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Preventing Acid Mine Drainage Generation: Using Dry Cover Systems for Potential Acid-Forming Waste Rock at Kyaukpahto Gold Mine

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Contents

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Abstract

Kyaukpahto gold mine is the first open-pit gold mine and the second largest gold deposit of Myanmar, located in the Kawlin Township of the Sagaing Region. Common ore minerals of mineralization include pyrite, arsenopyrite, and chalcopyrite. Gold ore are exploited by open-pit mining and waste rocks are disposed as waste dumps near mine site. The characteristics of AMD depend on the minerals contained in the rocks, climatic conditions, and the local hydrology. The dissolution of high concentrations of metal ions (iron, aluminum, manganese, zinc, copper, nickel, arsenic) has an environmental impact on the rivers and the surrounding environment. Therefore, it is important to implement effective measures to prevent the generation of AMD from waste dumps. The backfilling design of waste rock as a dry cover system is an effective method to prevent the generation of AMD from waste dumps. The cover system can reduce the infiltration of water and oxygen into the waste rock, which can minimize the generation of AMD. The column leaching test results showed that the cover system with PAFs and NAF can effectively reduce the generation of AMD. The assessment of waste rocks at the Kyaukpahto waste dump showed that the waste rocks have a high potential to generate AMD. Therefore, it is necessary to implement an effective cover system to prevent the generation of AMD from the waste dump.

Keywords: *Acid mine drainage, Dry cover, Column leaching, Metal sulfides, Waste dump*

ကျောက်ပုထိုးရွှေသတ္တုတွင်းရှိ အက်စစ်ဓာတ်ထွက်နိုင်သော စွန့်ပစ်ကျောက်များအား Dry Cover System အသုံးပြုပြီး Acid Mine Drainage ဖြစ်ပွားနိုင်မှုအား ကာကွယ်ခြင်း

သန့်ဆွေဝင်း၊ လက်ထောက်ညွှန်ကြားရေးမှူး
သတ္တုတွင်းဦးစီးဌာန

စာတမ်းအကျဉ်း

စစ်ကိုင်းတိုင်းဒေသကြီး ကောလင်းမြို့နယ်တွင် တည်ရှိသော ကျောက်ပုထိုး ရွှေသတ္တုတွင်းသည် မြန်မာနိုင်ငံတွင် ဒုတိယအကြီးဆုံး ရွှေသတ္တုသိုက်နှင့် ပထမဆုံးသော ဟင်းလင်းဖွင့် တူးဖော်သည့် နည်းစနစ်ဖြင့် တူးဖော်ထုတ်လုပ်နေသော ရွှေသတ္တုတွင်း ဖြစ်ပါသည်။ အဆိုပါ သတ္တုတွင်း၌ အဓိကတွေ့ရှိရသော သတ္တု ဆာလ်ဖိုက်များမှာ Pyrite၊ Arsenopyrite နှင့် Chalcopyrite တို့ ဖြစ်ပါသည်။ အဆိုပါ ရွှေသတ္တုတွင်းအားOpen-pit mining နည်းစဥ်ဖြင့် ထုတ်လုပ်ပြီး စွန့်ပစ်ကျောက်များ အား သတ္တုတွင်းလုပ်ကွက်အနီးရှိ စွန့်ပစ်မြေစာပုံ/ စွန့်ပစ် ကျောက်ပုံတွင် စုပုံပါသည်။ မိုင်းအက်စစ် ယိုစိမ့်မှု (Acid Mine Drainage) ဖြစ်ပွားရခြင်း၏ အဓိက အကြောင်းအရင်းများသည် ကျောက်များ တွင် ပါဝင်သော ဓာတ်သတ္တုများ၊ ရာသီဥတု အခြေအနေများနှင့် ဒေသဇလဗေဒဆိုင်ရာများ အပေါ်တွင် မူတည်ပါသည်။ သတ္တုအိုင်းယွန်းများဖြစ်သော (သံ၊ အလူမီနီယမ်၊ မင်းဂနီးစ်၊ သွပ်၊ ကြေးနီ၊ နီကယ်၊ အာဆင်းနစ်) တို့သည် ရေများထဲသို့ ပျော်ဝင်နေပါက မြစ်ချောင်းများနှင့် သဘာဝ ပတ်ဝန်း ကျင်အပေါ် ထိခိုက်ပျက်စီးမှု ရှိနိုင်ပါသည်။ ထို့ကြောင့် စွန့်ပစ်ကျောက်များမှ AMD ဖြစ်ပေါ်လာခြင်း ကို တားဆီးကာကွယ် နိုင်ရေးအတွက် ထိရောက်သော အစီအမံများဖြင့် အကောင်အထည်ဖော်ရန် အရေးကြီးပါသည်။စွန့်ပစ်ကျောက်စုပုံရာတွင် စွန့်ပစ်ကျောက်များမှ AMDဖြစ်ပေါ်လာခြင်းကိုတားဆီး ကာကွယ်နိုင်ရေးအတွက် Dry Cover System အသုံး ပြုခြင်းမှာ ပိုမိုထိရောက် ကာကွယ်နိုင်သော စနစ်တစ်ခု ဖြစ်ပါသည်။ Dry Cover System သည် စွန့်ပစ်ကျောက်များအား ရေနှင့် အောက်ဆီဂျင် စိမ့်ဝင်မှုကိုလျှော့ချနိုင်ပြီး AMD ၏ ဖြစ်ပွားမှုကို လျှော့ချနိုင်ပါသည်။ Column Leaching test ကို အသုံးပြုပြီး စမ်းသပ်မှု ရလဒ်များအရ အက်စစ်ဓာတ်ထွက်နိုင်သော (PAF) ကျောက်များနှင့် အက်စစ် ဓာတ်မထွက်နိုင်သော(NAF) ကျောက်များကို အသုံးပြုပြီး Cover System အသုံးပြုခြင်းသည် AMD ဖြစ်ပွားမှုအား လျှော့ချနိုင်ကြောင်း တွေ့ရှိရပါသည်။ကျောက်ပုထိုး စွန့်ပစ်ကျောက်ပုံရှိ စွန့်ပစ်ကျောက် များသည်AMD ဖြစ်ပွားနိုင်သည့် အလားအလာရှိကြောင်း တွေ့ရှိရသဖြင့် အဆိုပါ စွန့်ပစ် ကျောက် ပုံတွင် AMD ဖြစ်ပွားမှုကို ကာကွယ်ရန်အတွက် Cover System ကို အသုံးပြုပြီး အကောင်အထည် ဖော်ဆောင်ရွက်ရန် လိုအပ်လျက်ရှိပါသည်။

