	0.68	0.52	0.29	0.18	0.17	0.23	0.16	0.20	0.22
C-7	8.15	4.27	1.11	2.09	0.27	0.95	0.26	1.47	0.30	0.24
C-8	1.45	4.27	0.61	1.21	0.05	0.33	0.13	0.32	0.06	0.06
C-9	0.80	0.22	0.63	0.16	0.05	0.10	0.09	0.05	0.07	0.06

Table 5.9 Eluting ions Na (ppm)

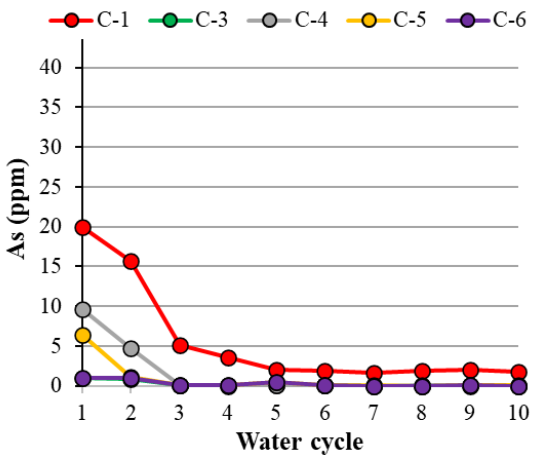
	Number of water cycle									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
C-1	50.65	40.78	16.71	3.29	1.55	1.46	1.44	0.48	0.45	0.43
C-2	29.01	39.12	8.31	4.01	1.90	1.52	1.08	0.89	0.74	0.56
C-3	18.02	133.87	11.62	12.97	6.34	4.67	3.05	1.59	1.52	1.76
C-4	26.64	50.90	5.01	4.00	3.26	2.01	1.33	1.09	0.98	0.91
C-5	28.24	66.30	5.24	4.83	2.68	1.46	1.27	0.83	0.80	0.76
C-6	46.02	92.10	9.20	6.66	3.58	2.37	1.52	1.91	1.54	1.08
C-7	16.80	42.42	9.15	4.60	2.92	2.36	1.74	1.44	1.03	0.99
C-8	15.91	4.27	14.02	6.98	4.25	3.97	2.38	2.24	2.16	2.03
C-9	25.39	16.72	6.37	3.90	2.15	1.73	1.51	1.29	1.07	0.99

Table 5.10 Eluted ions Ca (ppm)

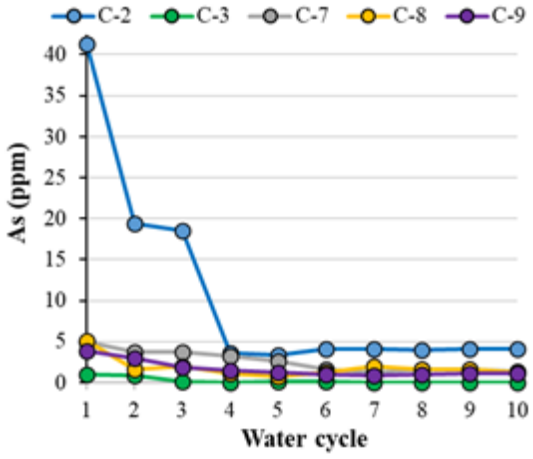
	Number of water cycle									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
C-1	31.25	13.78	6.41	3.27	2.51	2.75	0.91	0.96	1.04	1.21
C-2	41.83	27.07	6.75	5.11	1.92	1.90	1.63	1.57	1.51	1.02
C-3	29.12	35.40	8.75	11.91	8.82	6.81	3.64	2.42	2.40	3.38
C-4	32.39	16.48	4.23	4.77	3.58	3.84	1.66	1.14	1.03	2.14
C-5	19.26	21.60	3.33	4.65	3.86	2.75	1.97	1.42	1.40	2.08
C-6	54.66	43.25	5.79	8.85	4.76	3.99	2.71	2.09	2.06	2.60
C-7	24.36	21.45	7.96	3.51	3.03	2.87	2.16	1.95	1.57	1.46
C-8	23.07	4.27	7.45	4.74	2.96	2.32	1.91	1.76	2.24	2.02
C-9	18.16	8.85	5.10	3.62	2.99	1.87	1.49	1.83	2.13	1.93

Table 5.11 Eluted ions Mg (ppm)

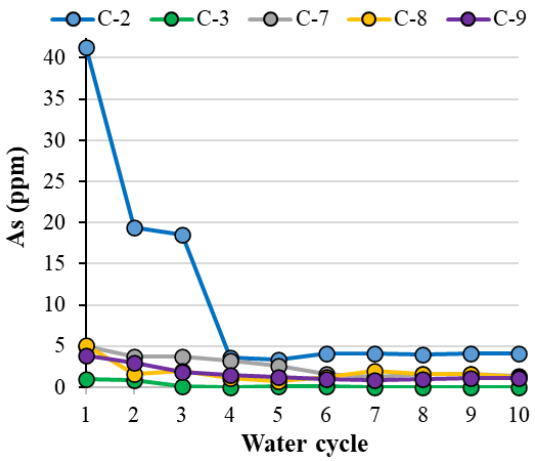
	Number of water cycle									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
C-1	12.45	18.49	49.67	7.47	7.02	7.82	5.27	2.67	2.68	2.68
C-2	21.16	43.72	11.89	5.98	3.90	3.27	2.82	2.04	1.22	0.95
C-3	19.42	64.63	6.54	10.15	5.12	4.35	2.30	1.85	2.00	2.55
C-4	107.01	74.59	19.74	18.92	24.74	13.19	19.21	9.44	10.52	12.78
C-5	144.87	93.45	40.89	47.26	34.15	20.25	23.06	23.07	21.96	17.72
C-6	172.07	114.05	37.64	43.46	25.93	18.55	15.28	18.98	16.73	12.72
C-7	13.32	37.53	19.47	8.98	11.39	11.13	10.22	6.53	2.99	2.43
C-8	30.17	4.27	23.57	20.09	15.87	13.99	13.85	12.97	13.94	11.09
C-9	68.65	81.07	26.86	28.71	20.11	20.37	18.61	14.96	10.88	9.39

