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Interrelation Hydrogeology and Geochemistry of Acid Mine Drainage in Groundwater: Mitigation Approach of Mine Water Management

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Abstract. Acid mine drainage (AMD) has been recognized as one of the major threats to the environment and water quality in mining. The main purpose of this paper is to provide an understanding of the principles of geochemistry of AMD analysis and hydrogeology characteristic as well as both interrelations in groundwater. To reduce the source of water quality problems caused by AMD, mitigation approach of geochemistry of AMD and hydrogeology study need to be developed earlier before mining phase resumed. Geochemistry analysis consisting analysis waste and ore rock for static test in laboratory or kinetic test in the field. Geochemistry study conducted to determine two possibilities of AMD forming named Potential Acid Forming (PAF) or Non Acid Forming (NAF). Hydrogeology mitigation can be performed through study of hydrogeology characteristic including core logging, RQD measurement, aquifer testing and determination of conductivity, storativity, transmisivity as well as groundwater flow rate. Rock fracture is media transportation of groundwater which conveying groundwater to down gradient area then emerge to surface as surface water. Therefore, it is important to perform groundwater and surface water monitoring as measure of tracking AMD in groundwater. The interrelation between hydrogeology and geochemistry AMD in groundwater becomes important for the mitigation of potential AMD forming and its management.

Keywords: *acid mine drainage, hydrogeology mitigation, fracture, groundwater conductivity, mine water management.*

1. Introduction

Acid mine drainage has been recognized as one of the major threats to the environment and water quality in mining. Acid mine drainage or commonly known as Acid Mine Drainage (AMD) is produced from the oxidation process of sulfide minerals, especially pyrite or iron disulfide (FeS_2). Acid formation occurs due to the exposure of sulfide minerals to the atmosphere (air and water) which is usually indicated by a decrease in the pH of the water. Mineral exposure can occur naturally or due to human activities such as rock excavation in construction and mining activities. Low pH generally increases the solubility of many elements or species of concern to the environment (for example, Cu, Zn, Ni and Pb) although it does not rule out the increase in the solubility of certain metals at neutral pH. Oxidation of sulfide minerals that produce AMD can spread into water bodies or rivers and infiltrate into the soil and be carried away by groundwater flows.

Groundwater flows generally follow or are in line with the topography in accordance with the respective groundwater aquifer boundaries. Groundwater flows also travel through fractures or faults and appear at a lower gradient as springs. AMD that is leached or infiltrated into groundwater can spread along the groundwater flow, causing a negative impact on the environment, AMD emerges to the surface. The spread of AMD in groundwater depends on the type of aquifer and the rate of groundwater transportation. In aquifer types that pass water and groundwater flow rates are high; the risk of AMD spreading through groundwater will be even greater.

For this reason, it is important to take a mitigation approach ofr AMD geochemistry and hydrogeology as well as an interrelation of both as an effort to control AMD's destructive force through mine water management (MWM).

2. Method

In looking for the relationship between acid mine drainage and hydrogeology, a systematic approach related to geochemistry and hydrogelogical mitigation needs to be developed. There are two approaches or methodologies used for this study, namely a study of rock geochemistry and an assessment of local hydrogeological characteristics.

Not all mineral rock mines will produce AMD, for that geochemistry mitigation is needed to describe the rock in the mining area that will be exploited as potentially forming acid (PAF) or not. Several geochemistry tests can be carried out to make PAF rock modeling, where the modeling will assist in the development of mining designs and material handling plans for PAF or AMD.

This geochemistry study begins with the characterization of rocks that will be disturbed in the laboratory through static tests to gain an understanding of the potential sources and mechanisms of AMD formation. In addition to laboratory-scale static tests, studies can be continued with kinetic tests, namely field experiments by leaching various types of rock samples according to their natural conditions. The results of the kinetic test are usually closer to the original conditions, but this can be an option, because the time span required by the kinetic test is longer than the static test. At the exploration stage, testing like this is crucial in terms of time and funding, so that laboratory tests can usually be considered representative.