အဓိကစကားလုံးများ။ မိုင်းအက်စစ်ယိုစိမ့်မှု ၊ Dry cover ၊ Column Leaching ၊ သတ္တုဆာဖိုဒ် ၊ စွန့်ပစ်ကျောက်ပုံ

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1. Introduction

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 (I. Moodley et al.,2018). The characteristics of AMD depend on the minerals contained in the rocks, climatic conditions, and the local hydrology. In other words, the chemical composition of the rocks, the amount of rainfall, and the local hydrology can all affect the acidity of the water that flows through the mine waste. This can lead to the release of toxic metals and other pollutants into the environment, which can have serious consequences for human health and the ecosystem (Gautama et al., 2013). 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 (Bernd G. Lottemoser, 2010). 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 (D.B. Johnson et al., 2005).

Myanmar, one of the Southeast Asian nations, is highly endowed with various mineral resources, such as gold, silver, copper, and lead (S.Win et al., 1998). 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). 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 (S. Maung et al., 1991 and Y. M. Swe et al., 2004). 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 (Y. M. Swe et al., 2017). 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 (R. K. Tiwary, 2001). 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 (Z. W. Than, 2015). However, the risk of AMD generation from Kyaukpahto gold mine has to be evaluated to avoid the severe environmental impacts for the future.

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, favoring 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 (T. S. Win et al., 2017). 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 (T. M. Htun et al., 2013). 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 (C. Nugraha et al., 2009). 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 (T. S. Win et al., 2017).

2. Objectives

The objective of this paper is to propose an effective cover system to prevent the generation of acid mine drainage (AMD) from waste dumps at the Kyaukpahto gold mine. This work focus on discussed the backfilling design of waste rock as a dry cover system considering the characteristic of Potentially Acid Forming (PAF). The same column leaching test was conducted with different cover scenarios by using the PAFs which have various characteristics and Non-Acid Forming (NAF) which has a higher Acid Neutralization Capacity (ANC). The proposed cover system is designed to reduce the infiltration of water and oxygen into the waste rock, which can minimize the generation of AMD.

3. Materials and Methods

Field investigation was carried out in Kyaukpahto gold mine in order to understand the field conditions in mining area with respect to waste rocks. 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 1. These areas are respectively located in the tailing pond, a waste dump, the mine town, the low-grade ore dump, the open pit, and downstream of the drainage from the mine area.

