

Geochemical and Mineralogical Characterisation of Two Contrasting Waste Rock Dumps — The INAP Waste Rock Dump Characterisation Project

A B Tran¹, S Miller¹, D J Williams², P Fines³ and G W Wilson³

ABSTRACT

This paper presents the results and findings of geochemical and mineralogical testwork conducted on samples collected from waste rock dumps at two mine sites, located in South Carolina, USA (Site 1) and Sudbury Ontario, Canada (Site 2). Important aspects of the relationship between the physical and geochemical aspects of the dumps are also presented. The overall aims of the project were to

1. determine if the physical and hydrological nature of the waste-rock dumps had any impact on the geochemical and mineralogical characteristics of the dump materials; and
2. to identify key implications for dump construction for ARD control.

The results of geochemical and mineralogical tests indicate that the waste rock at Site 1 had undergone significant in-dump weathering and was relatively advanced with respect to ARD evolution. In contrast, the waste rock at Site 2 had undergone some weathering, however still contained a considerable amount of sulfide minerals. Testing also suggested that flushing of oxidation products at Site 2 had been limited, which therefore promoted the storage of oxidation products at the site. In addition, materials that had a D₅₀ particle size in the range of 5 mm to 30 mm appeared to be more readily flushed than samples that had a D₅₀ particle size of <5 mm or >30 mm. This suggested that preferential water pathways may have developed within the dumps at both sites.

INTRODUCTION

Acid rock drainage (ARD), results from the oxidation of reactive mineral sulfides contained in waste materials at a mine site. Sulfide oxidation has the potential to produce sulfate, acidity and dissolved metals, all of which can be transported away from a waste-emplacement area by hydrological processes. ARD therefore poses a significant threat to the ecosystems and environments surrounding a mine site and to the sustainability of the mining industry itself (Miller *et al.*, 1991).

This paper presents the results and findings of geochemical and mineralogical testwork conducted on samples collected from two mine sites. One site is located in a temperate/subtropical climate in South Carolina, USA (Site 1) and the other in a cold continental region near Sudbury Ontario, Canada (Site 2). Site selection was opportunistic as both mines were relocating their waste rock dumps to pits as part of their decommissioning program. This provided an excellent opportunity to sample and characterise the waste materials in the dumps.

The project was divided into two components, the first of which involved the investigation of the physical and hydrological aspects of the dumps. The second, involved the geochemical and mineralogical characterisation of samples collected from the dumps. This paper addresses the geochemical component and key physical-geochemical relationships. The overall aims of the project were to:

1. determine if the physical and hydrological nature of the waste-rock dumps had any impact on the geochemical and mineralogical characteristics of the materials contained within the dumps; and
2. to identify key implications for dump construction for ARD control.

PROJECT SITES

Site 1

Site 1 is located 150 km from the Atlantic coast and receives approximately 1200 mm of rainfall annually. In the summer, warm, humid conditions prevail, with temperatures in excess of 30°C common (Fines, 2001). The geology of the area consists of shales and siltstones with seams of quartz, volcanic intrusions and evidence of metamorphic alteration. Gold mineralisation in the area is associated with hydrothermal alteration zones.

During operation, the mine consisted of two open pits located 1.6 km apart, processing facilities and a 50 ha tailings impoundment. The mine's waste-rock dump was constructed in 6 m lifts by end-tipping techniques, to an overall height of 15 to 18 m and contained a total of approximately two million tonnes of waste rock.

As ARD had been identified at the site, in-pit disposal of the waste rock was conducted in 2000 as part of the mine-closure plan. This involved moving the nine year old waste-rock dump to two pits, which would flood overtime, creating lakes that would be connected by approximately 14.7 ha of wetlands.

Site 2

Site 2 is a nickel mine located approximately 32 km north-northwest of Sudbury, Ontario, Canada. The mean monthly temperature in the region is approximately minus 13°C in January and 19°C in July. The mean annual precipitation is approximately 860 mm and monthly precipitation ranges from a high of 103 mm in September to a low of 49 mm in February. Annual snowfall averages 248 mm calculated as a water equivalent.

