Waste Rock Kinetic Testing Program: Assessment of the Scale Up Factor for Sulphate and Metal Release Rates

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Abstract

Kinetic testing involving laboratory columns (2 and 35 kgs), meso-scale panel (1 tonne), meso-scale field test pads (500 t) and full-scale trial dumps (100 kt) were conducted over a 10 year period at Grasberg Mine in Indonesia to investigate the kinetic of waste rock at the different experiment scale. Leachates were regularly analyzed for pH, acidity, sulphate and metal concentrations and loads. Volumes of seepage and oxygen concentrations in a full scale trial dump were also monitored.

The waste rock was acid generating with the average sulphur grade ranging from about 2 to 5%S. The carbonate minerals content was relatively low and there was only a short lag before onset of acid conditions. Pyrite and chalcopyrite were the primary identified sulphide minerals.

The characteristics of the kinetic of waste rock weathering at the different experimental scales were relatively showing consistent pattern, but not quantitatively equivalent. Based on the sulphate loading rates during the first four years of the trial dump operation, the scale up factor ranged from 11 to 58% of the oxidation rate from smaller scale experiments. Results also suggested that the infiltration, oxygen transfer, and grain size of waste rock could have a major role in determining the scale up factor between the full-scale trial dump and the small to meso-scale tests

Key Words: acid rock drainage, ARD, leach column, test pad

Introduction

Weathering of waste rock may produce acid rock drainage (ARD) at mine sites. Acid generation in a waste rock pile is the result of complex interactions between physical, geochemical, and biological processes. Physical processes include the flow of water, oxygen and heat within the waste rock profile. The geochemical processes involve the oxidation of sulphide minerals, the solution/dissolution process, and the buffering reactions from the carbonate/silicate minerals. Heat that is generated as a result of sulphide mineral oxidation often strongly affects the flow of oxygen in the waste rock dump (Ritchie, 2003; Lefebvre *et al*. 2001). In addition, the specific microorganisms present in the dump have critical roles in accelerating the oxidation rate of the sulphide minerals (Evangelou 1995).

Many studies have been established to understand the long-term leaching behavior of waste rock, most of them were carried out using small-scale kinetic cells, such as humidity cells (for example Sapsford *et al*. 2008; Hakkou *et al*. 2008; Hollings *et al*. 2001; Botz and Mason 1990; Fernandes *et al*. 1998) and free drainage leach columns (Miller et al. 2003; Stromberg and Banwart 1999; Eriksson *et al*. 1997). Various testing methods for a humidity cell (ASTM D5744-96, 2000) and also for the free drainage leach column (IWRI and EGI 2003) have been developed and documented over the past few decades. While the results of the small-scale kinetic tests are useful for providing information as to whether or not the leachate from the waste rock will become acidic, the results do not always represent the oxidation rate from a large-scale waste rock pile. These studies are not able to take into account, for example, the hydrological and physical processes within the waste rock piles that interact with the geochemical process that ultimately generate the acid drainage. In addition, the environmental conditions of the test such as temperatures, climates are different.

The different scale of the kinetic testing on the waste rock samples was conducted for the waste rock from the Grasberg Mine, Indonesia as a part of the ARD mitigation program. This paper summarizes the leaching rates measured from the different types of experiment on the scale up program.

Experimental Design

The kinetic testing program consisted of leach columns, meso-scale panels, test pads and a trial dump (Figure 1) with detail as follows