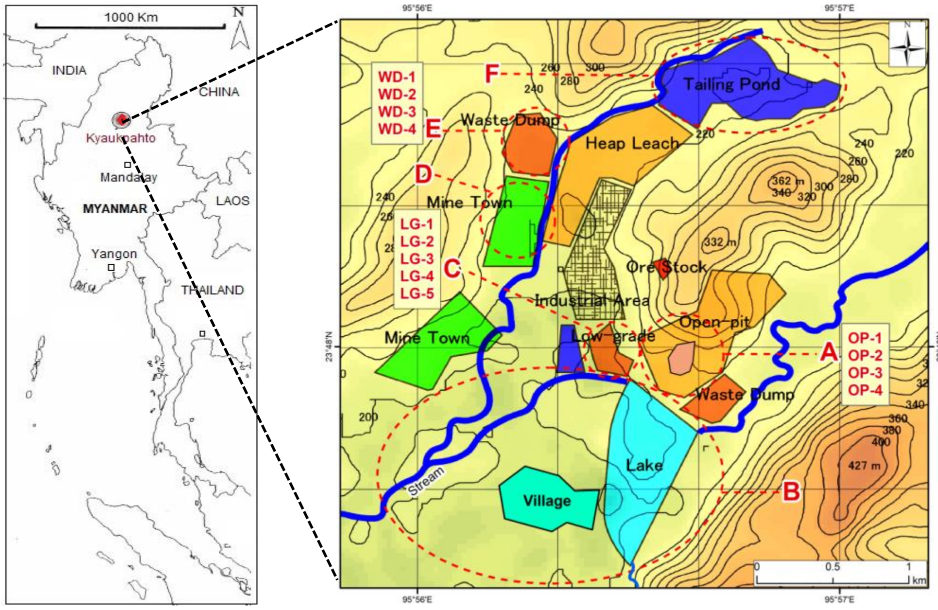
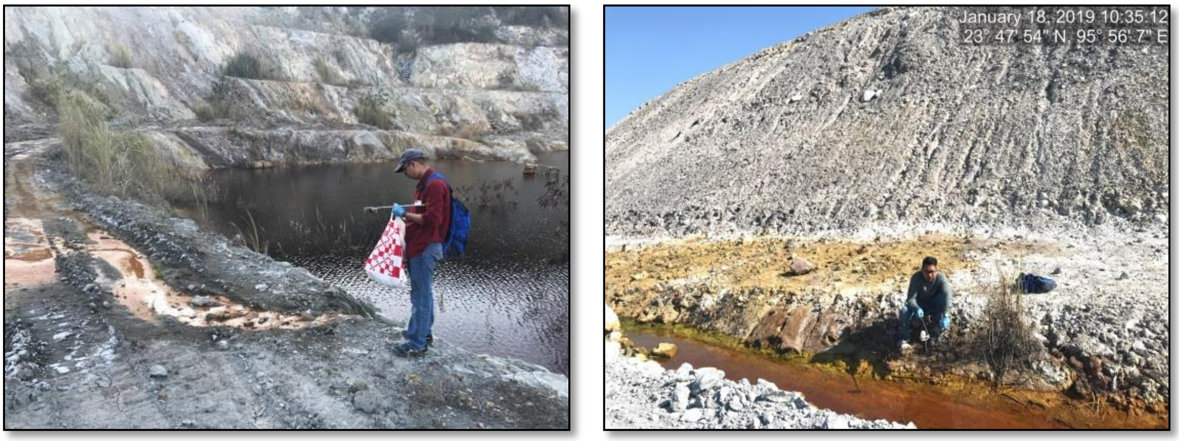


Figure 1. Location map of Kyaukpahto gold mine: red letters indicate Water-sampling areas; Open-pit (OP), Low-grade ore dump (LG), and Waste dump (WD) indicate waste rock sampling areas.

The water samples were introduced into an Agilent 7500 Series Inductively Coupled Plasma-Mass Spectrometer (ICP-MS) after adding 0.1% of HNO_3. Waste rocks were sampled from three areas in the mine site as marked in (Figure 1): the open pit (Area A), the low-grade ore dump (Area C), and the largest waste dump (Area E). These samples were named 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. The paste pH, Net Acid Generation (NAG) test, acid-base accounting (ABA), Acid Neutralization Capacity (ANC) and X-ray Fluorescence (XRF) analysis were performed to characterize the geochemical characteristics of the waste rocks (AMIRA, 2002). Acidic water with red-brick color was found in the open-pit and low-grade ore dump (Figure 2) and basically the water flow is north to south.



