



Prevention of Acid Mine Drainage (AMD) by Using Sulfur-Bearing Rocks for a Cover Layer in a Dry Cover System in View of the Form of Sulfur

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Abstract

Acid Mine Drainage (AMD) is one of the environmental problems caused in mining operation. The exposure of sulfide minerals in rocks to water and oxygen in the excavation process leads to AMD. The cover system has been constructed to prevent AMD in many cases in Indonesia for the availability and low-cost maintenance. Waste rocks are classified into Potentially Acid Forming (PAF), which is sulfur-bearing rocks, or Non Acid Forming (NAF) based on the results of geochemical analysis in the system. PAF is covered by NAF to prevent the contact of PAF with water and oxygen for the prevention of AMD in many cases in Indonesia. However, it is difficult to construct the cover system due to the shortage of NAF when most of waste rocks are PAF materials in the field. There are additionally varieties of PAF materials due to the content of sulfur in rocks in the field: some of them are unlikely to be the source of AMD. For the reasons, sample analysis of the waste rocks obtained in coal mines in Indonesia and the leaching test were conducted in order to discuss the use of some of PAF materials for the cover layer in such a case. The results indicated that it can be possible to use some of PAF materials in which most of sulfur compounds are readily-soluble for the cover layer instead of NAF after the reduction of the potential of acid production of rocks. Meanwhile, the rocks in which most of sulfur compounds are sulfide minerals have to be preferentially backfill in the dumping site since they can contribute to AMD for a long-term. The form of sulfur in rocks, therefore, should be taken into account to select PAF to utilize for the cover layer. This new concept of the cover system in which some of PAF materials are used for the cover layer makes the construction of the cover system without a large amount of NAF possible to prevent AMD in the mine.

Keywords: open cast mining, Acid Mine Drainage (AMD), cover system, sulfur-bearing rocks

Introduction

Acid Mine Drainage (AMD), which is caused by the exposure of sulfur-bearing rocks to oxygen and water, is one of the serious problems in the mining operation. Acidic water is low-pH and contains heavy metals, leading to a negative impact on the nature (Jennings et al., 2008). AMD has increased with the expansion of coal development recently in Indonesia. Most of the developments in Indonesia are open-cast mining in which a lot of waste rocks are produced. The dumping site for them is one of the main areas where AMD occurs as shown in Figure 1. Additionally, the severe condition in a tropical climate in Indonesia promotes AMD through the contact of sulfur-bearing rocks to oxygen and water.

There are several ways for the prevention of AMD and they are generally classified into 2 types: treatment to main source or that to acidic water (Johnson and Hallberg, 2005). In the former case, sulfur-bearing rock which is the source of AMD is treated to prevent AMD. In the latter case, treatment is conducted to acidic water such as limestone or chemical addition to reduce the impacts on the nature.

The former case is, generally, useful for long-term treatment of AMD due to the low-cost and the maintenance is not required; therefore, the cover system like in the former case is widely used for the prevention of AMD in Indonesia as described in Figure 2. In this method, waste rocks are classified into Potentially Acid Forming (PAF) and Non Acid Forming (NAF) based on the geochemical properties of them. PAF, which is a sulfur-bearing rock, is covered with NAF or topsoil in order to prevent the exposure of PAF to oxygen and water for the prevention of AMD. Thereby, the cover layer is required to prevent the intrusion of oxygen and water into the dumping site or to reduce oxygen concentration in the layer.

The Net Acid Generating (NAG) test and the Acid Base Accounting (ABA) analysis are utilized for the classification in many cases in Indonesia. The potential of acid generation of rocks is evaluated based on the change of water quality when rocks are dissolved by forced oxidation with hydrogen peroxide (Sobek et al., 1978). The potential of acid generation of rocks is also evaluated by calculating the total sulfur content and the buf-