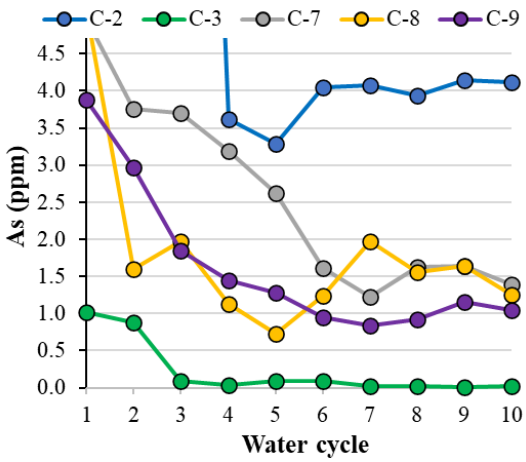


(a) Arsenic elution in PAF-1



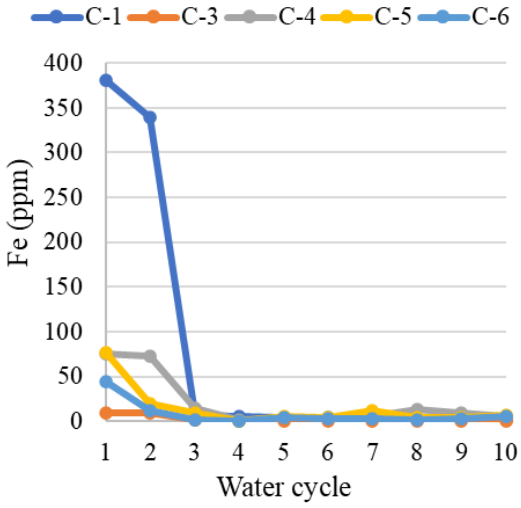
(b) Arsenic elution in PAF-2

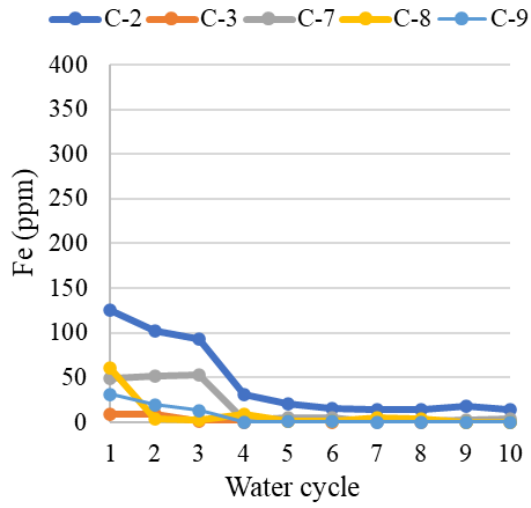




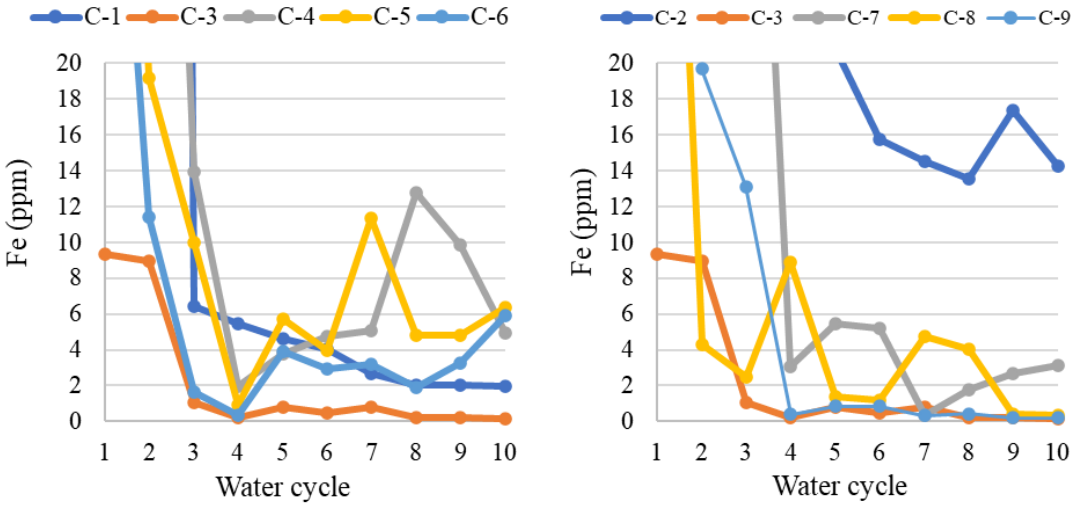
(c) Arsenic elution in PAF-1 large scale (d) Arsenic elution in PAF-2 large scale

Figure 5.7 Arsenic elution in Column leaching tests (a) Arsenic elution in PAF-1, (b) Arsenic elution in PAF-2, (c) Arsenic elution in PAF-1 large scale, and (d) Arsenic elution in PAF-2 large scale





(a) Fe elution in PAF-1 (b) Fe elution in PAF-2



(c) Fe elution in PAF-1 large scale (d) Fe elution in PAF-2 large scale

Figure 5.8 Arsenic elution in Column leaching test (a) Fe elution in PAF-1, (b) Fe elution in PAF-2, (c) Fe elution in PAF-1 large scale, and (d) Fe elution in PAF-2 large scale

5.3.4 Discussion

According to the results of the column leaching test, the column using PAF-1 did not meet Myanmar's standard for water quality [5], pH 6-9. Since the elution is also suppressed, it is considered that water quality can be improved by covering a sufficient amount of NAF. In PAF-2, the pH satisfies the water quality standard regardless of the layer thickness. This is probably due to NAPP in PAF-2 situation. However, when attention is paid to the dissolution of As, although some dissolution suppression is possible, no effective improvement is seen because the content is originally large.

5.4 Suppression of As Elution

In the previous section, a column leaching test showed that PAF with characteristics such as PAF-1 tended to improve both pH and As elution by covering a sufficient amount of NAF on the top to increase the thickness of the covered NAF. On the other hand, it was confirmed that PAF containing a large amount of As, such as PAF-2, would be difficult to improve with metal overburden only in the upper layer. In this section, focus on the suppression of As elution in PAF-2, and examine the improvement of water quality by laying NAF in the lower layer and sandwiching PAF.

5.4.1 Column leaching test with sandwiching design

A column leaching test [1] was performed using the same test procedure and column apparatus as in the previous section. As the samples, PAF-2 and NAF were used, and two types of columns were prepared as column numbers C-10 and C-11 in which the thickness of the lower NAF layer was changed as shown in Figure 5.9.

1. The wet filter paper was placed at the bottom of the column, and glass beads having a diameter of about 10 mm were placed thereon as a buffer.
2. PAF-2, NAF single layer was filled as control with a layer thickness of 30 mm (Column C-2, Column C-3).
3. At the bottom, NAF was filled with a layer thickness of 7.5 mm, PAF-2 was filled thereon with a thickness of 30 mm, and NAF was filled with an upper layer with a thickness of 15 mm (Column C-10).
4. NAF was filled at the bottom with a layer thickness of 15 mm, PAF-2 was filled thereon with a thickness of 30 mm, and NAF was filled with an upper layer with a layer thickness of 15 mm (Column C-11).

5 150 mL of deionized water was spraying 2.5 minutes through the top of the column, and the leachate water was collected from the bottom of the column.

6 After the passage of water, drying was performed for 48 hours in sunlight and lump temperature 35°C.

7 Steps 5 and 6 were defined as one cycle, and this was repeated in ten cycles.

8 Eluted water in each flow cycle was analyzed for water quality by pH, EC, ICP-MS, and IC.

9 After completion of the measurement, the sample used in the column water flow test was observed.

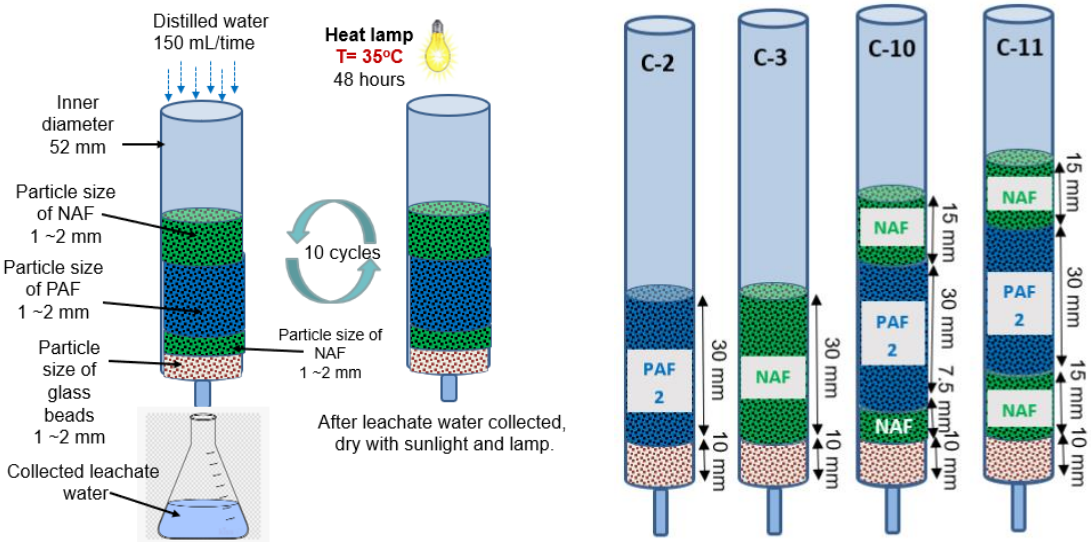


Figure 5.9 Sandwich column design

Table 5.12 Column leaching test results of NAPP and ANC

	Column No	C-2	C-3	C-10	C-11
PAF-2	**NAPP**	23.59	-2.04	12.61	10.78
	ANC	10.68	28.05	18.12	19.37

5.4.2 pH and EC measurement

Tables 5.13 and 5.14 show the results of the Column leaching test, along with the results of PAF-2. Figure 5.10 shows a graph of the pH change and Figure 5.11 shows the EC change in Column leaching test. The column leaching test that PAF with characteristics such as PAF-1 can be expected to improve water quality by covering a sufficient amount of NAF on the top. On the other hand, it was confirmed that PAF containing a large amount of As, such as PAF-2, would be difficult to improve with metal overburden only in the upper layer.