(a) Open-pit water (b) Surface water near low-grade ore dump

Figure 2. Field photos showing AMD generation in open-pit and low-grade ore dump.

The column device was designed and used as shown in Figure 3, and the sample was packed by changing the type and thickness of the sample as shown in Figure 4. 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. 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. 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 to Column C-3). NAF was filled into the upper part of PAF-1 and PAF-2 by changing the layer thickness to 15 mm, 30 mm, 45 mm (Column C-4 to Column C-9). 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). 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). 150 mL of deionized water was passed 2.5 minutes through the top of the column and, the leachate water was collected from the bottom of the column. After the passage of water, drying was performed for 48 hours in sunlight and lamp temperature with 35°C. Eluted water in each flow cycle was defined as one cycle, and this was repeated ten cycles. These cycles was analyzed for water quality by pH, EC, ICP-MS, and IC (Agilent Technology and JAIMA Japan). At the end of the measurement, the sample used in the column water flow test was observed.

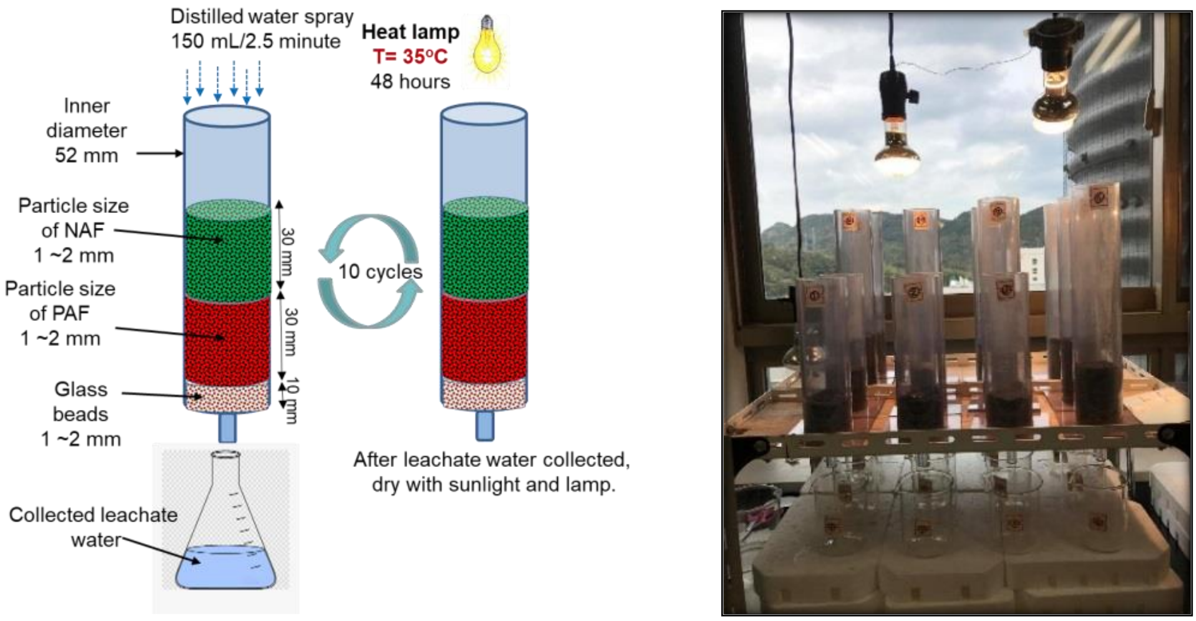


Figure 3. Outline of design for Column leaching test

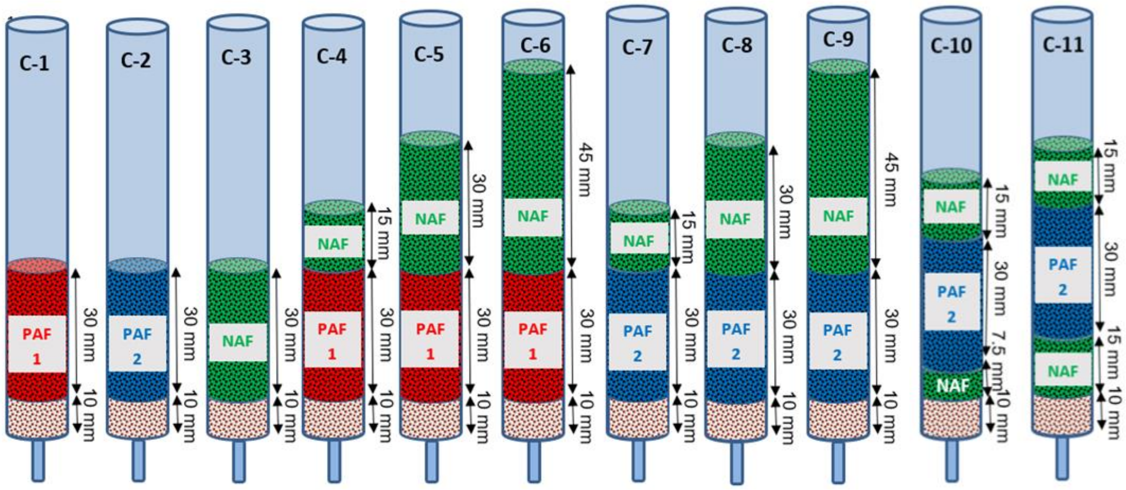


Figure 4. Column design conditions

4. Results and discussion

Table 1 summarizes the water quality results for surface water in areas **A**, **B**, **C**, **D**, **E**, and **F** (locations are shown in Figure 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, and Cu were detected in these areas samples when compared with those of areas **B**, **D**, **E** and **F**. These values exceed the Myanmar National Environmental Quality standards (MNEQs) (MNEQs, 2015), which are pH=6-9, Fe <2.0 mg/L, As <0.1mg/L, and Cu <0.3 mg/L. Although both the 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 1. Chemical concentrations (mg/L) in water samples from the research area. EC is in mS/cm.