Fig. 1. AMD in coal mines in Indonesia
Rys. 1. AMD w kopalniach węgla w Indonezji

fer action of carbonate minerals in ABA analysis in addition to the paste pH test in which the capacity is evaluated based on the change of water quality after dissolving rock sample in deionized water. The classified rocks based on the geochemical properties are backfilled in the dumping site by following the cover system for the prevention of AMD in many cases in Indonesia; however, it is difficult to construct the system when most of waste rocks consist of PAF on site. An alternative material to NAF is required for the construction of the cover layer in the situation due to the shortage of NAF. Moreover, the potential of acid production of rocks varies according to the types of rocks even though they are classified into PAF in the same way: it depends on the amount of the content of sulfur and carbonate minerals (Chotpantarar, 2011). Though, they are backfilled in dumping site as PAF in the current operation even if the potential of acid production of rocks is low. These PAF materials are likely to be utilized for the cover layer in the cover system owing to the low-potential. For these reasons, this study focused on the utilization of some of PAF materials which are sulfur-bearing rocks for the cover layer. This idea contributes to the solution of the difficulties of the construction of the cover system in the situation due to the shortage of NAF.

In this research, the new model of the cover system which can be established when most of the waste rocks are PAF materials was discussed through the sample analysis and the leaching test, aiming at the utilization of PAF for the cover layer.

Methods

The rocks were sampled from the inner part of the exposed layer in the pit in the coal mine

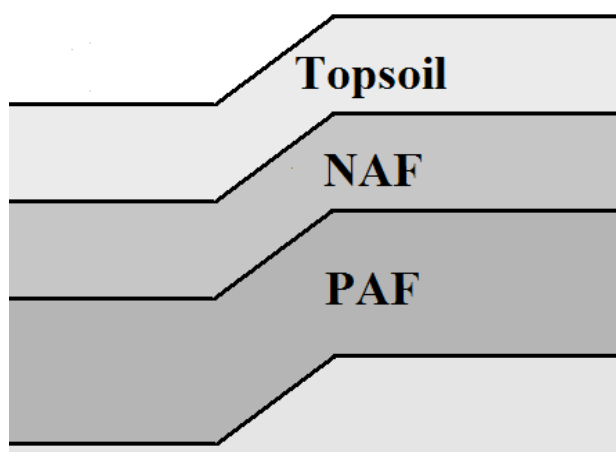


Fig. 2. Concept of the cover system
Rys. 2. Koncepcja system nakładu

in Indonesia. They were named as sample A, B, C, and D in this study. X-Ray Diffraction (XRD) analysis was conducted to identify the minerals in the samples, followed by NAG test, ABA analysis, and paste pH test to evaluate the potential of acid production of the samples. Moreover, sulfur in the samples was extracted with acids and the results were compared with the results of ABA analysis and the paste pH test in order to discuss the effect of the form of sulfur to AMD. Finally, the change of the water quality from the samples was discussed through the leaching test.

Geochemical Analysis

The potential of acid production in rocks is evaluated based on the change of pH after dissolving rock sample with hydrogen peroxide in NAG test (Sobek et al., 1978). The pH after the process of forced oxidation with hydrogen peroxide is reported as NAG pH, indicating the maximum potential of acid production of rocks. In ABA analysis, Net Acid Producing Potential (NAPP) is reported as the potential of acid production of rocks. NAPP is calculated based on Acid Potential (AP) and Acid Neutralizing Capacity (ANC): AP is based on the total sulfur content in rocks and ANC is calculated based on the titer of sodium hydroxide for neutralizing the solution of rock sample (AMIRA P387A, 2002). Rocks which have high NAPP generally can lead to low-pH condition.

In paste pH test, less than 75 μm of rock sample is dissolved in deionized water at a solid to water ratio of 1:2 (w/w), and then the change of pH is reported after 12–16 hours to evaluate the potential of acid production. This test was conducted followed by the standard of the ARD test handbook in this study (AMIRA P387A, 2002).