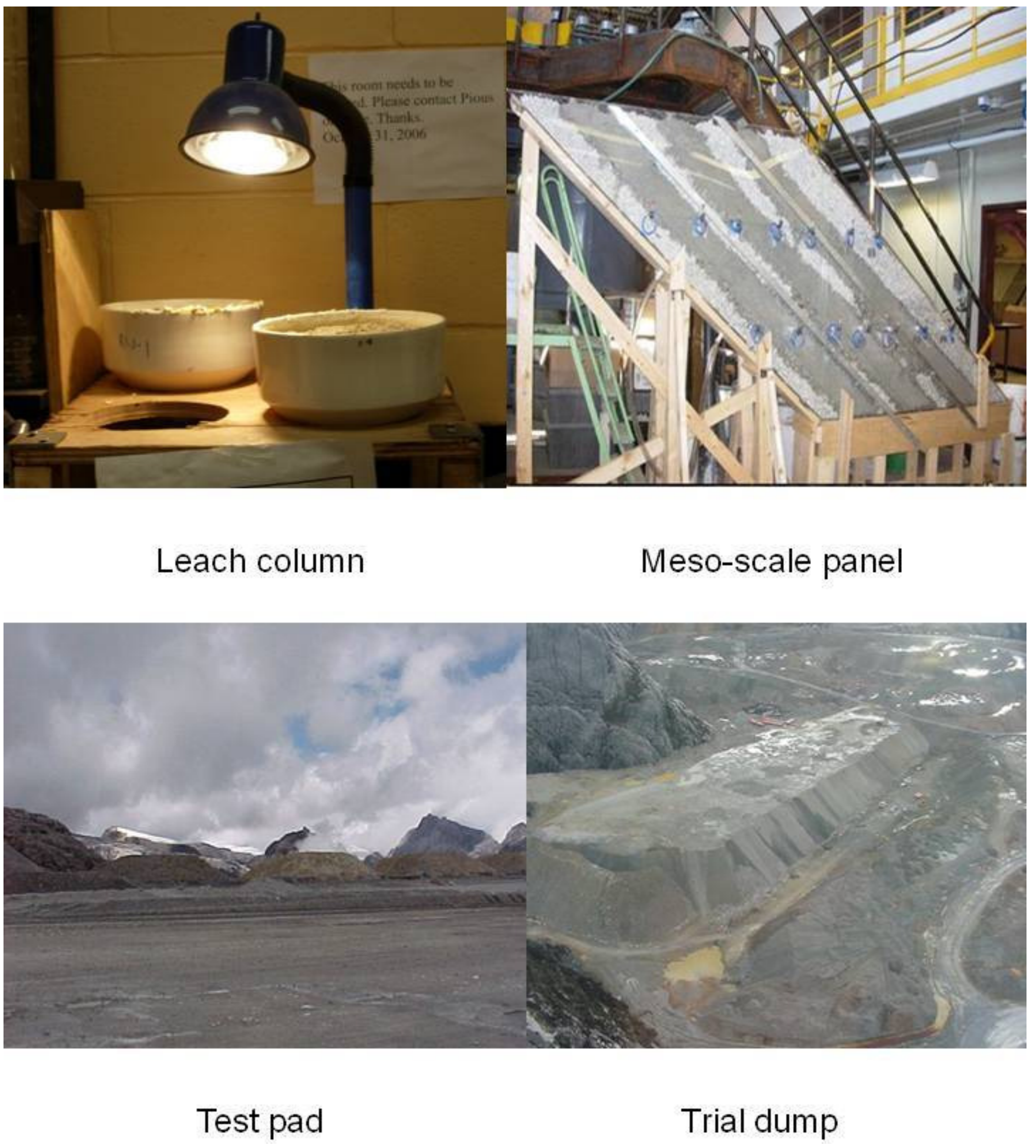

Figure 1 Kinetic testing program

Leach column

A small bench scale kinetic test was set up to gather information on the leaching behavior of the waste rock. The test was set up according to the methods developed by IWRI and EGI (2003). Approximately 2 kg of waste rock passing the 4.75 mm sieve was placed in a large funnel. The column was irrigated once a week with a rate of 100 ml/kg of deionized water for the first three weeks of each four week cycle and then flushed with 400 ml/kg of deionised water at the end of the cycle. In addition, a large column that could accommodate approximately 35 kgs of materials was set up for the waste rock samples with larger particle sizes. The columns were irrigated twice per week at a rate of 300 ml/kg for each four week cycle. Further detail on the column set up was described on Miller et al. (2003).

The cumulative leachates from the small and large columns were collected every four weeks. The collected leachate was analyzed for pH, electrical conductivity (EC), acidity, and sulphate. Some of the leach columns were operated for almost a decade.

Meso-scale panels

A meso-scale panel with 1,750 mm long, 1,500 mm high, and 250 mm wide was constructed using 10 mm-thick acrylic sheets. Approximately 1 tonne of waste rock materials was uploaded into the panel. The panel was assembled with the fine and coarse acid waste rock layers adjacent to each other. The layers were approximately 250 mm thick and at an angle of 37^{o} (i.e. angle of repose) representing the majority of current practice for constructing waste rock piles at mine sites worldwide.

A rainfall simulator was designed to provide a range of uniform and constant fluxes (i.e. rainfall intensity) to every layer. Drainage points were installed at the bottom of the layers and along the bottom boundary of the slope to collect the leachate.

A series of infiltration tests with irrigation rates ranging from 2 mm/day to 10 mm/day were performed to the panel. Leachate volumes were monitored daily and the leachate was collected at the end of the infiltration testing from each layer. The leachate was analyzed for pH, sulphate, alkalinity, and acidity. A sub-sample of leachate was also sent to a commercial laboratory for additional testing to determine the concentration of major cations, major anions, and dissolved metals. The meso-scale panels had been operated for around a year.