The second approach is to carry out hydrogeological modeling covering hydrogeological characteristics based on a physical framework such as aquifer type, groundwater level, aquifer boundaries, hydrological boundaries and also groundwater quality. To complete the physical framework, it is also important to carry out aquifer testing to determine the hydraulic conductivity and prediction of groundwater flow rates.

Thus the results of both mitigations will lead to interrelation and potential impacts arising from AMD. After knowing the correlation between the two, it is necessary to have appropriate handling to overcome the emergence of AMD which has the potential to pollute the environment. Details of the two methods are described in the following sections.

2.1.Abbreviations and Acronyms

One method that is widely used to predict the potential for acid mine drainage from material or rock is Acid Base Accounting (ABA). AMD in mining environments occurs when the opening and exposure of rock causes increased mineral solubility resulting in insufficient acidity and acid-neutralizing agents in abundance and / or reacting too slowly to neutralize the acidity that is formed. Several different mineral phases can contribute to the formation and neutralization of the acidity generated by the surface of a material that is newly exposed to atmospheric conditions. AMD formation rates depend on various parameters, some of which can be determined through geochemical testing.

For geochemistry static tests, a series of tests can be carried out as part of the ABA approach in an attempt to gain an understanding of the potential sources and mechanisms of AMD generation from different types of materials or rocks.

In conducting a geochemistry study, sample selection is an important stage and must consider all stages of the project. Selection of test samples needs to consider the geological conditions, spatial distribution and mineral composition of the rock.

Samples were collected and carried out the acid base accounting (ABA) test which consisted of the following tests: paste pH, acid neutralization capacity (ANC), analysis of total sulfur and chromium-reducible Sulfur (CRS) content, carbon content and net acid generation (NAG) tests. To get an indication of the relationship between elemental content and metal leaching behavior as well as metal mobility characteristics, a sample of four acid digestions can also be analyzed to determine the elements contained in rock in the solid phase and water extract / metal leaching (AMIRA 2002).

2.2.Symbol and units, numbers

Hydrogeological studies include hydrogeological characteristics which are a combination of geological and hydrological interpretations that are built based on input from the physical and hydrological frameworks (groundwater boundaries). The input physical framework consists of aquifer type, aquifer characteristics, and aquifer boundaries. Meanwhile, the input of the hydrological framework consists of hydrological boundary conditions, initial water level, and groundwater quality boundary conditions.

In addition to local hydrogeological characteristics, several aquifer tests need to be carried out to determine the conditions for hydraulic conductivity or permeability, storativity and transmissivity. There are several aquifer tests that can be carried out at each research location depending on the conditions and each difficulties such as the step test, constant rate test, falling head test / slug in test and raising head test / slug out test. One method that is easy to do in locations with difficult conditions is the slug test on monitoring wells. The hydraulic conductivity is calculated using the Hvorslev Method following the equation below:

$$K = \frac{r^2 \ ln\left(\frac{Le}{R}\right)}{2LeTo} \tag{1}$$

Where, r is the radius of the well casing, Le is the length of the well screen, R is the radius of the well screen and To is the time related to H / Ho = 0.37.

The weak zones such as fractures, discontinuities or dykes are areas of groundwater movement through which groundwater is also stored. Fractures and discontinuities can be identified in AMD drilling from core logging and calculating the fracture. The fracture can be identified from Rock Quality Designation (RQD), which is one of the rock strength parameters. RQD is obtained by adding the length between the cracks (> 10 cm) divided by the total length of the core drill bit from each run. Where if the RQD with a range of 0-25% is said to be very bad and 25-50% is said to be bad. The fracture intensity can be determined from the calculation of the RQD.

$$RQD = \frac{\sum length\ of\ each\ core > 10\ cm}{Total\ length\ of\ core}\ x\ 100\ \% \tag{2}$$