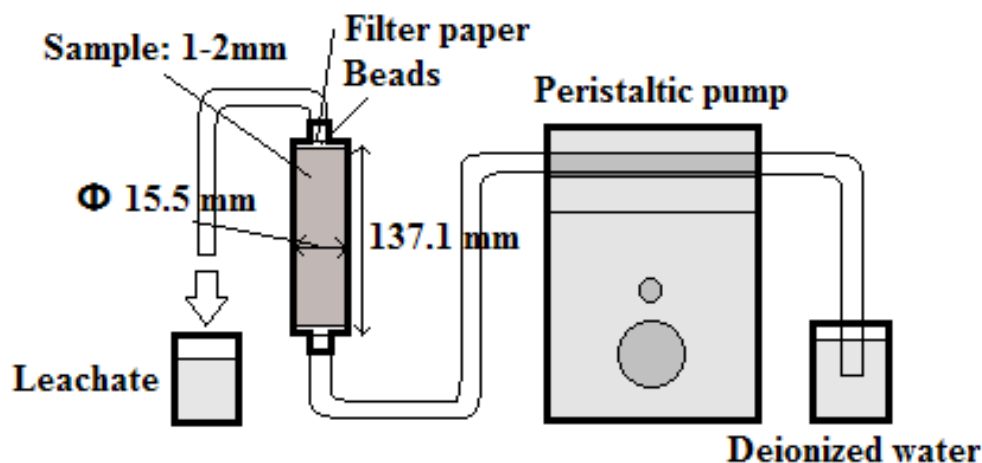


Fig. 3. Schematic view of the leaching test
Rys. 3. Schemat testu ługowania

The extraction of sulfur with acids is to elucidate the form of sulfur in rocks by extracting minerals at each step. Hydrogen chloride, hydrogen fluoride, and nitric acid were used at the 3 steps of the extraction by reference to the method proposed in 1990 (Huerta-Diaz and Morse, 1990). In this study, the titer of nitric acid was 20 mL and the time of the agitation was set in 5 hours to extract sulfide minerals completely since the content of sulfide minerals was likely to be high in the samples on the basis of the results of XRD and ABA analysis. The time was decided on the basis of the end of the generation of the gas in the chemical reaction of sulfide minerals and nitric acid. In this method, readily-soluble elements such as sulfate and precipitation are extracted at the step with hydrogen chloride and silicate minerals are extracted at the step with hydrogen fluoride. Refractory materials like sulfide minerals are extracted at the step with nitric acid (Sasaki et al., 2002). Thus, the form of sulfur which is considered as sulfur content for the evaluation of the potential of acid production can be discussed on the basis of the results, aiming at the discussion of the effects of the form of sulfur to AMD.

Leaching Test

The schematic view of the leaching test is described in Figure 3. 1–2 mm of grained rock samples were set in the column. Deionized water was pumped into the column with the peristaltic pump MP-2000 and pH in leachate was measured in each cycle in the leaching test: the length of the column was 137.1 mm and the inner diameter was 15.5 mm. The volume of supplied water was decided on the basis of annual rainfall in Indonesia, assuming that waste rocks are exposed to rainfall

after the backfill. 50 mL of deionized water was pumped into the column in each step at 0.1 mL/s of flow rate. The total volume of pumped water in this study was equal to the rainfall in 2 years in Indonesia. Glass beads and filter paper were, additionally, set at the bottom and top of the column to prevent the outflow of the samples.

The porosity was set in about 56% in order to set the surface area of the samples at the same rate in each column. Each process of pumping water was performed every 24 hours. This cycle was repeated until 20 times and the change of pH was measured with pH meter (TOADK) HM-21P in each cycle.

Results and Discussion *Geochemical Properties*

The result of XRD analysis is shown in Table 1 and it shows the content of each mineral in each sample. Pyrite was observed in sample B, C, and D except for samples A, indicating that sample B, C, and D can cause AMD. Other sulfide minerals such as galena and sphalerite were, moreover, observed in sample B and C. It suggested that these samples may cause strong acidic water in comparison with sample A and D. Table 2 is the summary of the results of NAG test, ABA analysis, and paste pH test. NAPP was high and paste pH was low in sample B and C in comparison with the others, suggesting that these samples can lead to strong acidic water more than the others due to the high potential of acid generation (Chotpantararat, 2011). This result was compatible with the prediction in XRD analysis. Moreover, sample A showed positive value of NAPP and acidic conditions: paste pH was 3.10. Although the peaks of sulfide minerals were not observed clearly in sample A in XRD

Tab. 1. Results of XRD analysis

Tab. 1. Wyniki analizy XRD

Sample	NAG pH	S (%)	AP	ANC	NAPP (kg H ₂ SO ₄ /t)	Paste pH
A	2.80	0.90	27.4	0.0	27.4	3.10
B	1.04	12.55	383.9	0.0	383.9	1.21
C	1.08	25.46	779.1	2.5	776.6	1.24
D	1.47	4.99	152.8	0.0	152.8	1.74