Test pad

Eight test pad was constructed at the Grasberg mine in 1996 where the site experiences precipitation throughout the year with the annual rainfall ranging between 3,000 mm and 5,000 mm. The size of test pad was 10m X10m X 3m. Approximately 500 tonne rock material was accommodated in the test pad. A lysimeter was installed underneath the test pad. Collection tanks with a capacity of 1 m3 were placed below the pad to collect the leachate. The outlet pipe form the tank was connected to a tipping bucket to monitor the leachate volume. Leachate samples were collected from the outflow pipe on a monthly basis for analysis of general parameters, major anion and cation, and metals.

Trial dump

The large scale field experiment termed 'trial dump' was constructed at Grasberg Mine in 1999. The trial dump was 480 m long, 80 m wide and 20 m thick consisting of 8 panels (or sections). Each panel was then divided into three sections, each to accommodate selected types of waste rock. High Potential Acid Forming (High PAF) waste rock was placed on the rear sections of panels 1 to 6, while the rear section of panels 7 and 8 had Low Potential Acid Forming (Low PAF) waste rock. Alternatively, the middle of panels 1 through 6 and the middle panels of 7 and 8 had Low PAF waste rock and High PAF waste rock, respectively. Approximately 50,000 tonnes of waste materials were placed in each section.

A 10 m x 10 m lysimeter was installed at the base of each section to collect the seepage giving a total of 24 (i.e. 8 panels X 3 lysimeters) leachate sampling points. A 50-mm drain hole was installed at the lowest (northeast) corner of the lysimeter and a 50-mm-internal diameter (ID) pipe connected the drain of each lysimeter to a one-cubic-meter storage tank that was installed beyond the toe of the dump for leachate collections. Overflow from the storage tank was directed to the tipping bucket through a 50-mm ID pipe. The tipping bucket was equipped with a trip counter to record the number of tips over a given time period.

Monitoring program was commenced in August 2000 and it continued until May 2004 for most panels. The volume of leachate collected from each lysimeter was recorded daily with exception of Sundays and holidays. Leachates samples were collected monthly and submitted to the laboratory to analyze the constituents related to ARD such as acidity, sulphate and dissolved metals.

The trial dump was also equipped with thermistors, and oxygen probes to monitor the internal temperatures and the oxygen levels within the dump. Regular monitoring for oxygen concentrations and temperature was carried out for the duration of the trials.

Characteristic of Materials

Two different types of waste rock were involved in the experiment including the Low PAF and the High PAF with exception of the Meso Scale Panels. Only High PAF material was used in the Meso Scale Panel. The geochemical properties of the waste rock samples are described in Table 1. The average sulphur grade ranged from about 2 to 5%. The variability of sulphur contents were observed on waste rock samples collected from the trial dump. The sulphur contents in the Low PAF rock samples (n=99) ranged from 0.2% to 7.56% with mean and median values of 2% and 1.7%, respectively. The High PAF rock samples (n=62) had sulphur contents that ranged from 0.3 to 9.4% with mean value of 4.7% and median value of 5%. Pyrite and chalcopyrite were the primary identified sulphide minerals. The chalcopyrite contents in the typical Low PAF were higher compared to the High PAF. The carbonate minerals content was relatively low and there was only a short lag before onset of acid conditions. Gangue minerals in both waste rock types were quartz and various micas such as muscovite, biotite, sericite and phlogopite.

Table 1 Average Geochemistry of waste rock in the trial dump and test pad

Waste type	Parameter	Column and Test Pad (Miller *et al.* 2003)	Meso Scale Panel	Trial Dump
Low PAF	% Sulphur	2	N/A	2
	Net Acid Generation (NAG), kg H_2SO_4/ton	15	N/A	107
	Acid Neutralization Capacity (ANC), kg H_2SO_4/ton	6	N/A	20
	Copper (mg/kg)	4,500	N/A	1,620
High PAF	% Sulphur	4.6	5.3	4.8
	Net Acid Generation (NAG), kg H_2SO_4/ton	82	76	95
	Acid Neutralization Capacity (ANC), kg H_2SO_4/ton	3	31	13
	Copper (mg/kg)	7,000	84	250

The material used in the leach column had particle size less than 3 mm and a larger particle size (19 to 39 mm) for the large column. The maximum particle size of the waste rock materials in the meso-scale panel was 10 mm with the majority of the material passed through the 4.75 mm sieve. The waste rock materials placed in the test pad were screened to pass 300 mm. The trial dump was constructed using the Run Off Mine (ROM) material.