The geology of the area consists of granite host rock with mineralised volcanic intrusions and a thin mantle of surficial till. The low topography and relatively impermeable nature of the region's igneous and metamorphic bed rock means that the area is poorly drained, giving rise to swamps and bogs.

The actual mine consisted of an open pit that covered an area of 9.7 ha and had an estimated volume of 3 200 000 m³. Waste rock generated throughout the mine life was placed in two waste-rock dumps. The northwest waste-rock pile consisted mainly of granitic rock, whereas the northeast dump was comprised of acid generating mafic rock.

The mine-closure plan involved relocating the two waste-rock piles into the open pit. Materials contained in the first layer of the Northeast Waste Rock Dump comprised of weathered sulfide ore which had been blasted as part of original development work at the mine site around 1910 and products from the erosion of the

1. Environmental Geochemistry International Pty Ltd, 81A College Street, Balmain NSW 2041.

2. Department of Civil Engineering, The University of Queensland, Brisbane Qld 4072.

3. Department of Mining and Mineral Process Engineering, 6350 Stores Road, Vancouver BC V6T 1Z4, Canada.

original orebody outcrop. The rest of the waste rock in the two dumps comprised of materials that were excavated between 1988 and 1998.

It is expected that up to 60 per cent of the relocated waste rock will become fully saturated as the pit floods. A cover system will also be installed to reduce oxygen entry into the underlying, unsaturated waste rock, and a non-game, wildlife habitat is the proposed land use of the mine site.

TESTING PROGRAM

The following geochemical testing program was conducted on all of the samples from both mine sites:

- pH tests on a one part sample to five parts deionised water (w/w) ratio;
- acid-base analysis (including total S analysis and acid neutralising capacity (ANC) determination by the modified Sobek procedure); and
- single-addition net acid generation (NAG) testing.

In addition, the following tests were performed on selected samples:

- acid buffering characteristic curve (ABCC) tests;
- kinetic NAG tests;
- sequential NAG tests;
- multi-element scans on solids;
- multi-element scans on water extracts;
- free draining leach column testing; and
- surface and bulk mineralogical investigations (EDTA and deionised water extractions, scanning electron microscopy, optical microscopy and x-ray diffraction).

A brief description of a few of the tests is provided below. A detailed test procedure for the ANC, single addition NAG, kinetic NAG, sequential NAG, ABCC, free draining leach column and EDTA tests can be found at Environmental Geochemistry International Pty Ltd.

pH and electrical conductivity (EC) determination

The pH and electrical conductivity (EC) of the samples were performed on a 1:5 w/w crushed sample: deionised water slurry.

Acid-base accounting (ABA)

The acid-base accounting (ABA) procedure requires the total S and ANC of a sample to be determined and is a modified version of the Sobek procedure.

The total sulfur content was analysed by the Leco high temperature combustion method and was expressed as a percentage.

The ANC was determined by first giving each sample a Fizz Rating in order to determine the amount and concentration of acid required to be used in the test. Each sample was then reacted with a known and standardised amount of acid (commonly HCl or H₂SO₄). The mixture was then heated and back titrated with NaOH to see how much acid had been consumed by the sample. The ANC is expressed in the units of kgH₂SO₄/t.

Net acid generation (NAG) test

The net acid generation (NAG) test is a laboratory procedure that measures the geochemical nature of a sample by allowing both the acid forming and acid neutralising reactions to occur together in a single flask. The test involves oxidising the sulfides in a pulverised sample of mine rock with 250 ml of 15 per cent hydrogen peroxide (H₂O₂). The sample is also heated to remove

any remaining unreacted peroxide and allowed to cool. After cooling, the pH is measured (NAGpH) before titrating the solution with a standardised NaOH solution. Titration of the solution to a pH of 4.5 accounts for acidity due to free acid such as H₂SO₄, and the release of Fe and Al, whereas titration of the solution to a pH of seven accounts for metallic ions that precipitate out as hydroxides at pHs between 4.5 and seven such as Cu and Zn.

The sequential NAG (Seq NAG) test is a variation of the NAG test. The sequential NAG test is conducted in the same manner as the single addition NAG except, after the NAG solution has been boiled, allowed to cool and the NAGpH measured, the NAG liquor is separated from the solid residue, and titrated to a pH of 4.5 and then to 7.0. The remaining solid residue is then reacted with a further 250 ml of 15 per cent H₂O₂ and the procedure is repeated until the NAGpH reaches a value of 4.5 or greater.