Tab. 2. Results of NAG test, ABA analysis, and Paste pH test

Tab. 2. Wyniki testów NGA, ABA, pH

Sample	Quartz	Pyrite	Galena	Sphalerite	Kaolinite	Albite	Biotite
A	O				O		
B	O	O	O	O	O	O	O
C	O	O	O				
D	O	O			O		

Tab. 3. Ratio of sulfur extracted at the step with hydrogen chloride and nitric acid on the assumption that the amount of sulfur extracted at the step with hydrogen chloride is 1.00

Tab. 3. Stosunek ilości siarki wylugowanej chlorowodem i kwasem azotowym przy założeniu, że ilość siarki wyekstrahowanej HCl wynosi 1

Acid for extraction	Sample			
	A	B	C	D
HCl	1.00	1.00	1.00	1.00
HNO ₃	0.03	9.23	26.25	0.11

analysis, sample A can lead to AMD for the results (Chotpantararat, 2011).

In mining operation in Indonesia, waste rocks are classified into PAF and NAF based on NAG pH and NAPP value in many cases (AMIRA P387A, 2002). Figure 4 shows the classification of the samples in this study. All of the samples were classified into PAF in the classification; however, NAPP was varied in each sample. This suggests that the potential of acid production is varied even if the rocks are likewise classified into PAF. Thus, the difference of the potential of acid production of waste rocks should be taken into account for the classification of PAF even if they are classified into same category.

Table 3 shows the summary of the ratio of extracted sulfur at the step with hydrogen chloride and nitric acid on the assumption that the amount of sulfur extracted at the step with hydrogen chloride is 1.00. Figure 5 shows the amount of sulfur extracted at the step with hydrogen chloride and nitric acid. Paste pH was also plotted on the figure for comparison of the amount of sulfur and the potential of acid production. It would appear that the samples were classified in two types: samples in which the content of sulfur extracted at step with hydrogen chloride was high and samples in which that extracted at the step with nitric acid was high. Sulfur which is extracted at the step with hydro-

gen chloride is readily-soluble such as sulfate and precipitate, and they affect the change of water quality in paste pH test since they can be dissolved in liquid in a short time. This was the reason that the amount of sulfur extracted at the step with hydrogen chloride was in the same values in sample B and C, and it resulted in the same value of paste pH in Figure 5. Meanwhile, sulfur which is extracted at the step with nitric acid is a refractory material like sulfide mineral, and they affect the change water quality for a long term (Sasaki et al., 2002). For the reason, sample B and C in which most of sulfur compounds consist of sulfide minerals can be the source of AMD for a long term in the field. These rocks must be preferentially back-filled in dumping site in order to prevent AMD.

On the other hand, most of the sulfurs in sample A and D were extracted at the step with hydrogen chloride, indicating that they were readily-soluble materials which dissolve in liquid in a short time.

The high value of NAPP implied that the potential of acid production was high in sample D in Table 2; however, it can be expected that the potential in sample D decreases in a short time after the progress of AMD in terms of the form of sulfur. In short, the potential of acid production can decrease in sample A and D in which most of sulfur compounds consist of a readily-soluble material after the progress of AMD, and they can