Results and Discussion

Leachate pH, temperature and oxygen concentrations in the trial dump
Since the early of the experiment, the leachate from all of the lysimeters had already turned acidic with pH ranging from 1.9 to 2.9. As the monitoring continued, the pH decreased gradually, and it reached the minimum value between six and twelve months. The pH continued at approximately the minimum value for several months, and then tended to increase gradually. When the waste rock had been exposed for three to four years, the leachate pH ranged from 2.2 to 3.8.

As a result of sulphide mineral oxidation, temperatures as high as 56^{o} C were recorded at the base of the trial dump, while higher temperatures, approximately 72^{o} C, were measured in the face of the dump. The high temperature readings continued to be recorded when the waste rock had been placed for four years, with temperatures of 40^{o} C to 50^{o} C still being measured in thermistors at various locations of the trial dump.

High oxygen concentration, as high as atmospheric value (i.e. 20%) were measured at most of the locations at the trial dump. Low oxygen concentrations (i.e. <5%) were also detected occasionally at some dump locations.

Average sulphate and copper release rates
The release rate of constituents from the kinetic testing was estimated according to the concentration and the volume of leachate, and then divided by the waste rock mass. The release rates from the trial dump were estimated by assuming that the leachate was generated only by the waste rock mass that was directly above the area of the lysimeters. These values are presented in gram/ton per day.

In general, the sulphate and copper release rate from the Low PAF waste located within the front zones of the trial dump had the highest release rate, while the release rates from the Low PAF waste rock located at the middle sections of the trial dump panels were comparable with the Low PAF waste rock located at the rear sections (L3 lysimeters) of the trial dump.

The average sulphate release rates for the Low PAF waste rock samples at the trial dump ranged from approximately 1.6 to 9.4 g/t/day (Figure 2). The average copper release rate ranging from 0.04 g/t per day to 0.95 g/t per day was reported for the trial dump (Figure 3). The maximum release rate of those constituents for the Low PAF materials (i.e. L1 lysimeter) occurred approximately nine months after placement of the waste rock material. The maximum sulphate and copper release rates from middle of panels (i.e. L2 lysimeter) occurred between eleven months and thirteen months after the waste rock placement. The average sulphate release rates were 12.4 g/t/day and 10.4 g/t/day for the Low PAF materials at the test pad and the leach column, respectively, during the four year exposure time. The Low PAG at the test pad reported the average copper release rate of 2.53 g/t/day. The Low PAF leach column had average copper release rates of 1.8 and 1.95 g/t/day.

As shown in Figure 4, the average release rates of sulphate for the High PAF waste rock were higher compared to the Low PAF waste rock that ranged from 3.8 g/t/day to 17 g/t/day. On the other hand, the copper release rates of the High PAF were lower than the copper release rates from the low PAF waste rock.

The average copper release rates from the High-PAF waste rock were reported from 0.018 g/t/day to 0.072 g/t/day (Figure 5). The average sulphate release rate from the test pad was 33.8 g/t/day and the average sulphate release rates from the leach column were 15.5 g/t/day and 33.8 g/t/day. The High PAF waste rock reported the average copper release rates of 0.45 g/t/day for the test pad and 0.3 g/t/day for the leach columns.