Another variation is the kinetic NAG (KNAG) test, where 250 ml of 15 per cent H₂O₂ is added to a pulverised sample and the pH and temperature of the NAG liquor are monitored throughout the test. Occasionally the electrical conductivity of the NAG liquor may also be monitored. The KNAG test is used to evaluate the lag period that may be experienced by a material type before acid generation begins.

Acid buffering characteristic curve (ABCC)

An alternative to the ANC procedure is the acid buffering characteristic curve (ABCC) test. This test takes longer to complete than the ANC test and involves the addition of 100 g of water to 2 g of a sample and then slow titration with acid (HCl), with continuous stirring, of the mixture to a pH of 3. The acid increments and molarity of acid used for the titrations is based on the ANC measured for each sample (see Table 1). This procedure measures the portion of the ANC, which would be readily available in the field.

TABLE 1

Suggested incremental additions and concentrations of HCl.

ANC of sample (kg H ₂ SO ₄ /t)	Concentration of HCl (molar)	Increments of HCl (ml)
≤10	0.1	0.1
20	0.1	0.2
50	0.1	0.5
100	0.5	0.2
200	0.5	0.4
500	0.5	1.0
1000	0.5	2.0

Free draining leach column testing

The small free-draining leach column test was used to assess the sulfide reactivity, metal solubility and leaching behaviour of the Site 1 and Site 2 samples. The samples were crushed to -4 mm to increase the surface area being exposed to the leaching solution, and then approximately 2.5 kg of each sample was placed in each column. The columns underwent weekly wet-dry cycles and monthly leaching cycles. Heat lamps were used to dry the column samples between solution additions and scraping of the surface of the column was conducted to prevent the development of preferential leaching pathways, which would bias the results of the test. Leachates up to week 24 were analysed for pH, electrical conductivity (EC), acidity/alkalinity, and selected elements (Al, Ca, Cd, Cl, Co, Cu, Fe, K, Mg, Mn, Na, Ni, Si, SO₄ and Zn). Leachates were analysed after week 24 for pH, electrical conductivity (EC) and acidity/alkalinity only.

EDTA test

The EDTA solution was made by dissolving 30 g of EDTA di-sodium salt in deionised water and making the solution up to 1 L. The solution was then purged with nitrogen gas for 30 minutes before the test. One gram of each sample was weighed and placed into a 125 ml plastic bottle and 100 ml of EDTA solution was added to the bottle. The mixture was then purged with nitrogen gas for 15 seconds, vigorously shaken and then purged again for 15 seconds, before being placed in a tumbler for 30 minutes. After 30 minutes, the samples were filtered (0.45 µm filter paper), acidified and then analysed for various elements.

RESULTS

Acid forming characteristics

A total of 90 samples from Site 1 and 38 samples from Site 2 were analysed. A summary of the results of pH tests, acid-base accounting, single-addition NAG tests and multi-element scans on solid and water extracts are presented in Table 2.

The existing pH of the Site 1 samples indicated that the majority were already acidic, with more than 50 per cent of the samples having a pH of less than 4.5. In contrast, the existing pH of the majority of the Site 2 samples indicated that only 8 per cent were acidic at the time that they were analysed.

The average total S of samples from Site 1 was relatively low (0.4 per cent S) and only 20 per cent of that of the Site 2 samples (two per cent S). The mean acid neutralising capacity (ANC) of the samples from Site 1 was also low at 3 kgH₂SO₄/t. This indicated that the waste rock from Site 1 had very little ability to buffer acidity, whereas the moderate ANC (20 kgH₂SO₄/t) of the Site 2 samples indicated that the samples did have some acid buffering capacity.

The mean net acid producing potential (NAPP) of both sites was positive, with the Site 1 samples having an average NAPP of 9 kgH₂SO₄/t and the Site 2 samples having a relatively high average NAPP of 44 kgH₂SO₄/t.