Table 5.13 Results of Column leaching test pH

	Number of water cycle									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
C-2	3.04	3.27	3.36	3.70	3.80	3.81	3.83	3.84	3.84	3.90
C-3	7.12	6.46	6.58	7.05	7.23	6.96	6.69	6.54	6.60	6.75
C-7	5.08	5.40	5.69	5.92	6.09	6.06	6.10	6.15	6.13	6.20
C-8	5.28	5.98	5.83	6.28	5.87	6.00	6.15	6.17	6.19	6.25
C-9	5.38	6.18	6.28	6.44	6.67	6.50	6.35	6.45	6.80	6.82
C-10	5.86	6.06	6.59	6.62	6.43	6.49	6.56	6.80	6.92	6.89
C-11	6.15	6.54	6.79	6.89	6.05	6.10	6.12	6.10	7.10	7.00

Table 5.14 Results of Column leaching test EC (mS/cm)

	Number of water cycle									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
C-2	1.31	1.21	0.54	0.34	0.15	0.14	0.12	0.12	0.12	0.12
C-3	0.49	1.86	0.27	0.30	0.17	0.14	0.07	0.06	0.06	0.06
C-7	0.71	1.15	0.41	0.23	0.16	0.15	0.13	0.13	0.13	0.13
C-8	0.72	1.17	0.60	0.37	0.19	0.20	0.18	0.17	0.17	0.17
C-9	0.86	0.93	0.49	0.42	0.18	0.18	0.15	0.15	0.15	0.14
C-10	0.91	1.21	0.64	0.36	0.19	0.20	0.25	0.25	0.20	0.20
C-11	0.38	1.42	0.72	0.49	0.19	0.20	0.22	0.21	0.20	0.20

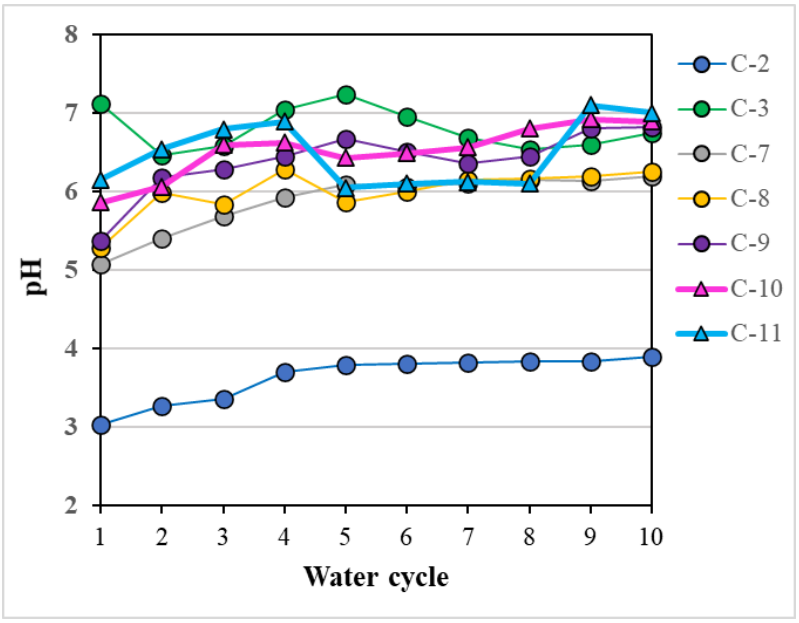


Figure 5.10 pH change of PAF-2

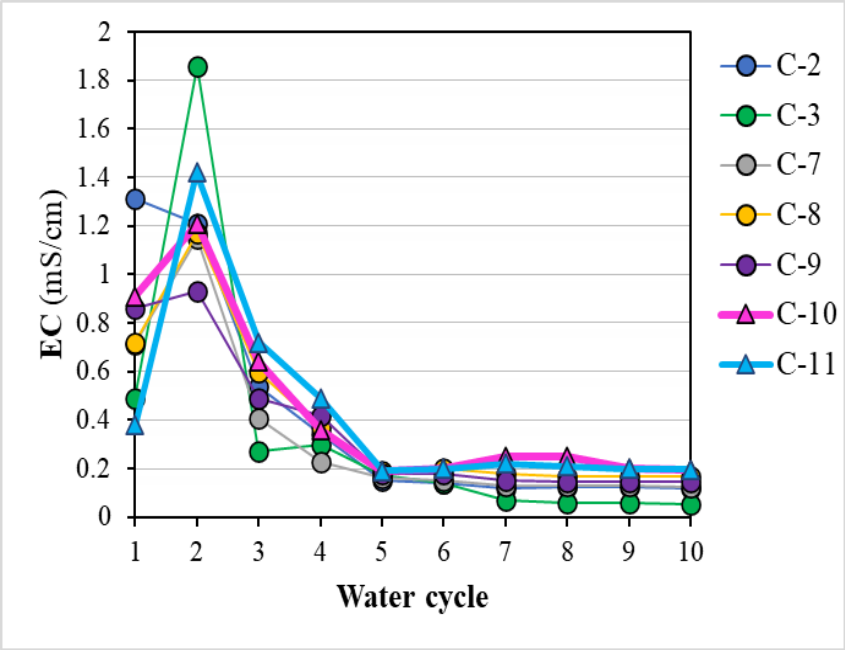


Figure 5.11 EC change of PAF-2

5.4.3 Eluting ions

To grasp specific eluted ions, a measurement was performed using ICP-MS [3] and ion chromatography [4] used in Chapter 3. The results are shown in Tables 5.15 to 5.20, and Figure 5.12 and 5.13 shows a graph of the As and Fe change in Column leaching test.

Table 5.15 Eluted ions As (ppm)

	Number of water cycle									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
C-2	41.344	19.440	18.536	3.613	3.283	4.050	4.074	3.942	4.141	4.110
C-3	1.022	0.878	0.099	0.038	0.097	0.088	0.027	0.017	0.013	0.021
C-7	4.978	3.750	3.701	3.195	2.622	1.618	1.230	1.628	1.635	1.393
C-8	5.093	1.597	1.969	1.136	0.731	1.233	1.971	1.563	1.646	1.259
C-9	3.884	2.971	1.845	1.447	1.280	0.955	0.840	0.927	1.162	1.046
C-10	1.712	1.425	0.987	0.696	0.663	0.426	0.418	0.403	0.719	0.547
C-11	1.018	1.404	1.003	0.630	1.606	0.444	0.354	0.366	0.397	0.285

Table 5.16 Eluted ions Fe (ppm)