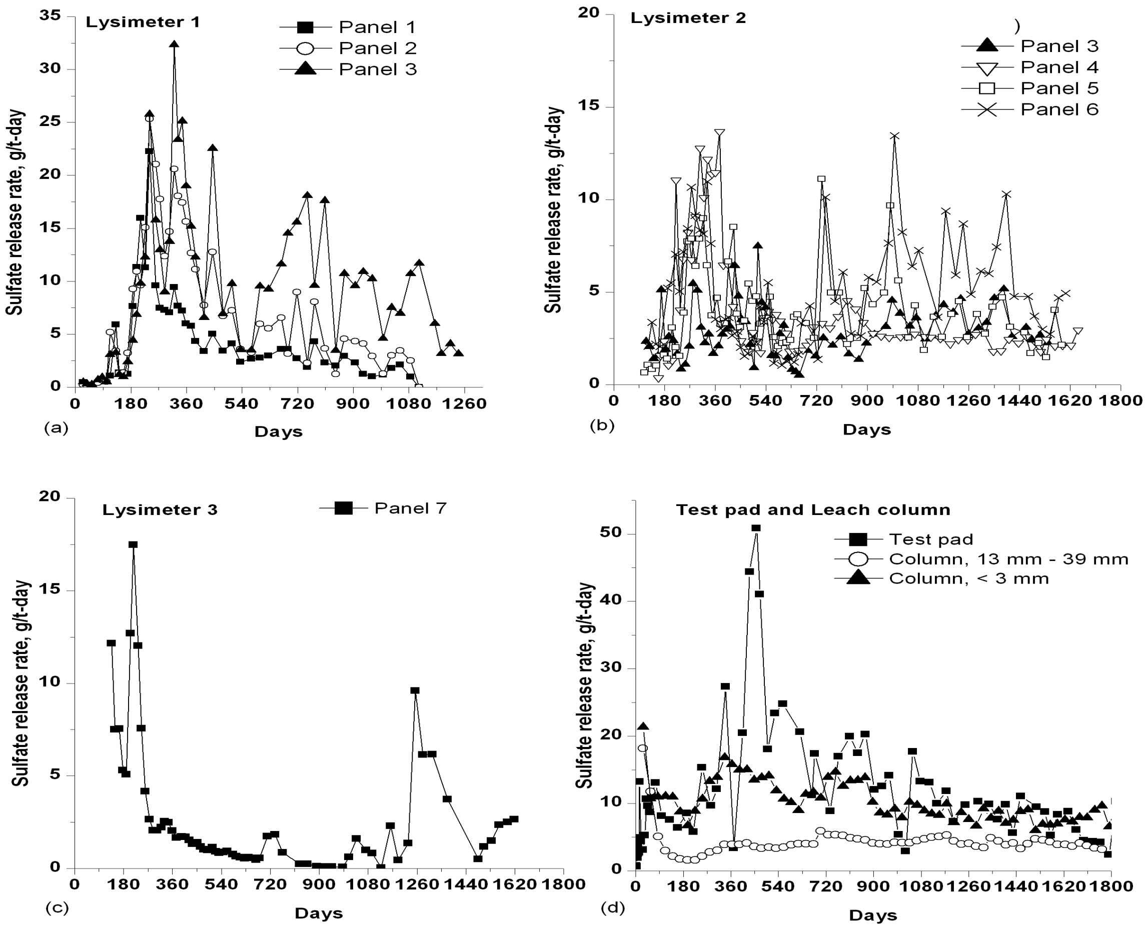

Figure 2 Sulphate release rate trends from the Low PAF waste located at (a) front sections (i.e. L1 lysimeter) of panels 1 to 3, (b) middle sections (i.e. L2 lysimeter) of panels 3 to 6, (c) rear sections (i.e. L3 lysimeter) of panel 7 in the trial dump, and (d) in the 500 tonne test pad and leach columns

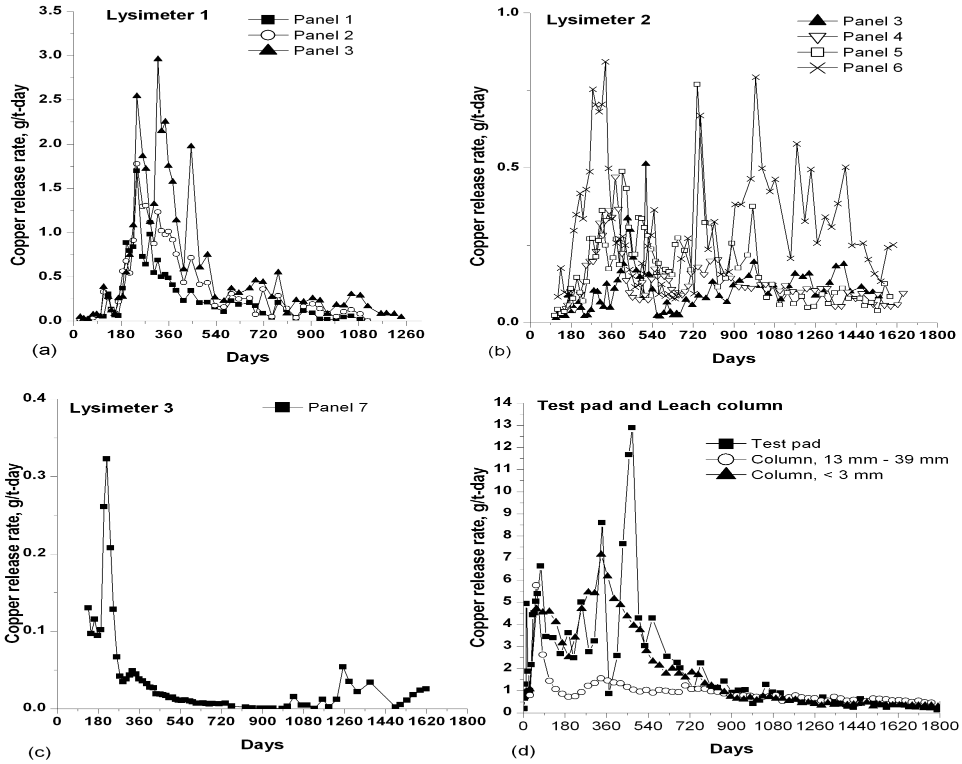

Figure 3 Copper release rate trends from the Low PAF waste located at (a) front sections (i.e. L1 lysimeter) of panels 1 to 3, (b) middle sections (i.e. L2 lysimeter) of panels 3 to 6, (c) rear sections (i.e. L3 lysimeter) of panel 7 in the trial dump, and (d) in the 500 tonne test pad and leach columns