Area	No	pH	EC	Fe	As	Cu
A	1	2.61	3.8	9519	373	14
	2	7.23	0.93	359	10.7	0.9
	3	6.76	3.7	522	9.8	8.8
	4	2.59	2.7	170	1.6	14
	5	7.24	2.2	233	3.7	11
	6	2.68	2.7	114	0.7	9.7
	7	2.85	3.9	79	0.3	20
	8	2.66	2.7	87	0.3	15
	9	2.53	4	171	0.5	16
B	10	7.63	0.49	2	0	0.5
	11	7.62	0.44	1	0	0.5
	12	7.6	0.39	1	0	0.4
	13	7.94	0.38	1	0	0.3
	14	7.73	0.42	11	0	0.4
	15	7.19	0.66	2	0.5	0.6
	16	7.98	0.59	0	0	0.4
	17	8.3	0.31	0	0	0.1
	18	8.41	0.36	0	0	0.1
C	19	2.57	6.5	299	0.2	30
	20	2.5	6	539	1.5	15
	21	1.54	12.6	5586	132	119
D	22	8.64	0.64	1	0	0.3
	23	8.25	0.59	1	0	0.5
	24	8.2	0.67	2	0	0.3
	25	8.35	0.05	0	0	0.2
	26	8.59	2.7	55	0.4	17
	27	8.19	1.09	4	0.1	2.9
	28	8.31	0.85	2	0	1.6
	29	8.41	0.53	3	0.1	0.5
	30	8.89	0.64	3	0.1	1.7
	31	8.77	0.92	3	0	0.7
E	32	7.67	1.67	99	0.4	37
	33	7.44	1.56	31	0.4	12
	34	7.92	1.64	41	0.4	7.5
	35	8	0.73	1	0	0.7
	36	8.18	1.31	13	0	3.6
	37	5.18	1.28	12	0.1	6.9
F	38	5	1.46	4	0	0.7
	39	4.87	1.48	2	0.1	0.6
	40	6.48	1.43	2	0.1	3.7
	41	6.58	2.04	21	0.2	4.7
-	-	-	-	-	-	-

The geochemical properties of the waste rocks are summarized in (Table 2). **OP-1** to **OP-4** in the open pit area and **LG-1** to **LG- 5** in the low-grade ore dump area were classified as PAF. The paste pH for LG-1 which exceeds the Myanmar Environmental standard value for pH. The NAG pH ranged from 2.31 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 **A** and **C**. On the other hand, **WD-2**, **WD-3** and **WD-5** was classified as NAF, and **WD-4** were classified as PAF. **WD-1** was classified as UC due to its positive NAPP and NAG pH of more than 4.5. In the Area **E** waste rocks has high carbonate mineral 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 5.18 to 8.18 in (Table 2). Although **WD-4** were classified PAF and its paste pH were 4.3, its NAG pH was 2.93, and its NAPP was 33.11kg H_2SO_4/ton. The more positive NAPP values of rock indicates 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 complete dissolution of the rock sample with H_2O_2, indicating that **WD-4** are AMD contamination risk in the future, although there is currently no AMD in area **E**.