	Number of water cycle									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
C-2	125.73	101.61	92.96	31.11	20.82	15.76	14.51	13.54	17.36	14.25
C-3	9.36	8.95	1.04	0.20	0.79	0.49	0.83	0.19	0.19	0.17
C-7	49.21	51.17	52.66	3.06	5.47	5.19	0.37	1.77	2.65	3.12
C-8	60.39	4.27	2.47	8.89	1.38	1.18	4.77	4.06	0.42	0.33
C-9	31.53	19.67	13.13	0.38	0.86	0.85	0.34	0.43	0.19	0.21
C-10	18.86	9.53	7.47	0.93	1.37	1.09	0.29	0.30	0.22	0.24
C-11	8.62	7.52	2.26	1.31	0.29	0.49	1.87	1.57	0.19	0.13

Table 5.17 Elution ion Al (ppm)

	Number of water cycle									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
C-2	38.53	11.37	13.17	3.82	1.62	1.05	1.06	1.49	1.23	1.13
C-3	2.21	0.86	0.53	0.16	0.04	0.08	0.10	0.10	0.07	0.04
C-7	8.15	4.27	1.11	2.09	0.27	0.95	0.26	1.47	0.30	0.24
C-8	1.45	4.27	0.61	1.21	0.05	0.33	0.13	0.32	0.06	0.06
C-9	0.80	0.22	0.63	0.16	0.05	0.10	0.09	0.05	0.07	0.06
C-10	0.44	0.37	0.52	1.32	0.06	0.13	0.21	0.10	0.06	0.10
C-11	0.26	0.36	0.50	0.09	0.05	0.04	0.12	0.12	0.05	0.03

Table 5.18 Eluted ions Na (ppm)

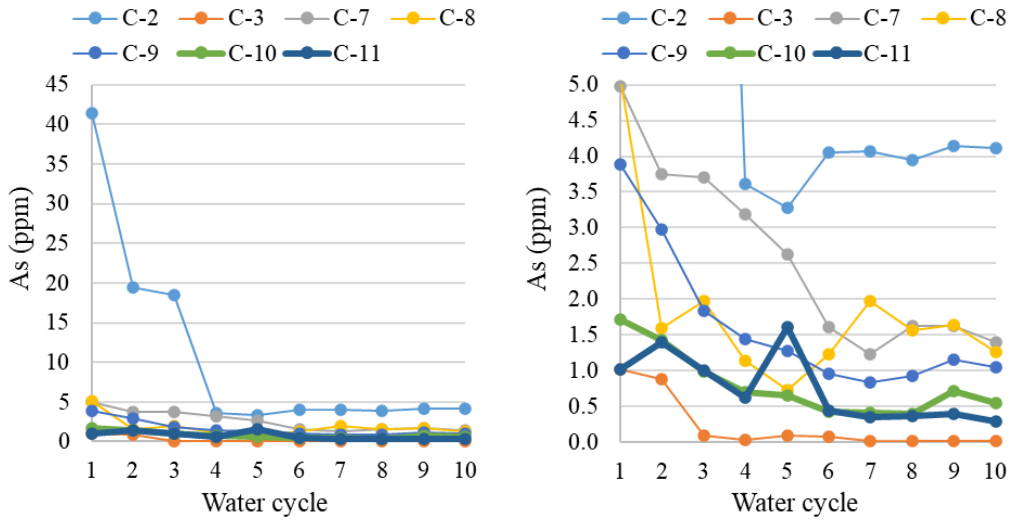
	Number of water cycle									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
C-2	29.01	39.12	8.31	4.01	1.90	1.52	1.08	0.89	0.74	0.56
C-3	18.02	133.87	11.62	12.97	6.34	4.67	3.05	1.59	1.52	1.76
C-7	16.80	42.42	9.15	4.60	2.92	2.36	1.74	1.44	1.03	0.99
C-8	15.91	4.27	14.02	6.98	4.25	3.97	2.38	2.24	2.16	2.03
C-9	25.39	16.72	6.37	3.90	2.15	1.73	1.51	1.29	1.07	0.99
C-10	23.77	37.89	11.87	5.77	3.25	3.02	1.66	1.55	1.44	1.10
C-11	29.68	51.66	16.26	8.63	4.22	2.35	1.98	1.67	1.53	1.63

Table 5.19 Eluted ions Ca (ppm)

	Number of water cycle									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
C-2	41.83	27.07	6.75	5.11	1.92	1.90	1.63	1.57	1.51	1.02
C-3	29.12	35.40	8.75	11.91	8.82	6.81	3.64	2.42	2.40	3.38
C-7	24.36	21.45	7.96	3.51	3.03	2.87	2.16	1.95	1.57	1.46
C-8	23.07	4.27	7.45	4.74	2.96	2.32	1.91	1.76	2.24	2.02
C-9	18.16	8.85	5.10	3.62	2.99	1.87	1.49	1.83	2.13	1.93
C-10	35.76	22.57	9.04	4.83	3.68	2.57	1.68	1.92	2.26	1.93
C-11	31.67	21.02	9.15	5.74	5.22	3.26	1.74	1.87	2.09	1.96

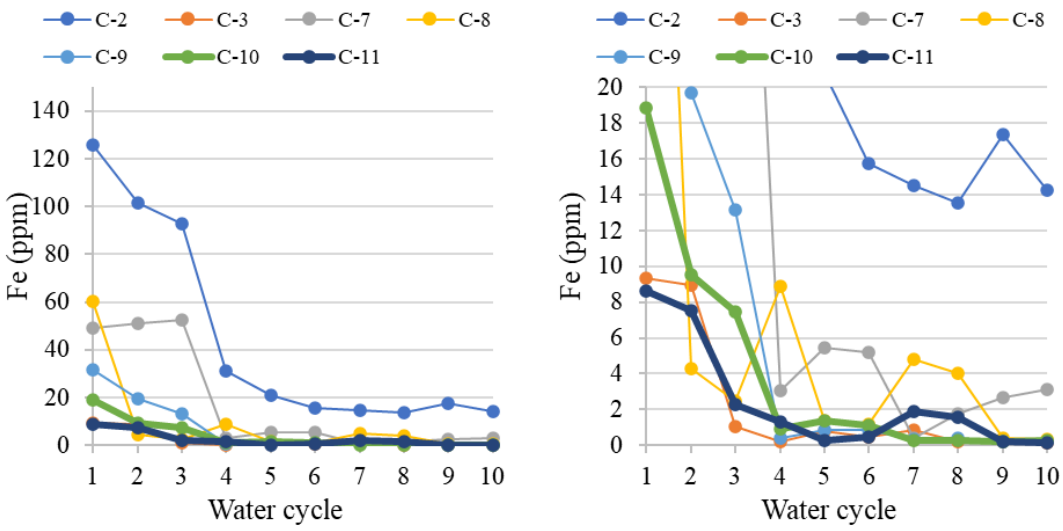
Table 5.20 Eluted ions Mg (ppm)

	Number of water cycle									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
C-2	21.16	43.72	11.89	5.98	3.90	3.27	2.82	2.04	1.22	0.95
C-3	19.42	64.63	6.54	10.15	5.12	4.35	2.30	1.85	2.00	2.55
C-7	13.32	37.53	19.47	8.98	11.39	11.13	10.22	6.53	2.99	2.43
C-8	30.17	4.27	23.57	20.09	15.87	13.99	13.85	12.97	13.94	11.09
C-9	68.65	81.07	26.86	28.71	20.11	20.37	18.61	14.96	10.88	9.39
C-10	41.85	85.25	43.65	20.84	21.14	16.60	13.16	12.93	12.42	11.25
C-11	23.19	109.90	47.26	31.55	20.65	17.90	12.90	9.96	9.18	9.02



(a) As elution in PAF-2 (b) As elution in PAF-2 large scale

Figure 5.12 Arsenic elution in PAF-2, (a) As elution in PAF-2 and (b) As elution in PAF-2 large scale



(a) Fe elution in PAF-2 (b) Fe elution in PAF-2 large scale

Figure 5.13 Fe elution in PAF-2 (a) Fe elution in PAF-2 and (b) Fe elution in PAF-2