Single-addition net acid generation (NAG) test results confirmed that the majority of the samples from both mine sites were potentially acid forming (PAF), with 63 per cent of the Site 1 samples and 79 per cent of the Site 2 samples being PAF. The percentages of samples classified as non-acid forming (NAF) were similar at both sites, and 18 per cent of the Site 1 samples were classified as uncertain (UC) compared with only five per cent of the Site 2 samples. An uncertain classification was given to samples that had conflicting NAPP and NAG test results.

Multi-element scans on the solids of selected samples from both mine sites were conducted to identify elements, especially heavy metals and metalloids that were elevated in the waste rock. For the Site 1 samples, As, Mo and Se were indicated to be at concentrations significantly above background. Ag, Cu, Ni, S and Sc were elevated in the solids fraction of the Site 2 samples.

Multi-element scans of water extracts were also conducted to identify those elements that were water soluble and therefore potentially mobile if leached. However, scans were only conducted on those samples that had an existing pH of 4 or less. It was found that Al, Co, Mn and Ni were elevated in the water extracts of the Site 1 samples. With respect to the Site 2 samples, only one sample (TP13GS1) had an existing pH of ≤4, and Al, Co, Cu, Fe, Ni, Sr and Zn were elevated in the water extract of this sample.

The existing pH of a water extract and NAGpH can be used to provide an indication of the extent of oxidation of a sample. Figure 1 compares the existing water pH and NAGpH of potentially acid forming (PAF) samples from both sites.

Samples plotting near the NAGpH = Water pH line have most likely undergone significant in-dump weathering and are relatively advanced with respect to ARD evolution. Samples where water pH >> NAGpH are either unweathered or still within the lag phase of the ARD evolution scale. Figure 1 shows that the majority of the PAF samples from Site 1 plot near the NAGpH = Water pH line and are likely to have undergone significant weathering, and are well advanced with respect to ARD evolution. In contrast, the majority of the samples from Site 2 have an existing water pH that is above pH 5.5 and plot well to the right of the line. Site 2 samples are at an early stage of ARD evolution and still contain a considerable amount of sulfide minerals.

Column leach test results

Two free draining leach columns were set up for each of the mine sites. The acid forming characteristics of the columns are provided in Table 3.

Site 1 column results

At the time of writing, the Site 1 columns had been in operation for a period of 60 weeks. Leachates collected up until week 24 were analysed for pH, EC, acidity/alkalinity and selected elements.

Figure 2 presents the pH trend of the Column 1 and 2 materials. The pH ranged from 2.2 to 2.6 for Column 1 and remained steady at 2.4 between weeks 52 and 60.

TABLE 2

Summary of the acid forming characteristics and elemental composition of Site 1 and Site 2 waste rock samples.

Parameters	Site 1 (90 samples)	Site 2 (38 samples)
Existing pH	More than 50% (48 samples) had pH < 4.5	8% (3 samples) had pH < 4.5
Average total S	0.4%	2%
Average acid neutralising capacity (ANC)	3 kgH ₂ SO ₄ /t	20 kgH ₂ SO ₄ /t
Average net acid producing potential (NAPP)	9 kgH ₂ SO ₄ /t	44 kgH ₂ SO ₄ /t
Potentially acid forming (PAF)*	63%	79%
Non-Acid Forming (NAF) *	19%	16%
Uncertain (UC) *	18%	5%
Elements enriched in solids	As, Mo and Se	Ag, Cu, Ni, S and Sc
Elements enriched in water extracts	Al, Co, Mn, Ni	Al, Co, Cu, Fe, Ni, Sr and Zn

* Percentage of total samples.

TABLE 3
Acid forming characteristics of Site 1 and Site 2 columns.

Parameters	Site 1		Site 2	
	Column 1	Column 2	Column 3	Column 4
Total S (%)	0.64	0.06	2.02	1.12
ANC (kgH ₂ SO ₄ /t)	0	0	15	26
NAPP (kgH ₂ SO ₄ /t)	20	2	42	8
NAG _{4.5} [@] (kgH ₂ SO ₄ /t)	17.8	0.17	17.3	0.7
NAG _{7.0} [@] (kgH ₂ SO ₄ /t)	19.9	1	29.0	3.5
NAGpH	2.4	4.1	2.5	3.9
Average SRR* (mg/kg/wk)	96	8	62	26
IOR (kgO ₂ /m ³ /s) [#]	2.3 × 10 ⁻⁷	1.9 × 10 ⁻⁸	1.4 × 10 ⁻⁷	6.0 × 10 ⁻⁸
Weight (kg)	2.5	2.5	2.5	2.5

[@] NAG_{4.5} indicates that the NAG solution was titrated to a pH of 4.5. This accounts for any acidity associated with H⁺ and Al.