The groundwater flow rate needs to be known in order to calculate the rate of groundwater release to the surface, so that in areas contaminated with AMD, the groundwater flow can be known. Calculations using Darcy's law, where the flow rate (q) covering the aquifer area is:

$$q\ =\ KIA \tag{3}$$

Where, K is the average hydraulic conductivity across the thickness of the aquifer, I is the hydraulic gradient, and A is the cross-sectional area (Drisscol, 1987 in Hamlin, Alpers, 1995). However, seasonal changes usually change the hydraulic gradient so that it affects the discharge of groundwater (Hamlin & Alpers, 1995).

3. Results and Discussion

The mining process for mineral or coal rocks includes several stages, starting from land clearing and grabbing, top soil stripping, excavating of overburden to rock excavation. During mining and mineral excavation, the exposed rock mass intensely increases the surface opening area, resulting in a consequent increase in the rate of acid production.

Land clearing and rock excavation are intended to support mining operations. For this reason, several mining support facilities are needed, such as waste rock dumps, settling ponds, tailing dams and other supporting facilities. Some of the common sources of AMD in mining areas can come from these facilities including other sources as presented in Table 1.

Table 1. Source of Acid Mine Drainage (Sangita et al., 2010)

Primary Source	Secondary Source
Mine rock dump	Treatment Sludge pounds
Tailings impoundment	Rock cuts
Underground and open pit mine working	Concentrate load out
Pumped/nature discharge ground water	Stockpiles
Diffuse seeps from replaced overburden in rehabilitated areas	Concentrate spills along roads
Construction rock used in roads, dams, etc	Emergency ponds

AMD is a process caused by contact sulfide minerals with water and air. Although sulfide minerals such as pyrite are minor elements in some mineral and coal deposits, during the normal weathering process of these mineral deposits, acidity can be generated even at a slow rate, so that the natural process of neutralization can eliminate this acidity (McCarthy, 2011).

General characteristics of AMD include low pH and high metal concentrations such as iron, aluminum and sulfate concentrations (Todd, 1980, in Hamlin and Alpers, 1995). Some of the sulfide minerals that give rise to AMD are presented in Table 2.

Table 2. Sulphides responsible for acid generation (Sangita et al., 2010)

Sulphide	Formula
Pyrite	FeS_2
Pyrrhotitirotite	Fe_xS_x
Chalcocite	Cu_2S
Covelite	CuS
Chacopyrite	$CuFeS_2$
Arsenopyrite	$FeAsS_2$
Molibdenite	MoS_2
Galena	PbS
Millerite	NiS
Sphalerite	ZnS

AMD volume may still be quite large at the end of the mine period and may still continue even after mining operations have closed. For this reason, AMD management and environmental monitoring programs need to be implemented during operation and post-mining.

3.1.Acid Mine Drainage Mitigation

The data obtained from geochemistry testing is used for the interpretation of possibility samples in order to produce acidity. Based on the test results, an environmental classification scheme is then proposed to gain a deeper understanding of the geochemistry and characteristics of the material to be mined.

The pH value of the paste in a static test provides an understanding of the amount of ready-to-react acidity neutralization available in a sample indicating whether a sample is actively producing acidity prior to sampling or not. The pH value of individual pastes is not a predictor of the potential acidity (or neutralization) of a sample; however, the pH of the paste can be used as the main indicator to determine the direct buffering capacity contained in a sample being tested.

The capacity for acid formation is estimated from the sulfur content in a sample. Sulfur is present in rocks in three main forms: a) sulfides, b) sulfates, and c) organic-S. Chromium Reducible Sulfur (CRS) which provides an indication of oxidizable sulfide species or speciation that may form acids under atmospheric conditions.