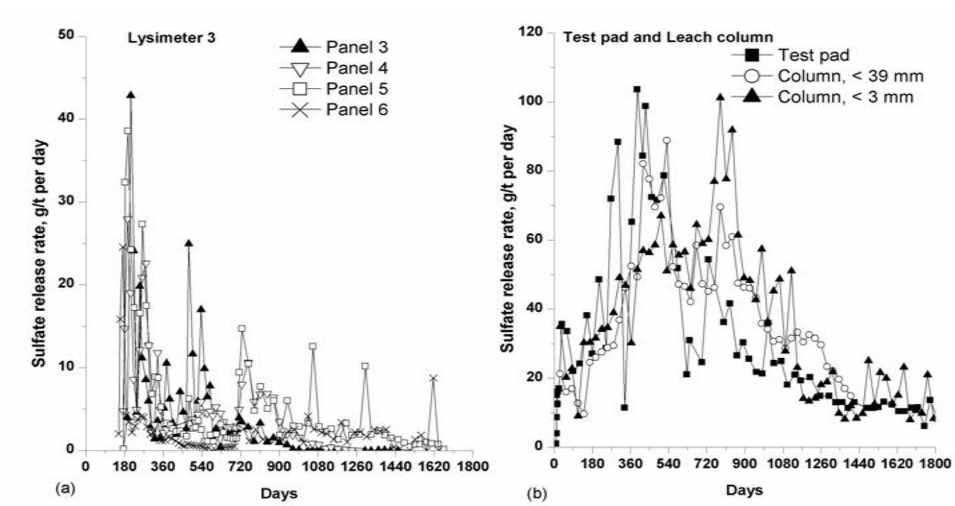

Figure 4 Sulphate release rate trends from the High PAF waste rock located (a) at rear sections (i.e. L3 lysimeter) of panels 3 to 6 on the trial dump, and (b) in the 500 tonne test pad and leach columns