[@] NAG_{7.0} indicates that the NAG solution was then titrated to a pH of 7.0. This accounts for acidity released from reactions where metals such as Cu and Zn precipitate out of solution.

* SRR = Sulfate release rate.

[#] Estimated from SRR (assumed that SO₄ not precipitating or accumulating within the columns).

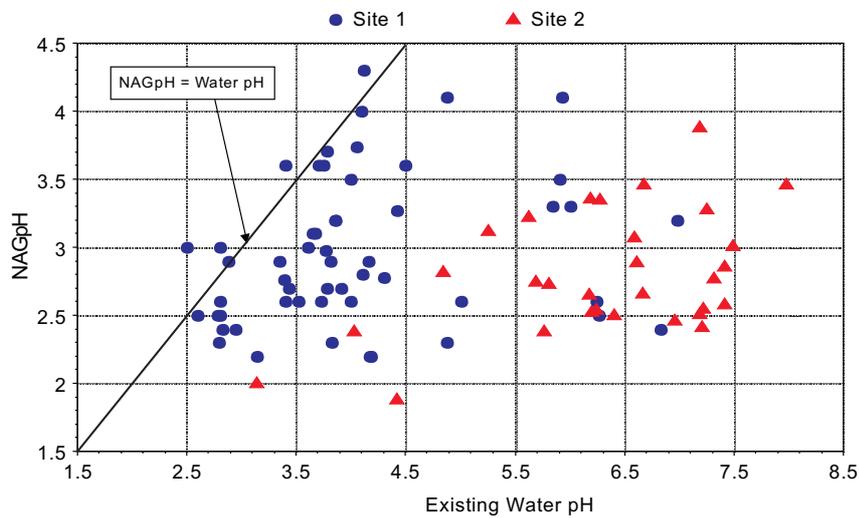


FIG 1 - Comparison between the existing pH and NAGpH of potentially acid forming samples from Site 1 and Site 2.

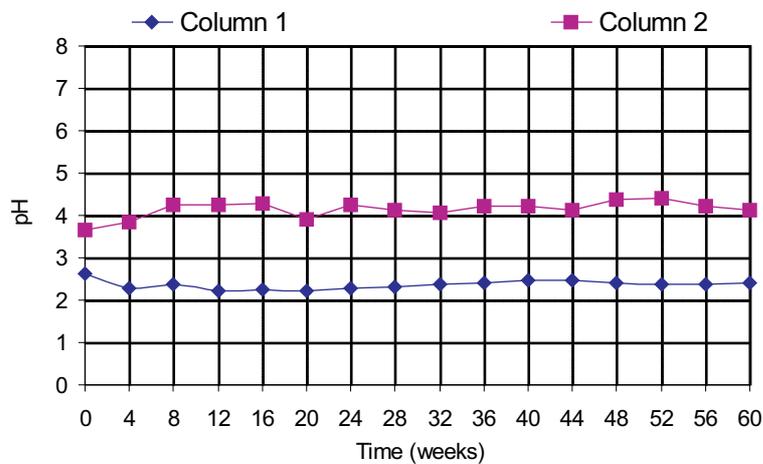


FIG 2 - pH trend of leachates collected from Column 1 and Column 2 – Site 1.

The pH of Column 2 ranged from 3.7 to 4.4 and varied between 4.1 and 4.4 from weeks 24 to 60. Figure 3 presents the cumulative acidity trends for both of the columns.

Figure 3 shows that the cumulative acidity of Column 1 is one to two orders of magnitude higher than that of Column 2. By week 60 the cumulative acid released from Column 1 was found to be 5 kgH₂SO₄/t, which was approximately 25 per cent of the predicted NAPP and NAG of the column materials.