Table 2. 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-4	8.09	0.61	0.63	19.28	19.91	-0.63	6.65	NAF
Area C (Low grade ore dump)	**LG-1**	3.60	2.1	0.60	18.36	0.84	17.52	3.27	PAF
	LG-2	6.45	1.50	0.91	27.85	4.59	23.26	3.04	PAF
	LG-3	7.49	2.60	2.27	69.46	21.84	47.63	2.66	PAF
	LG-4	5.28	1.50	1.12	34.27	10.68	23.59	2.77	PAF
	LG-5	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-2	8.70	1.08	0.71	21.73	55.56	-33.83	8.49	NAF
	WD-3	8.54	0.59	0.13	3.98	19.26	-15.28	7.79	NAF
	WD-4	4.30	1.70	0.98	29.99	-3.12	33.11	1.70	PAF
	WD-5	8.41	0.89	0.85	26.01	28.05	-2.04	8.28	NAF

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

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

Classification:
NAF : NAG pH $\geq$ 4.5; NAPP $\leq$ 0
PAF : NAG pH < 4.5; NAPP > 0
PAF: Potentially Acid Forming
NAF: Non-Acid Forming
UC: Uncertain

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 Table 3 and Table 4. **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 3. Composition elements of PAF-1, PAF-2, and NAF from XRF results

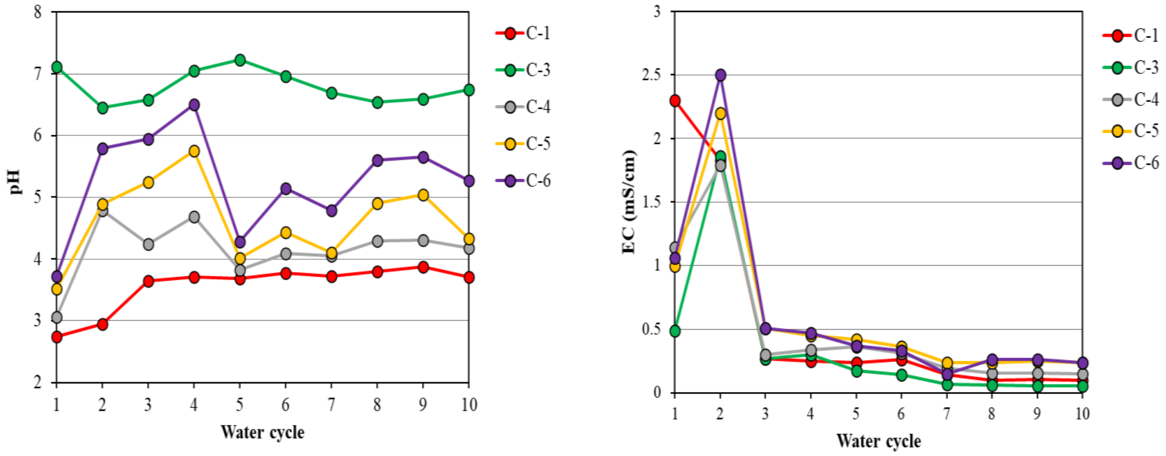
Sample	SiO_2 (%)	Al_2O_3 (%)	FeO (%)	MnO (%)	MgO (%)	CaO (%)	S (%)	Cu (ppm)	Zn (ppm)	As (ppm)
PAF-1	85.6	6.37	1.53	0.01	0.41	0.07	0.98	10	29	356
PAF-2	86.0	5.49	2.02	0.00	0.36	0.01	1.12	6	34	5,941
NAF	42.5	9.26	8.16	0.67	6.66	12.01	0.85	92	82	434