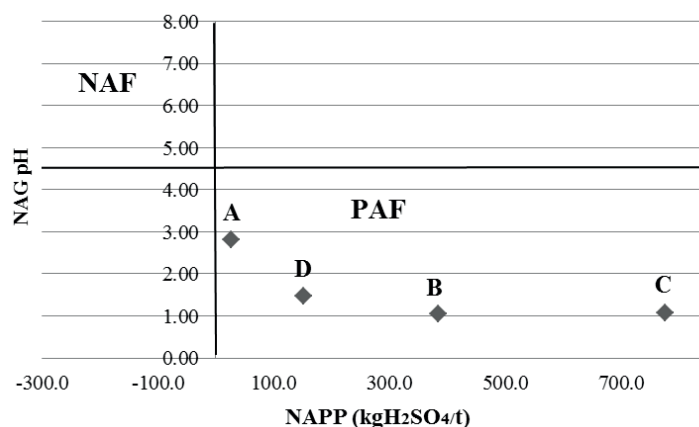


Fig. 4. Classification of the rock samples

Rys. 4. Klasyfikacja próbek skał

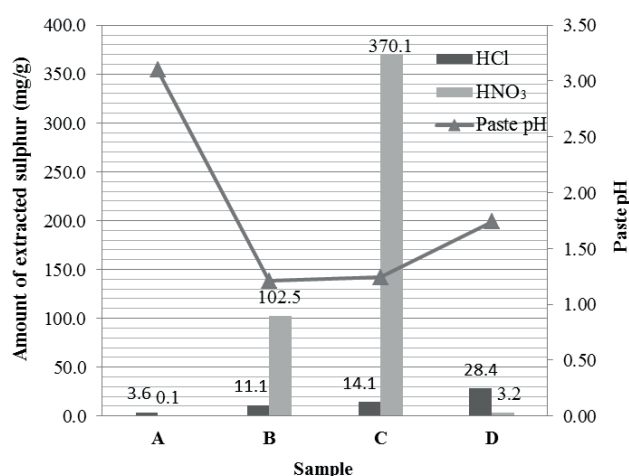


Fig. 5. Comparison of sulfur extracted at the step with hydrogen chloride and nitric acid and paste pH

Rys. 5. Porównanie ilości siarki wylugowanej za pomocą HCl i HNO₃

be not the source of AMD after the period. These rocks are possibly used for the cover layer in cover system after the decrease of the potential.

Change of Water Quality

The changes of pH and electric conductivity (EC) in the leaching test are shown in Figure 6.

The change can be classified into two types: pH slightly increased after 10 times of the cycle in sample A and D, and pH kept a steady at low-pH after that in sample B and C. Moreover, EC in sample A and D was lower than that in sample B and C after 10 times of the cycle. It can be seen for the results that the potential of acid production in sample A and D decreased in terms of the increase of pH and change of EC at low-level. According to the change and the result of the extraction with acids, the rocks in which sulfurs consist mainly of sulfate such as sample A and D decreased the potential of acid production after generating AMD for a while. Briefly, the form of sulfur in rocks

has to be considered for the selection of materials for the cover layer in cover system regardless of NAPP, which indicates the potential of acid production of rocks.

Additionally, the supply of oxygen into the column was limited due to the small diameter of the inflow and outflow head of the columns in the leaching test: oxygen concentration in the columns was less than 8.7 mg/L. It would appear that AMD is promoted and the decrease of the potential of acid production in rocks is accelerated under the condition that much of the oxygen is supplied into the columns (Bourgeot et al., 2011). The pH in sample A and D is supposed to increase to around 7.0 under the condition with the decrease of the potential in rocks.

For these results, it is important to consider the form of sulfur in rocks in order to construct the cover system for the prevention of AMD: waste rocks such as sample A and D should be utilized for the cover layer after the decrease of the po-

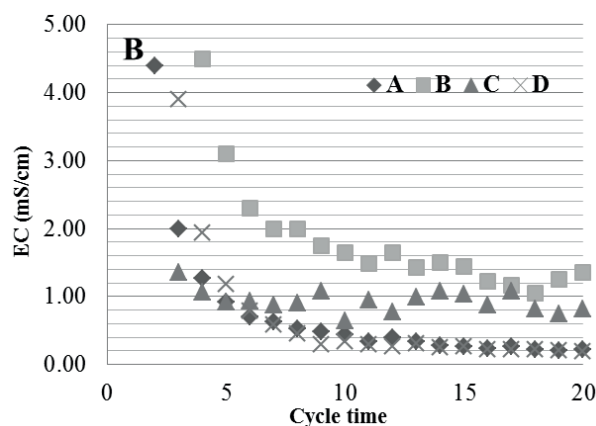
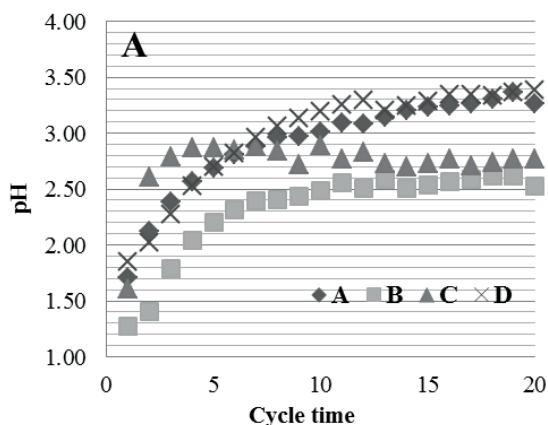