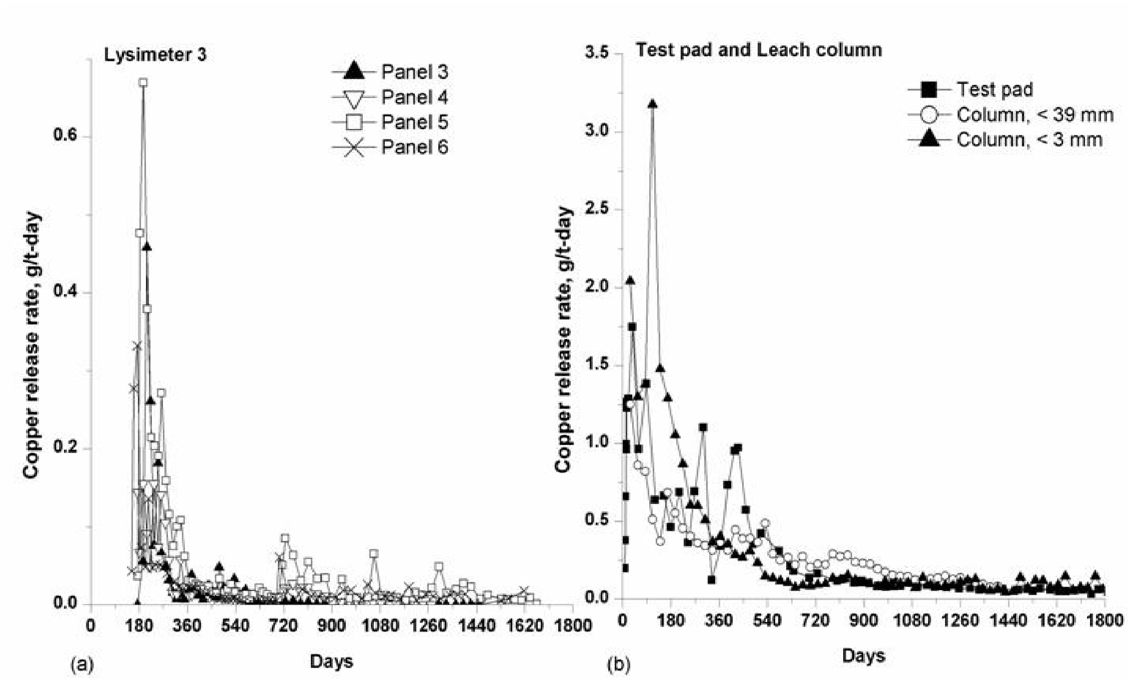

Figure 5 Copper release rate trends from the High PAF waste rock located (a) at rear sections (i.e. L3 lysimeter of panels 3 to 6 on the trial dump, and (b) in the 500 tonne test pad and leach columns

The sulphate release rates from the meso-scale panel ranged from 22.2 to 24.3 g/t/day which were slightly lower compared to sulphate release rates from the leach column and the test pad.

Scale up

The cumulative sulphate loadings produced from these different experiments were examined to understand the kinetics of the waste rock for the different scale of experiments,

The cumulative sulphate load from these experiments increased towards a maximum sulphate loading in the range between 3,500 g/t and 11,000 g/t for the Low PAF waste at the trial dump and from 18,000 g/t to 20,000 g/t for the Low PAF waste from the 500 tonne test pad and leach column during three to four years of exposure time. The cumulative sulphate loading varied between 3,000 g/t and 8,000 g/t for the High PAF waste from the trial dump during four years of exposure. On the other hand, between 50,000 g/t and 65,000 g/t of cumulative sulphate was released from the High PAF waste in the 500 tonne test pad and leach column during the four year period following placement of the waste rock.

Based on the sulphate loadings, an intrinsic oxidation rate (IOR) for waste rock within the trial dump, the 500 tonne test pad, and leach columns were estimated. The IOR is calculated based on the cumulative sulphate that was released from the waste rock over the duration of the experiment. Reaction (1) was used to calculate the IOR and oxygen consumption rates equal to 0.583 times the sulphate loadings based on the stoichiometry of reaction (Bennett et al., 2000).

Pyrite oxidation: $FeS_2 + 7/2\ O_2 + H_2O \rightarrow Fe^{+2} + 2\ SO4^{-2} + 2\ H^+$; heat = 1440 kJ/mol (1)

Table 2 summarized the IOR from the different kinetic testing. The overall oxidation rate of the Low PAF and the High PAF waste rock for the different sections of the trial dump were up to one order of magnitude lower compared to the overall IOR of the Low PAF waste in the leach column and the test pad. The IOR for small scale experiments such as humidity cells and leach columns can be referred as the oxidation rate for the waste rock material itself, while the IOR at a larger scale experiment such as the trial dump can be considered as the oxidation rate of the entire waste rock dump. The ratio between the IOR values for the small scale experiment and the oxidation rate at the large scale experiments was considered a scale up factor.

Table 2. Comparison of oxidation rates from different scale experiments

Waste type	Experiment Type	Oxidation Rate, kg O_2/kg material-second				
		Year 1	Year 2	Year 3	Year 4	Overall period
Low PAF Waste Rock	Front section of the trial dump panels (panels 1 to 3)	9.5 X 10^{-11}	7.6X10^{-11}	5.4X10^{-11}	N/A	7.5 X 10^{-11}
	Middle section of the trial dump (panels 3 to 6)	3.5 X 10^{-11}	3.7X10^{-11}	4.3X10^{-11}	3.7X10^{-11}	3.8 X 10^{-11}
	Rear section of panel (panel 7)	4.5 X10^{-11}	1.3X10^{-11}	6.5X10^{-12}	2.5X10^{-11}	2.2 X 10^{-11}
	Leach column	1.2 X 10^{-10}	1.3X10^{-10}	1.4X10^{-10}	1.4X10^{-10}	1.3 X 10^{-10}
	Test pad	1.2 X 10^{-10}	2.7X10^{-10}	1.5X10^{-10}	1.1X10^{-10}	1.6 X 10^{-10}
High PAF Waste Rock	Rear section of the trial dump (panels 3 to 6)	7.5 X 10^{-11}	5.9X10^{-11}	3.6X10^{-11}	1.3X10^{-11}	5.1 X 10^{-11}
	Leach column	3.4 X 10^{-10}	6.7X10^{-10}	6.0X10^{-10}	2.1X10^{-10}	4.7 X 10^{-10}
	Test pad	4.6 X 10^{-10}	6.5X10^{-10}	3.2X10^{-10}	1.8X10^{-10}	4.0 X 10^{-10}
	Meso-scale panel	2.6 X 10^{-10}	N/A	N/A	N/A	2.6 X 10^{-10}

The scale up factors for the release rates from the waste rock in the trial were approximately 11% to 58% of the overall oxidation rate for the waste rock materials in the test pad and leach columns. The scale up factor for the Low PAF waste located in the front and middle sections of the trial dump were approximately 24% to 58% of the overall oxidation rate for the same waste rock materials in the test pad and leach columns. The lower scale factors ranging from approximately 11% to 17% were estimated for the Low PAF and High PAF waste located in the rear sections of the trial dump.