Table 4. 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

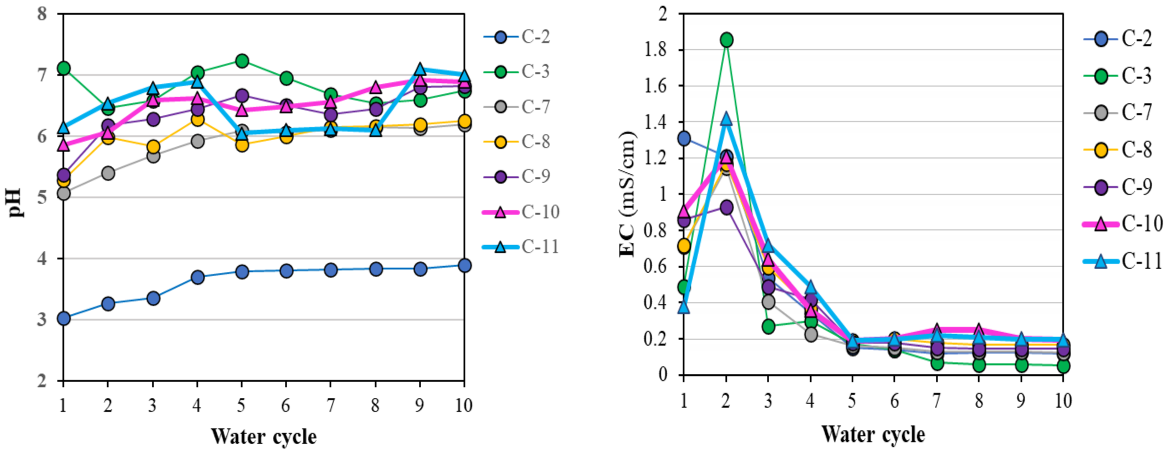
Figure 5 and Figure 6 shows a graph of the pH change and the EC change in Column leaching test. According to the results of the column leaching test, the column using **PAF-1** did not meet MNEQs standard for water quality, pH 6-9. Since the elution is also suppressed, it is considered that water quality 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 as shown in Figure 6. This is probably due to NAPP in **PAF-2** situation. However, when attention is paid to the dissolution of As (Figure 7 and Figure 8), although some dissolution suppression is possible, no effective improvement is seen because the content is originally large. 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.

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.