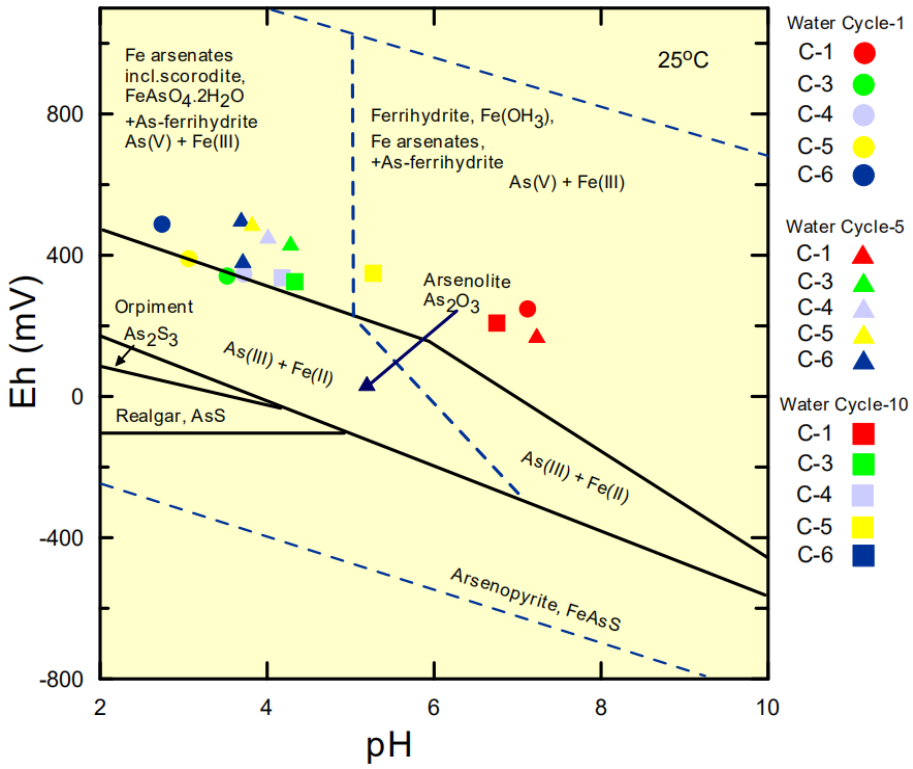


Figure 5.14 The pH-redox diagram for arsenopyrite results of PAF 1 column leaching test

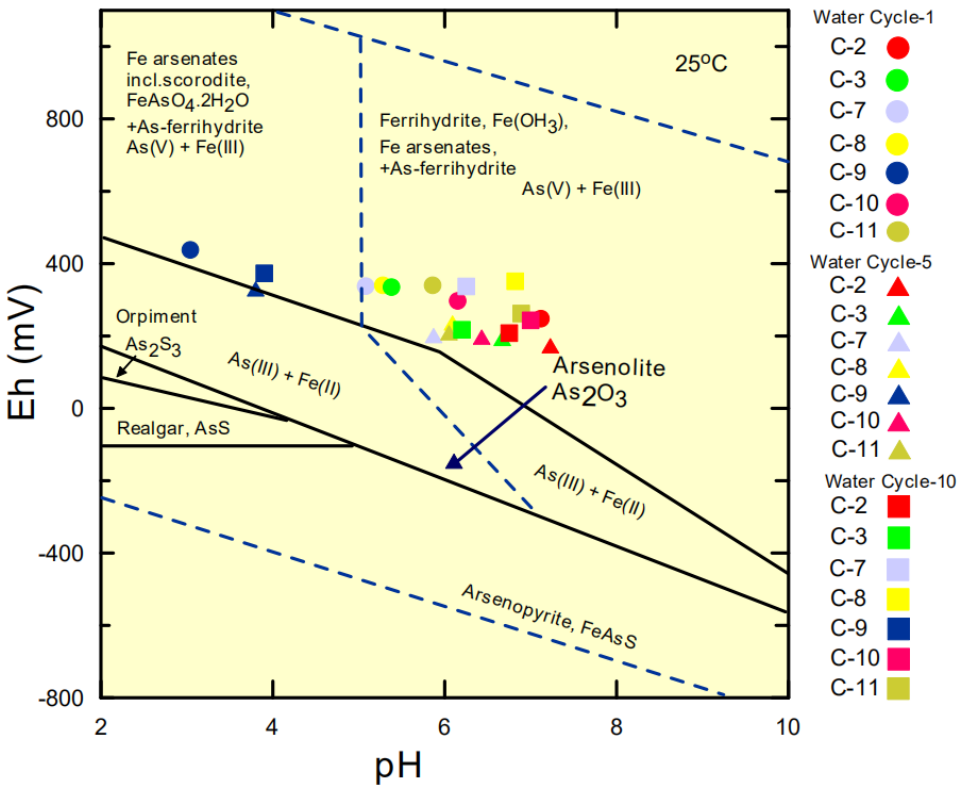


Figure 5.15 The pH-redox diagram for sarsenopyrite results of PAF 2 column leaching test

5.4.4 Discussion

From Table 5.15, significant elution suppression of As was confirmed in Columns C-10 and C-11 in which NAF was provided in the lower layer. Comparing Column C-8 with C-11, it can be seen that C-11 is much more effective in reducing metal elution, despite using the same amount of NAF for cover NAF. Also, considering that a significant metal elution suppression effect is exhibited even in the Column C-10 using a smaller amount of NAF, a method of laying NAF on the lower layer in backfilling waste rock containing a large amount of As such as PAF-2 is considered. In general, co-precipitation with iron hydroxide (III) is known in diarsenic [6, 7]. Fe (III) precipitates iron hydroxide (III) (Fe (OH) $_3$) over a wide range of pH 2 or higher, but As, which is an oxyanion, changes ionic species depending on pH, but precipitates. However, As is adsorbed on iron hydroxide (III) in the weakly acidic to neutral range, it can be treated using this property. From the above, it is considered that As is co-precipitated with Fe in the lower NAF.

5.5 SEM-EDX Analysis

5.5.1 Introduction

The results of the elution ion analysis described in the preceding section suggested that As may co-precipitate As with Fe in the lower layer NAF in Columns C-10 and C-11. Therefore, in this section, the sample surface was analyzed by SEM-EDX analysis [8]. In addition, the analyzed samples are three types of NAF in column C-3 after the completion of the water cycle (Figure 5.16), NAF in the lower part of Column C-10 (Figure 5.17), and NAF in the lower part of Column C-11 (Figure 5.18).

Figure 5.16 NAF of Column C-3

Figure 5.17 NAF at the bottom of Column C-10

Figure 5.18 NAF at the bottom of Column C-11

5.5.2 Principle of SEM-EDX

Scanning electron microscopes (SEMs) [8, 9] can obtain the sample shape information by utilizing electrons emitted from a solid or powder sample when the sample is irradiated with an electron beam. The energy held by electrons emitted from a scanning electron microscope is as low as several tens of eV and affects only the depth of a sample of 10 nm or less. Therefore, scanning the electron beam irradiation position is used to observe the sample surface shape. Further, since the electron emission efficiency depends on the unevenness of the surface of the sample, by converting the electrons into image information, the shape of the particle surface can be observed as a contrast.

When an electron beam is irradiated, characteristic X-rays are also emitted. Using an energy dispersive X-ray analyzer (EDX), various types of characteristic X-rays are converted into pulse signals, and the elements on the sample surface are analyzed. At this time, the element contained in the sample surface can be known from the energy of the characteristic X-ray, and the content of the element can be known from the number of pulse signals generated per unit time [8].

5.5.3 Analysis procedure

The analysis procedure is shown below. For the analysis, Hitachi scanning electron microscope (SEM) SU3500 [8] was used.