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An estimate of the potential acidification of a sample can be made from the total sulfur content in the rock sample. Given that the problem of acidic waters at the mine site is usually the result of the oxidation of sulfide minerals, measuring the total sulfur content is not always an accurate way of predicting the acid potential generated by rock samples. The estimate of the total acid potential, as estimated using the total sulfur in the sample, assumes that all sulfur content is measured in the form of pyrite and will be completely oxidized to form sulfate and iron hydroxide [$Fe(OH)_3$].

In weathered rocks containing acid-forming minerals such as pyrite, AMD will only form if an insufficient amount of acid-neutralizing alkalinity is produced. The acid-neutralizing capacity of decaying material depends on the mineral content which dissolves in response to acid build-up and acts as a buffer for acidity. Carbonate minerals (such as calcite / dolomite) are by far the most important minerals as neutralizing agents because of their relatively high solubility and are generally contained in mine rock. Certain minerals such as silicates or aluminosilicates can also contribute to neutralizing capacities, particularly in geological environments where carbonate minerals are not abundant, but they have slower solubility kinetics than carbonate minerals and may only act as an acidity buffer when acid formation is low. The likelihood and time for a mined rock material to form acidity depends on its relative abundance, reactivity and the distribution of the phases that produce and neutralize the acidity. Static testing makes it possible to make a direct comparison between the maximum potential total acidity (MPA) and the acid neutralization capacity (ANC) present in each sample, however, the timing of AMD formation is generally represented by kinetic testing.

The potential for acid formation in the sample is estimated by a comparison of two approaches, the NAG (Net Acid Generation) and NAPP (Net Acid Production Potential) tests. Based on this assessment, generally there are three groups or classes identified, namely: NAF (Non Acid Forming - does not form acids), PAF (Potential Acid Forming - has the potential to form acids), and Uncertain. PAF and NAF materials are expected to produce distinctly different chemical characteristics in the waters in the environment when mined and exposed to atmospheric conditions, the uncertain group sample requires further investigation to assess whether the sample produces acid or not, one of which is by kinetic testing.

Kinetic testing is carried out to mimic or simulate the oxidation process that occurs in the field under controlled environmental conditions. From this kinetic test, it is also hoped that a picture of the quality of the drainage formed due to exposure to the material, the process that occurs, and confirmation of the results of the characterization of the static test and the formation time of acid mine drainage is also expected. Kinetic testing can be carried out on a laboratory scale or on a larger scale in the field. All the methods described above support one each other in estimating the potential for AMD at a mine site.

Based on the information from the static and kinetic tests, it can be used as input in the development of environmental model blocks to estimate the volume and distribution of materials that potentially need attention in the environment. A mine site with a significant amount of rock with a PAF class must ensure prevention and treatment of AMD in its technical and environmental studies, covering all stages of mining from operation to mine closure.

3.2. Hydrogeologi Mitigation

Geological data and mine hydrology play an important role in hydrogeological mitigation, including water quality. These data include the physical framework, namely aquifer types, aquifer characteristics, and aquifer boundaries. Meanwhile, the input of the hydrological framework consists of hydrological boundary conditions, initial water level, and groundwater quality boundary conditions. Some of the other important parameters are the physical frame, internal inflow or outflow and the aquifer environment. All of these data build a conceptual hydrogeological model of the study area which will provide an overview of the condition of the local groundwater system.

To be able to determine the existence of a hydrogeological correlation or interrelation with AMD, apart from developing a conceptual model, a hydrogeological well drilling program needs to be carried out. This drilling program will provide actual data related to rock strength, rock weak zones, local aquifer systems, hydraulic conductivity until groundwater flow rates, Rock type to groundwater can be estimated based on rock type and geological structure in the study area. Rock types and structures in the study area are known from the description of the results of drilling (core logging). Based on the description of the drilling results, it can be seen the possible relationship between geological conditions and the occurrence of water-bearing rocks. Meanwhile, to find out more about the condition of groundwater and its lithological composition, information is needed on the results of drilling and wells construction (Muchamad et al., 2017).