The scale up factors ranging from 4% to 50% were obtained when the copper release rates from the trial dump were compared to the copper release rates from the leach column and the test pad.

The different oxidation rates at the different scale experiments were also reported by Stromberg and Banwart (1999), Malström *et al* . (2000), Frostad *et al*. (2005), and Wagner *et al*. (2006) who conducted the scale-up experiment from the laboratory scale to the meso-scale using large columns and also test piles that were comparable to the size of the 500 tonne test pad. Results from these researches indicated that higher oxidation rates were observed in the small scale kinetic tests such as the humidity cell compared to the meso-scale experiment. However, the results for scale up program reported here indicated that the oxidation rates for the waste rock were comparable between the leach columns and the 500 tonne test pad.

The test pad was exposed to continuously high rainfall rates which resulted in a continuous flushing of the oxidation products. Thus, the test pad acted like a large column.

An oxidation rate that is calculated according to the quantity of sulfate released can be underestimated if some of the sulfate precipitates such as gypsum and jarosite. When precipitation of these secondary minerals occurred in the pile, the actual amount of sulfate and copper released from the trial dump is probably higher than indicated by the measured concentrations. However, the relatively steady rainfall over the year at the trial dump location leads to a continuous flushing of oxidation products from the pile. Thus, the precipitation of the secondary minerals is considered to be minimal in the trial dump.

The experimental leach columns used waste rock containing particles less than 39 mm, and the waste rock used in the test pad had a maximum particle size of up to 300 mm. Although the ranges of particle size between these two experiments were different, the oxidation rates from both these tests were comparable. The range of particle size distribution for the waste rock used in the trial dump was much wider compared to the one for the test pad. Waste rock as large as 1 m in size was observed in the trial dump. Although the portion of waste rock with sizes larger than 300 mm at the trial dump was unknown, the portion of larger-size waste rock (i.e. larger than 300 mm) may have contributed to lower oxidation rates for sulphide minerals since the total exposed surface for the large particles would be greatly reduced compared to an equivalent mass of fine waste rock.

The size of trial dump, which was much larger than the 500 tonne test pad, may have influenced the oxygen transport within the panels that could possibly have reduced oxidation rates. In general relatively high oxygen concentrations measured in the different locations of the trial dump; however low oxygen concentrations were also observed occasionally in the trial dump, particularly at the rear sections of the trial dump.

The hydrological processes within the trial dump are considered to be more complicated when compared to the hydrological process in the test pad pile due to the existence of a complex structure such as coarse and fine layers that influence the leaching process and discharge of oxidation products. Based on the leachate volume collected from the lysimeter the average net infiltration in the trial dump (82%) was lower when compared to the average net infiltration in the test pad (i.e. 90%). Furthermore, the net infiltration for particular sections of the rear sections of the trial dump was lower than the average net infiltration from the entire trial dump. The highest net infiltration was recorded at the front sections of the trial dump and the lowest net infiltration occurred from the rear section of the trial dump. The rate of net infiltration can be compared with the oxidation rate for each section in the trial dump. The greatest oxidation rate was recorded for the waste rock located within the front sections of the trial dump and the lowest oxidation rate occurred in the rear of the trial dump. Thus, the oxidation rate that was calculated according to the sulphate release rate was comparable with the net infiltration rate in the panels

Conclusion

The characteristics of the waste rock kinetics in the large-scale experiment were found to be consistent, but not quantitatively equivalent with the performance observed in the smaller-scale experiment.

The release rate of these key constituents was higher in the smaller experiment than the trial dump. The oxidation rates of the waste rock from the leach columns, 500 tonne test pads, and meso-scale panels were comparable. When the waste rock was exposed for three to four years, the oxidation rate from the trial dump was lower, up to one order of magnitude, than the oxidation rate from the smaller scale experiment

The lower oxidation observed in the trial dump was considered to be due to the scale up factor which was limited by the difference in dump hydrology, particle size distribution between the full-scale trial dump and the small-scale/meso-scale experiments, and the oxygen concentration.

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