By week 60 the equivalent of 0.18 kgH₂SO₄/t had been released from the Column 2 materials. This indicates that the column materials have released the equivalent of 11 per cent of their predicted NAPP.

The average acid release rate of the Column 1 and Column 2 materials over the 60-week testing period was about 11 g/t/day and 0.3 g/t/day, respectively.

Site 2 column results

At the time this paper was written, the Site 2 columns had been in operation for a period of 32 weeks. Like the Site 1 columns, the leachates from the Site 2 columns (Column 3 and Column 4) were tested for pH, EC, acidity/alkalinity, and selected elements for collections made in the first 24 weeks of testing. Leachates collected after week 24 did not undergo selected element scans.

Figure 4 presents the pH trends for the Site 2 columns.

The Column 3 leachates remained relatively stable between pH 3.1 and 3.4 from week 4 to week 32. The Column 4 leachates however, were initially alkaline with a pH remaining above pH 6.5 until the week 24 collection. The pH then decreased significantly to pH 4.4 by week 32. This indicates that the materials represented by the Column 4 sample have a lag period (approximately six months) whereby acid generation will be buffered by neutralising minerals contained within the waste rock.

Figure 5 presents the cumulative acidity released from the Column 3 materials.

By week 32 the cumulative acid released from Column 3 was calculated to be 0.89 kgH₂SO₄/t, which is equivalent to two per cent of the predicted NAPP of the column materials.

The Column 4 materials remained alkaline up until week 24. An ABCC test was conducted on the Column 4 sample and is presented in Figure 6. The ANC of the column materials was determined to be 26 kgH₂SO₄/t. The results of the ABCC test indicate relative strong pH buffering up to the equivalent of 10 kgH₂SO₄/t. The pH then dropped rapidly with further acid addition. This may explain why the pH of the Column 4 materials remained above 6.5 for the first 24 weeks of testing. The results indicate that the Column 4 materials have a lag period of approximately six months before acid conditions develop in the field.

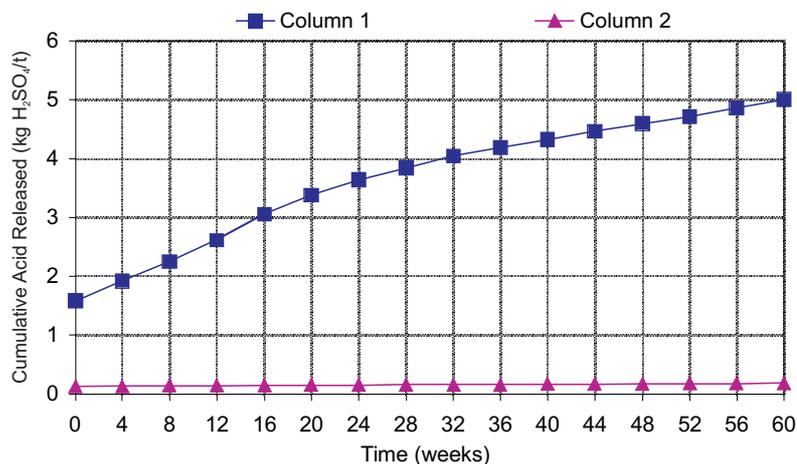


FIG 3 - Cumulative acidity trends of Columns 1 and 2 – Site 1.

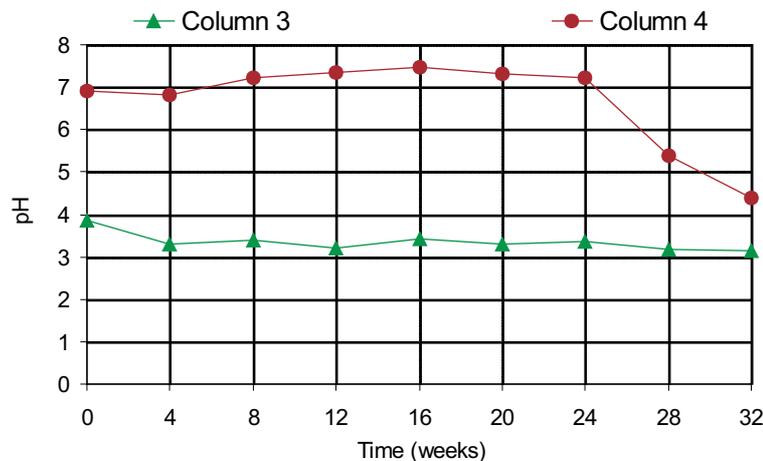


FIG 4 - pH trend of Columns 3 and 4 – Site 2.