The condition of the geological structure in the mining area can be evaluated based on RQD data from exploration wells. RQD reflects the condition of rock discontinuity in the rock core sample. RQD values range from 0-100%, the greater the RQD value the smaller the effect of the discontinuity or the more massive the rock.

Fractures and discontinuities are among the most important geological structures. Most rocks have fractures and discontinuities that facilitate the storage and movement of groundwater through them. On the other hand, some discontinuities, for example, fractures and dykes can also act as barriers to water flow (Singhal and Gupta, 2010).

In general, aquifers, which are pore media and fracture zones, are unconfined aquifer systems. Such systems are usually interconnected with different lithologies, so there is the possibility of hydraulic connectivity between groundwater and various geological formations and related water chemistry. The free aquifer system in mining is characterized by its permeability heterogeneity and also the chemistry of groundwater which of course depends on the geological formation.

The permeability value has a strong negative correlation with the RQD value, in other words, a lower RQD has a greater hydraulic conductivity. This suggests that the fracture zone or pore media in the rock acts as an aquifer and the extent of the fracture controls the permeability of the rock in the region.

The occurrence and movement of groundwater depends on the hydrogeological characteristics of subsurface formations. These natural formations vary widely in terms of lithology, texture, and structure that affect their hydrological characteristics (Singhal and Gupta, 2010). AMD contaminated groundwater will move towards the discharge area according to the groundwater flow pattern in the area. Groundwater flow discharge conditions will be influenced by the season where the hydraulic gradient of groundwater fluctuates with changing seasons.

The presence of dissolved metal elements in groundwater can be used as an indicator of the interrelation between AMD and / or metal leaching and hydrogeology, where AMD can be transported via groundwater. Groundwater moves through cracks or pore media following the local groundwater flow pattern. The presence of AMD in groundwater can be due to the metal leaching process or AMD infiltration from surface water or from infiltration of overburden or mine hole walls (see Figure 1). AMD transportation in groundwater is influenced by local geological conditions including fracture zones, pore media areas, hydraulic gradients and mining topography, groundwater flow patterns and flow transport rates.

Fig. 1. Acid Mine Drainage Seep

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Plume from contaminated water is usually delineated by low pH, stable isotopes of oxygen and hydrogen, dissolved sulfates, and dissolved metals. Low pH values are associated with high concentrations of sulfates and dissolved metals in groundwater. Areas with a low pH are also usually associated with the presence of isotopics in high isotopes (δD and δ18O). The presence of isotopic is usually the result of evaporation of settling ponds and then infiltration into groundwater (Hamlin, Alpers, 1995). The distribution of contaminated groundwater plume is influenced by the flow rate of groundwater. Groundwater appears on the surface in weak areas such as fractures or cut topography in the form of springs. Seepage areas or springs such as these are suitable locations for monitoring groundwater quality.

3.3. Mine Water Management

AMD that appears to the surface as springs or in monitoring wells will certainly have an environmental impact in that location. For this reason, it is important to apply AMD handling from mining areas and overburden in the form of mine water management as well as processing or handling of potentially acidic materials (PAF).

Considering that surface water and groundwater are the transportation media for AMD above and below the surface, the AMD movement can be controlled by controlling the flow of water through the management of mining material rock and mine water. Mining material handling can be done by engineering the design of mining facilities such as pits and ore stockpiles in such a way as to minimize contact between acid-forming rocks and water and oxygen. Mine water management includes diverting runoff water away from disturbed areas, preventing groundwater infiltration, preventing hydrological water infiltration into disturbed areas and good handling of AMD generation (Akcil and Kodas 2006 in Sangita et al., 2010).