Fig. 6. The change of pH and EC in leachate: A is the change of pH; B is the change of EC

Rys. 6. Zmiana pH i EC w odciekach; A – zmiana pH; B – zmiana EC

tential of acid production, and waste rocks such as sample B and C which contribute to AMD for a long term have to be preferentially backfilled. The utilization of some of PAF materials for the cover layer enables the construction of the cover system without enough NAF materials. However, the ideal condition for the process of decreasing the potential of acid production of rocks and the baseline of the potential to utilize PAF for the cover layer should be discussed for introducing this system to the site.

Conclusions

The results are summarized below:

i) The rocks in which most of sulfur compounds are sulfide minerals have to be preferentially backfill in the dumping site since they can contribute to AMD for a long-term.

ii) The potential of acid production in the rocks in which most of sulfur compounds are readily-soluble can be decreased after the progress of

AMD. These rocks are possibly used for the cover layer in the cover system in order to prevent AMD.

iii) The form of sulfur in rocks should be taken into account for the selection of the materials which are utilized for the cover layer.

These results suggested that AMD can be prevented by utilizing sulfur-bearing rocks in which most of sulfur compounds are readily-soluble for the cover layer as the new cover system after decreasing the potential of acid production regardless of the amount of NAF. Though, the ideal condition for the process of decreasing the potential of acid production of rocks and the baseline of the potential to utilize PAF for the cover layer should be discussed for introducing this system to the site.

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Zapobieganie Kwaśnemu Drenażowi z Kopalń (AMD) – za pomocą skał zawierających siarkę jako warstwy izolującej przy systemie suchej izolacji w zależności postaci siarki

Kwaśny drenaż kopalniany (ang. skrót AMD) stanowi jeden z problemów ekologicznych spowodowanych działalnością kopalń. Kontakt minerałów siarczkowych zawartych w skałach z wodą i tlenem, zachodzący podczas prac wydobywczych, prowadzi do wytwarzania AMD. Metoda izolacji przez przykrycie, jako sposób na zapobieganie AMD, została opracowana w Indonezji ze względu na dostępność i niski koszt utrzymania. Skały odpadowe klasyfikuje się na podstawie wyników analizy geochemicznej i dzieli na Potencjalnie Wytwarzające Kwas (ang. skrót PAF), do których zalicza się skały zawierające siarkę, oraz na Niewytwarzające Kwasu (ang. skrót NAF). Skały PAF zakrywa się skałami NAF, aby uniemożliwić kontakt skał PAF z wodą i tlenem. Jest to częsta metoda zapobiegania wytwarzania AMD stosowana w Indonezji. Jednakże, ciężko jest skonstruować system pokrywający ze względu na niedobór skał NAF, jako że większość skał odpadowych należy do PAF. Dodatkowo, istnieje podział PAF ze względu na zawartość siarki w dostępnych skałach: niektóre z nich nie mają tendencji do wytwarzania AMD. Z tych powodów, przeprowadzono analizę próbek skał odpadowych otrzymanych w kopalniach węgla w Indonezji oraz zbadano wpływ ługowania, aby omówić możliwość użycia niektórych rodzajów PAF jako warstwy ochronnej.

Wyniki wykazały, że jest możliwe użycie niektórych materiałów PAF, w których związki siarki są łatwo rozpuszczalne oraz po redukcji jako warstwy pokrywającej zamiast NAF. Jednocześnie, skały w których większość związków siarki to minerały siarczkowe, muszą być preferencyjnie pokryte zasypką w miejscu składowania, jako że w dłuższym okresie mogą przyczynić się do powstawania AMD. Zatem, przy wyborze PAF jako warstwy zabezpieczającej, postać siarki zawartej w skale powinna być brana pod uwagę. Nowe podejście do systemu izolowania, zakładające użycie PAF jako warstwy ochronnej do zapobiegania produkcji AMD w kopalniach, umożliwia jego budowę bez dużej ilości NAF.

Słowa kluczowe: kopalnie odkrywkowe, Kwaśny Drenaż Kopalniany (AMD), system izolacji, skały zawierające siarkę