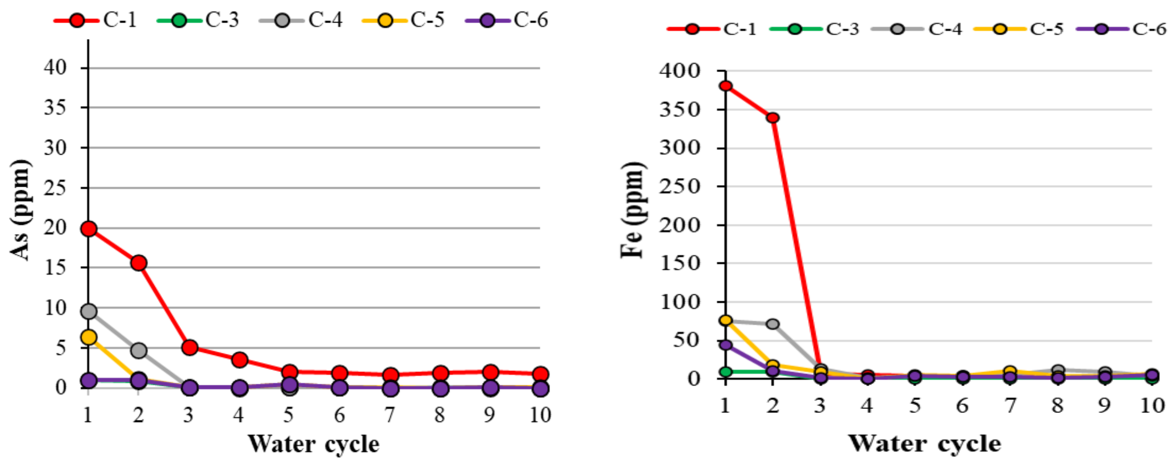
(a) pH (b) EC

Figure 5. The pH and EC values of PAF-1 results from Column Leaching test



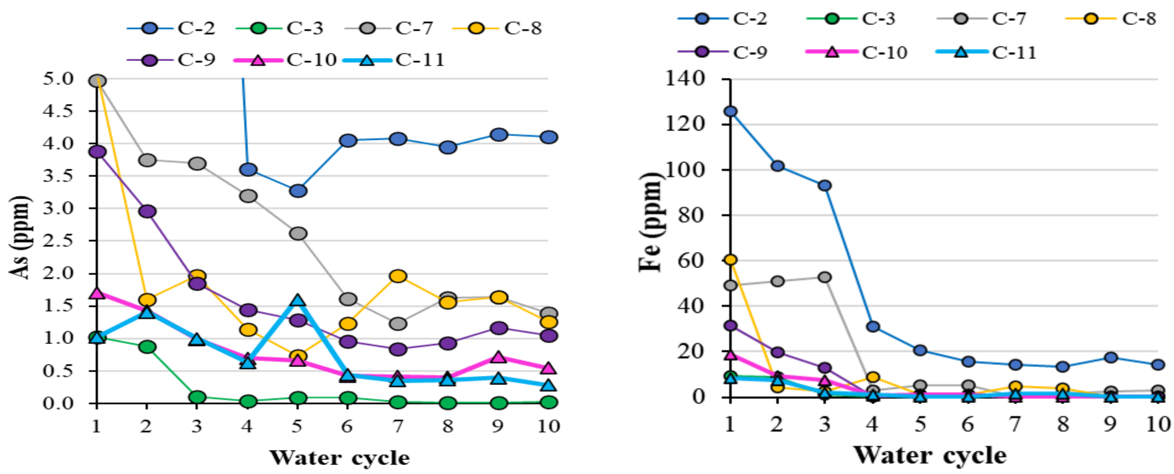
(a) pH (b) EC

Figure 6. The pH and EC values of PAF-2 results from Column Leaching test



(a) As (b) Fe

Figure 7. The As and Fe values of PAF-1 from Column Leaching test



(a) As (b) Fe

Figure 8. The As and Fe values of PAF-2 from Column Leaching test

From Figure 8, significant elution suppression of As was confirmed in Columns C-10 and C-11 in which NAF was provided in the lower layer by Sandwich design. 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 (Yanagase Kenjiro, 1983 and Chiharu Tokoro, 2014). 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. Conclusions

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.

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7. References

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

AMIRA. "ARD Test Handbook, Project P387A. Prediction and Kinetic Control of Acid Mine Drainage," AMIRA International Limited, Melbourne, Australia, pp. A1-G2, 2002.

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

C. Nugraha, H. Shimada, T. Sasaoka, M. Ichinose, K. Matsui, I. Manege, "Waste rock characteristics at tropical coal mine area: A case study of PT. Kaltim Prima Coal, Indonesia," International Journal of the JCRM, Vol. 5, Issue. 2, pp. 77–82, 2009.

Chiharu Tokoro: Safe and Efficient Treatment of Mine Wastewater, Chemistry and Education, Vol. 62, No. 4, 2014.

D. B. Johnson, K. B. Hallberg, "Acid mine drainage remediation options: A review," Science of the Total Environment, Issue. 338, pp. 3-14, 2005.

Gautama, S.R., et al. Study on Capping Options for Overburden Encapsulation to Prevent Acid Mine Drainage in Lati Coal Mine, Kalimantan, Indonesia. Proc. of the Annual International Mine Water Association Conference: Reliable Mine Water Technology, Golden, Colorado, pp. 341-347, 2013.

I. Moodley, C. M. Sheridan, U. Kappelmeyer, A. Akcil, "Environmentally sustainable acid mine drainage remediation: Research developments with a focus on waste/ by-products," Minerals Engineering, Issue. 126, pp. 207–220, 2018.

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

JAIMA Japan Analytical Instruments Manufacturers Association: Principle and application of wavelength dispersive X-ray fluorescence spectrometer, (https: //www.jaima.or.jp/jp/ analytical/basic/xray/wds/).

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

R. K. Tiwary, "Environmental Impact of Coal Mining on Water Regime and Its Management," Water, Air, and Soil Pollution, Vol. 132, pp.185-199, 2001.

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.

S. Win, M. M. Myint, "Mineral Potential of Myanmar," Resource Geology, Vol. 48, Issue.3, pp. 209-218, 1998.

T. M. Htun, Y. M. Swe, C. C. Aye, "Arsenic and Metal Contamination in Stream Sediments and Waters of Kyaukpahto Mine Area, Kawlin Township, Sagaing Division," Dagon University Research Journal 2013, Vol. 5, pp. 137-142, 2013.

T. S. Win, H. Shimada, A. Hamanaka, T. Sasaoka, S. Wahyudi, M. M. Tun, "Preliminary Study on Acid-Generating Waste Rocks in the Open-pit Backfilling of Monywa Copper deposit, Myanmar," In the Proceedings of 2017 International Symposium on Earth Science, Japan, pp. 351-356, 2017.

Yanagase Kenjiro: Removal of arsenic in geothermal water by iron (III) hydroxide co-precipitation method, J-STAGE Analytical Chemistry, Vol. 32, No. 11, p.T111-T116, 1983.

Y. M. Swe, C. C. Aye, K. Zaw, “Gold Deposits of Myanmar,” Myanmar: Geology, Resources, and Tectonics, Geological Society, London, Memors, Vol. 48, pp. 557-572, 2017.

Y. M. Swe, I. Lee, T. Htay, M. Aung, “Gold Mineralization at the Kyaukpahto Mine Area, Northern Myanmar,” Resource Geology, Vol. 54, Issue. 2, pp. 197–204, 2004.

Z. W. Than, “Environmental Management Report for Kyaukpahto gold mine,” unpublish; 2015.

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