1. Three to five soil particles serving as samples were sufficiently dried at 30 ° C.
2. A carbon tape was stuck on the sample stage, and the sample was stuck thereon.
3. It was confirmed that the sample did not drop even if the sample stage was turned upside down.
4. The analysis was performed with a scanning electron microscope SU3500 (Figure 5.19).

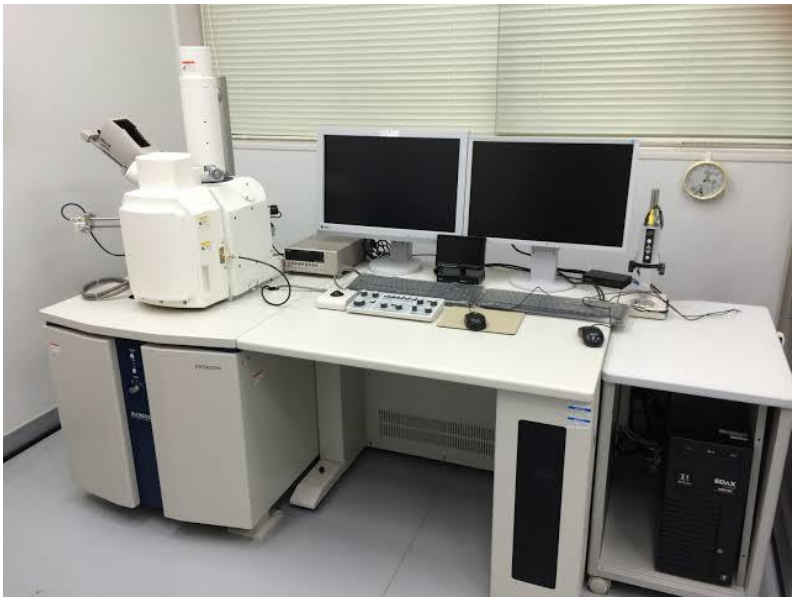


Figure 5.19 Scanning electron microscope SU3500

5.5.4 Result of analysis

The results of three types of analysis, NAF in Column C-3, NAF at the bottom of column C-10, and NAF at the bottom of column C-11, are shown in Figures 5.20 to 5.22 and Table 5.21.

According to SEM test analysis, Fe and As contents are higher in Column C-10 and C-11 (sandwich design) than those in control column C-3. According to the SEM results, the significant suppression of the arsenic elution is confirmed. This is due to the co-precipitation of the arsenic with iron hydroxide (III) in the bottom layer [6, 7]. The reduction of the arsenic and iron elution from leachate and the rise of these metals in the bottom layer is also confirmed from the results of SEM.

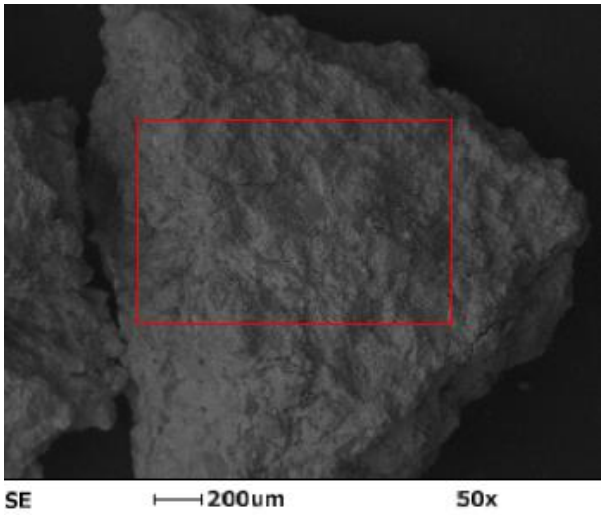


Figure 5.20 NAF of Column C-3

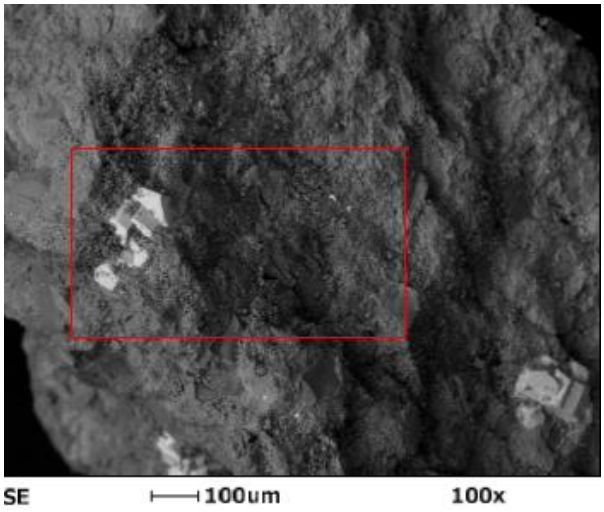


Figure 5.21 NAF at the bottom of Column C-10

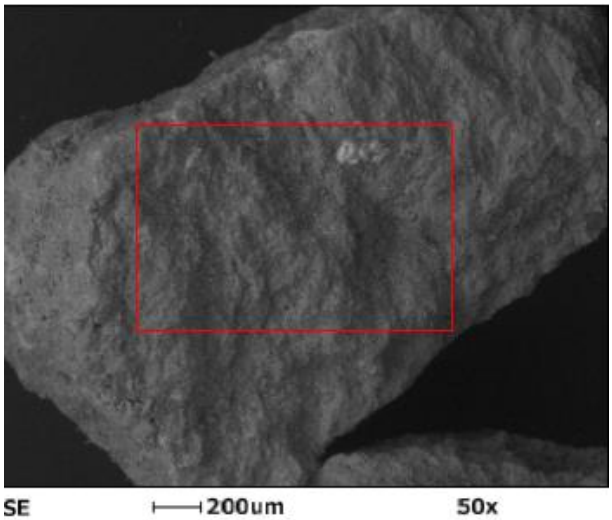


Figure 5.22 NAF at the bottom of Column C-11

Table 5.21 Results of surface analysis using SU3500

	Mg (Wt %)	Al (Wt %)	Ca (Wt %)	Fe (Wt %)	As (Wt %)
Column 3	1.87	13.67	3.43	3.81	0.26
Column 10	2.18	7.16	5.02	16.25	1.29
Column 11	2.11	6.20	7.93	25.73	2.62

5.6 Elution of cover design in term of reducing the metal elution

5.6.1 Cover efficiency

Cover efficiency can be characterized by the ability of the cover to minimize the loss of specific metal components, compared with an uncovered control case. The higher the percentage of cover efficiency, the higher the reduction of the eluted metal ion by cover design. The cover efficiency can be calculated using the formula described below [10].

$$\%\ \text{Efficiency}_{\text{component}} = \left(1 - \frac{\text{Mass}_{\text{component}}\ \text{leachate test column}}{\text{Mass}_{\text{component}}\ \text{leachate control column}}\right) \text{X } 100 \quad (11)$$

Table 5.22 Cover efficiency % of Fe and As in each Column leaching test

	Column No.	**Total amount of PAF (mm)**	**Total amount of NAF (mm)**	**Cover Efficiency %**	
				As	**Fe**
PAF-1 (Cover design)	**C-4**	30	15	66.4	72.7
	C-5	30	**30**	**75.9**	80.9
	C-6	30	45	84.0	89.4
PAF-2 (Cover design)	**C-7**	30	15	69.8	61.0
	C-8	30	**30**	**75.9**	**80.3**
	C-9	30	45	76.6	84.9
PAF-2 (Sandwich design)	**C-10**	30	22.5	83.4	91.0
	C-11	30	**30**	**82.9**	**94.6**

The cover efficiency percentage of As and Fe resulted from column leaching test of the cover design of PAF-1, and the cover design and sandwich design of PAF-2 are shown in Table 5.22. When the thickness of NAF is increased, the cover efficiency percentage of both As and Fe are also increased. Using the same amount of NAF (i.e., 30 mm) in cover design (C-8) and sandwich design (C-11), the cover efficiency of both As and Fe are higher in the sandwich design as compared to the cover design.