AMD treatment is divided into two types, namely active and passive treatment. Active treatment is the addition of chemicals to AMD sources and AMD contaminated water streams, to increase pH and precipitate metals (neutralization). Some of the chemicals commonly used for active treatment are calcium carbonate, hydrated lime, caustic soda (sodium hydroxide), soda ash (sodium carbonate), and in some cases ammonia (NH_3). Several other active handling methods are used together with neutralization and other methods such as ion exchange, reverse osmosis, electrodialysis, and electrolytic recovery, but they are usually expensive so they are rarely used (Prasad et al., 1999 in Sangita et al., 2010).

Another treatment is passive treatment, this method uses chemical and biological reactions that occur naturally to then reduce the concentration of metals and neutralize acidity. This treatment requires a large area of land but cheaper in terms of chemical use and maintenance (Hadin et al., 1993 in Sangita et al., 2010). Some passive treatment methods to mitigate AMD (Champagne et al., 2005; Ziemkiewicz et al., 2005 in Sangita et al., 2010) include: aerobic wetland, anaerobic wetland, open channel limestone, anoxic limestone drains (ALD), and a successful alkalinity producing system. (SAPS).

If AMD has been formed, the AMD formation process will continue until the acid-forming agent has been oxidized and in some cases until mining operations are completed. For this reason, AMD prevention efforts need to be carried out by managing mine water and mining materials, this strategy can be used during operations and mine closure, including:

- Encapsulation of potentially acid generating (PAF) material in waste rock dump.
- Mixing PAF material with neutralizing material such as NAF material or lime.
- Separation of natural runoff water from around the mine with water from inside the mine.
- Establishment of a channel for diverting runoff water from natural areas away from disturbed areas such as waste rock dumps, mine pits and tailings dams.
- Manage tailings properly, keeping the tailings slurry below the water level and saturated.
- Create an underdrain system that can be used to keep groundwater in contact with PAF material.

In addition, the environmental monitoring program in the form of monitoring the quality of groundwater in the area under the waste rock dumps, mine pits and tailings dams, is one of the tools to assess how well the AMD treatment program has been implemented.

4. Conclusion

AMD geochemistry and hydrogeological investigations should be carried out long before the mining operation stage is carried out, namely the exploration stage. Geochemistry investigations, both on a laboratory scale (static test) and original conditions (kinetic test), will produce rock models that have the potential to generate acidic water (PAF). Meanwhile, hydrogeological mitigation will provide an overview of local hydrogeological characteristics or conceptual hydrogeological models. Both studies will provide a comprehensive description or modeling of the relationship between AMD and groundwater, when oxidation of sulfide materials occurs.

AMD often appears during the operational stage, where the PAF rock material is exposed to the air. The presence of dissolved metal elements in groundwater can be used as an indication of the interrelation between AAT and groundwater. Dissolved metal elements, such as iron and sulfate, which are transported through groundwater, are indicative of a positive correlation in groundwater from the oxidation of pyrite or other sulfide materials. Groundwater transports AMD through fractures or pore media following the local groundwater flow pattern. In addition, the presence of AMD in groundwater can be due to the metal leaching process or the infiltration of AMD from surface water or from infiltration of waste rock dump or mine drain walls.

If this happens, efforts to deal with AMD are required. Handling of AMD can be done in two ways, namely active treatment such as ion exchange, reverse osmosis, electrodialysis, and electrolytic recovery, and passive treatments such as aerobic wetlands, anaerobic wetlands, open channels of limestone, anoxic limestone drains (ALD), and successive alkalinity producing systems (SAPS).

Other AMD control measures are mine water management (MWM), for example the encapsulation of PAF material, separation of water from disturbed areas and construction of diversion channels, handling of tailings and underdrain installations. This strategy can be used during operations and mine closure.

In order to ensure the effectiveness of the mine water management program, it is necessary to develop an environmental monitoring program in the form of monitoring water quality, both groundwater and surface water. Groundwater quality monitoring is carried out in areas under waste rock dumps, mine pits and tailing dams, while surface water in rivers or water flows originates from disturbed areas or mines.

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