5.7 Guideline of the field application to the epithermal gold mine in Myanmar

The cross-section along Line 20 in Kyaukpahto gold mine and how the dumps high-grade ore stockpile, the Low-grade ore and the waste rock are put in the mine site are illustrated in Figure 5.23. The characteristic of rock samples used in column leaching test is shown in Table 5.23 and the volume of ore stockpile, low-grade ore dump and waste dump in Kyaukpahto gold mine are shown in Table 5.24 [11].

Table 5.23 Characteristic of rock samples used in Column leaching test

Sample	MgO (%)	CaO (%)	FeO (%)	As (ppm)	Total S %	MPA*	ANC*	NAPP*	ANC type
PAF 1	0.41	0.07	1.53	356	0.98	29.99	-3.12	33.11	Low
PAF 2	0.36	0.01	2.02	5,941	1.12	34.27	10.68	23.59	Medium
NAF	6.66	12.01	8.16	434	0.85	26.01	28.05	-2.04	High

Note. * in kg H_2SO_4/ton
MPA: Maximum Potential Acidity
ANC: Acid Neutralizing Capacity
NAPP: Net-Acid Potential Production
NAG: Net-Acid Generation

Calculation:
MPA= Total S% * 30.6
NAPP = MPA - ANC

Classification:
PAF : NAG pH < 4.5; NAPP > 0
NAF : NAG pH > 4.5; NAPP < 0
PAF: Potentially Acid Forming
NAF: Non-Acid Forming

Table 5.24 Volume of ore stock pile, low-grade ore dump and waste dump in Kyaukpahto gold mine

Location	Volume (m^3), (Million)
Ore Stock pile	48.31 M
Low-grade ore dump 1	200 M
Low-grade ore dump 2	8 M
Waste dump	15,700 M

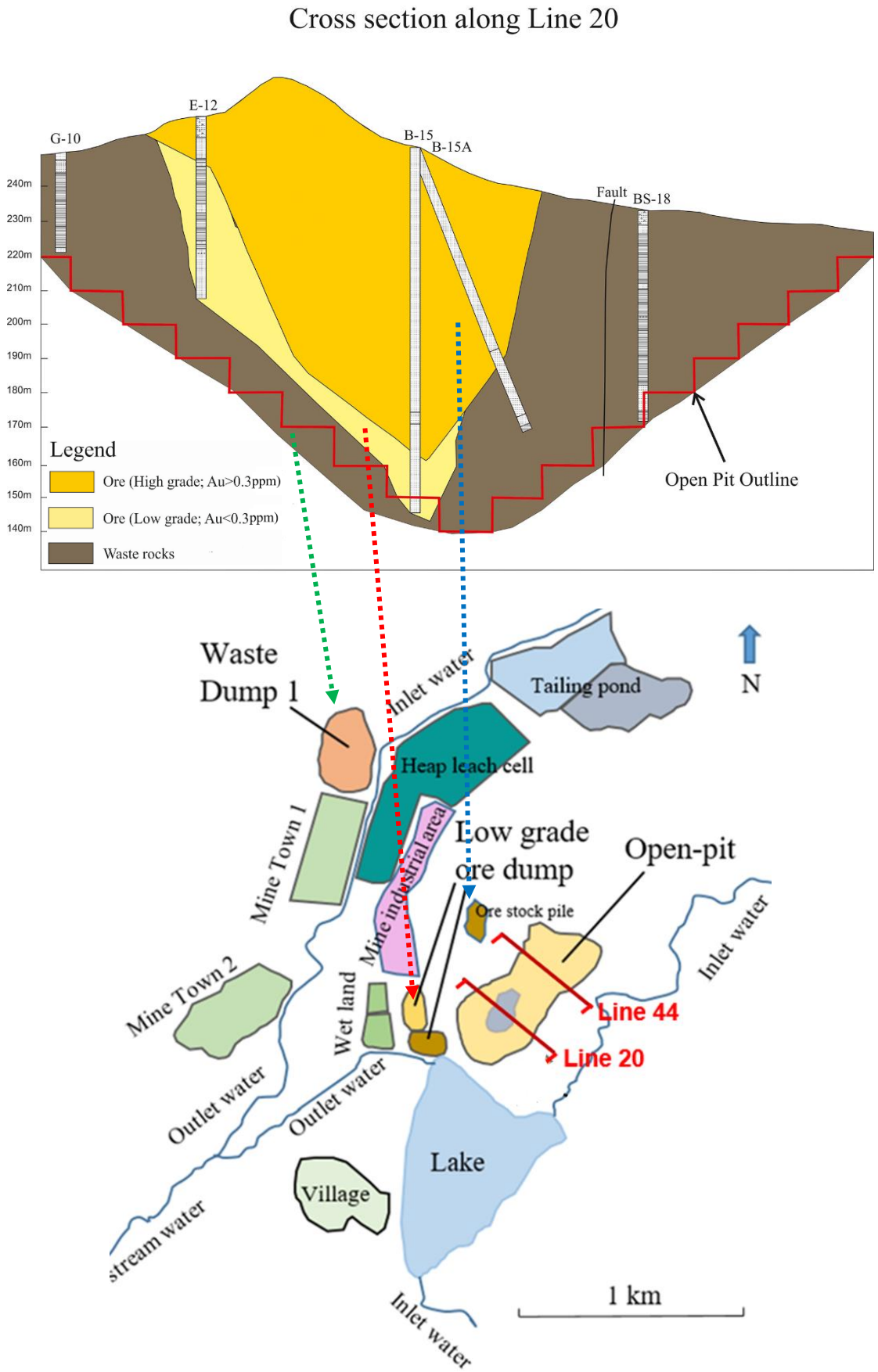
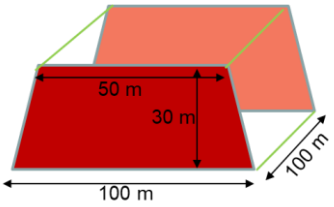


Figure 5.23 The cross section of Kyaukpahto open-pit and location map of its dump

In Table 5.25, the volume of NAF to be used in cover design and sandwich design of waste dump is shown. The thickness ratio of PAF to NAF that will be used in cover design and sandwich design is based on the column leaching test. When the same PAF to NAF ratio is assumed in both cover design and sandwich design, i.e. 1:1, the volume to be used in each design is found different. The cover design needs a greater amount of NAF (405,000 m^3) while the sandwich design will require 352,500 m^3.

Table 5.25 The volume of NAF to be used in cover design and sandwich design of waste dump based on column leaching test

	Thickness PAF: NAF	Amount of PAF volume (m^3)	Amount of NAF volume (m^3)
Cover design	**1:0.5**	225,000	180,000
	1:1	225,000	**405,000**
	1:1.5	225,000	675,000
Sandwich design	**1: 0.5+0.25**	225,000	266,250
	1: 0.5+0.5	225,000	**352,500**



The presence of potentially acid-forming (PAF) which may form acidic water is confirmed in the open-pit and the Low-grade ore dump where AMD generation is identified. Additionally, AMD generation is clearly found from Low-grade ore which is the waste rock under the cut-off grade 0.3 g/ton. The current risk of water pollution due to AMD generation is expected to be low because the volume of low-grade ore is quite small compared to that of waste rocks. Moreover, there is a possibility to adopt the dry cover system in this mine due to the high stripping ratio (1:16) and the large volume of the waste rock with carbonate minerals which have the acid-neutralizing capacity. The application of waste dump design for epithermal gold mine can be seen in Figure 5.24.

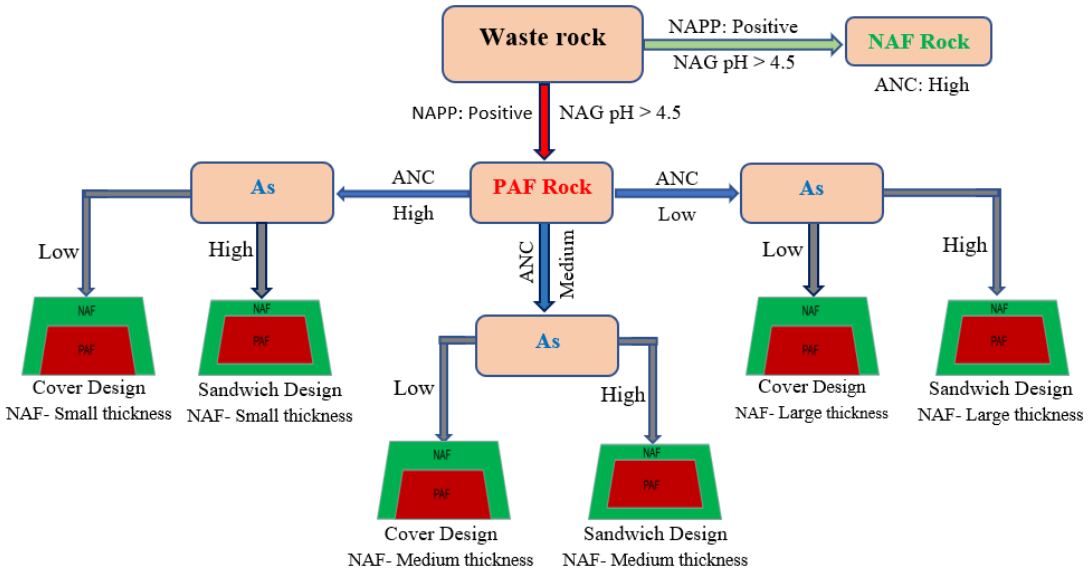


Figure 5.24 Application of waste dump design

If the ANC value is negative in a PAF rock, and the As content is low, then the cover design can be used with a large thickness of NAF. If the ANC value is low but the As content is higher, then the sandwich design with a large thickness of NAF should be used.

If the value of ANC in a PAF rock is medium, and the As content is low, then the cover design with a medium thickness of NAF can be used. If the ANC value is medium but the As content is higher, then the sandwich design with a medium thickness of NAF should be used.

If the ANC value is higher in a PAF rock, and the As content is low, then the cover design should be used with a small thickness of NAF. If the ANC value is high and the As content is also higher, then the sandwich design with a small thickness of NAF should be used. In some gold mines which have a small amount of NAF, sandwich design can be used with a small amount of NAF.

5.8 Conclusion

In this chapter the backfilling design of waste rock as a dry cover system considering the characteristic of PAF. The same column leaching test was conducted with the different cover scenarios by using the PAFs which have different characteristics and NAF which has a higher ANC. The results show that the pH of leachate improves as the layer thickness of NAF increases while the small amount of

cover is enough to prevent AMD generation if PAF has a higher ANC. The ratio of NAF/PAF to minimize the AMD generation in terms of pH should be determined with net acid-producing potential (NAPP) and ANC of the column.

For the metal elution, the high concentration of the arsenic elution is confirmed from the PAF contained a lot of the arsenic even in the case of increasing the cover thickness, meaning that it is difficult to reduce the arsenic elution with only the upper layer cover from such PAFs. Therefore, the sandwich design to place NAF not only on the upper layer but also as a bottom layer is suggested to prevent metal elution efficiently. According to the results, the significant suppression of the arsenic elution is confirmed. This is due to the co-precipitation of the arsenic with iron hydroxide (III) in the bottom layer. It is also confirmed that the reduction of the arsenic and iron elution from leachate and the rise of these metals in the bottom layer from the results of scanning electron microscopy, SEM.

By increasing the cover thickness, the cover efficiency of As and Fe increases accordingly. If the sandwich design is used, the cover efficiency is larger, and less NAF amount can be used as compared with the cover design. If the amount of As is high in the PAF rock, sandwich design may be more suitable whereas the cover design may be more suitable when the amount of As is low in PAF rock. The thickness of NAF may vary with the ANC value. If the ANC value is high, the small thickness of NAF will be required. If the ANC value is low, a thicker NAF cover should be used. Finally, the guideline for the application of the dry cover system in the epithermal gold mine of Myanmar is suggested in this chapter.

5.9 References

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CHAPTER 6

Conclusion

In this study, we conducted on-site surveys, collected water and rock samples, geochemical analysis of samples, A test was conducted, and the phenomena that caused the results were examined. Geochemical tests and batch leaching tests on rock samples and quality analysis on wastewater from the immediate vicinity of Kyaukpahto gold mine in Myanmar to evaluate the potential contamination risk from AMD. It was found that, although the pH and heavy metal concentrations of surface water outside the mine area currently meet official standards for wastewater quality because AMD is treated before being discharged from the mine area, this is not so in the mine area itself. The pH and concentrations of toxic chemical elements (e.g. Fe, As, Al, Zn, etc.) exceed the standards at several points, and there is a major area of AMD near the open-pit mine and at a low-grade ore dump, where the pH is less than 3.0 and the concentrations of Fe and As are very high.

In this study, the mechanism of acid mine drainage generation, the elements contained in rocks, and the general elution elements were identified based on the water quality inside Kyaukpahtoe Gold Mine and the geochemical analysis of rock samples. A column water flow test was performed on the rocks with acid generating ability contained in the dump, and the rocks were classified based on the difference in elution characteristics expected at the site.

Some of the effluents from rocks show strong acidity and elute a lot of heavy metals, i.e., the rocks that cause acidic mine drainage are mainly those found in low grade ore dump. The rock may be present in the pit cross-section where it indicates low-grade rock. It is thought that the acidity of acid mine drainage does not depend on the sulfur content, but rather on the neutralization of carbonate minerals. As a result of conducting a column flow test under conditions close to the site, rocks that could generate acidic mine drainage water were roughly classified into two types in terms of elution rate and metal elution amount.

The rocks that show strong acidity and have a large amount of heavy metal eluted at the beginning, while the rocks with weaker acidity of the elution water have a slower rate of heavy metal elution and longer-term elution. In particular, rocks rich in carbonate minerals elute heavy metals for a long period of time, even if the acidity is weak. If a rock with a high initial elution volume is mixed with a rock with a slow elution rate but a long-term elution, more metal may elute at the initial elution.

At the Kyaukpahto gold mine in Myanmar, low-grade ore dump confirmed the generation of acidic mine drainage. The low-grade ore dump contains PAF with high acid generation ability and PAF containing a large amount of As, and there is a risk of elution of a large number of harmful ions. It is necessary to study the dry covering method. For PAF with high acid generation ability, acid neutralization ability is high and pH can be improved by dry covering with an appropriate amount of NAF containing carbonate minerals. As for the PAF containing a large amount of As, it is difficult to suppress the elution of As with the NAF covering only at the upper part, but the elution can be suppressed by laying the NAF on the lower part.

In addition, during the processes of weathering the oxidation of pyrite will still go on due to increasing of total reactive surface area, and it should also be taken into consideration. Moreover, the results of NAG and two-step sequential leaching tests indicate a potential As-bearing AMD contamination risk in the future in the waste dump area, through the quality of its wastewater indicates that there is currently no AMD there. In conclusion, to ensure the sustainable development of resources at this mine, long-term contamination of wastewater by As and metal dissolutions should be considered in AMD prevention measures regardless of the evidence for AMD at the present time. Finally, the guideline for the application of the dry cover system in the sediment-hosted epithermal gold mine of Myanmar is suggested in this research.