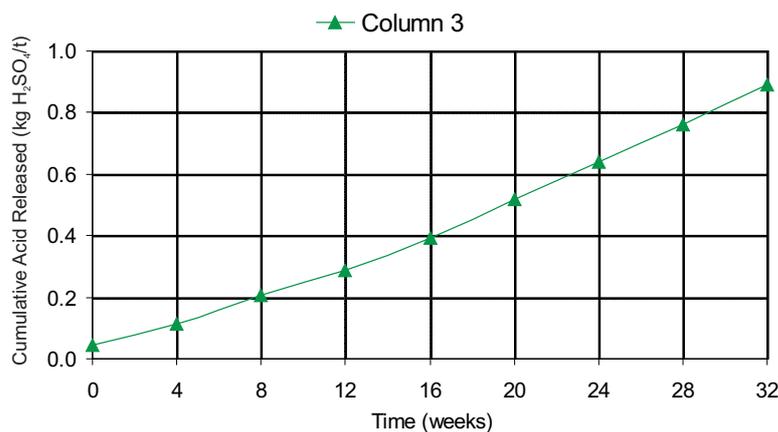


FIG 5 - Cumulative acidity of Column 3 materials – Site 2.

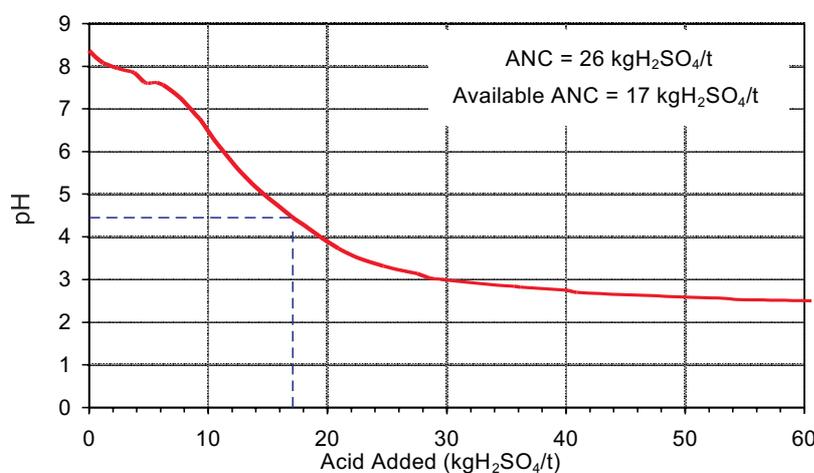


FIG 6 - ABCC plot of the Column 4 materials - Site 2.

Surface chemistry and bulk mineralogy

Surface and bulk mineralogical testing of the Site 1 and Site 2 samples included:

- optical microscopy;
- X-ray diffraction (XRD);
- scanning electron microscopy (SEM); and
- EDTA and deionised water extraction tests.

Optical microscopy, XRD and SEM testing were conducted on six Site 1 and six Site 2 samples. EDTA and deionised water extraction tests were conducted on 12 Site 1 and 20 Site 2 samples.

Optical microscopy results of the Site 1 samples revealed that three out of the six samples tested contained no visible sulfides. Pyrite and minor chalcopyrite grains were observed in the other three Site 1 samples. The Site 1 samples were also found to be predominantly comprised of clay/mica and quartz minerals, which represented more than 80 per cent by mass of the gangue minerals in the samples. Goethite/limonite were also observed in all of the samples. XRD was used to determine if secondary mineralisation had occurred. Secondary kaolinite was observed in five of the six samples analysed and significant quantities of jarosite was only detected in one of the samples. SEM testing indicated that sulfides in the Site 1 samples were reacted, with reaction pits observed on the surfaces of the pyrite grains. Iron hydroxides/oxides were only detected in one of the samples.

Optical microscopy results of the Site 2 samples indicated that all six samples that were tested contained pyrrhotite and/or minor chalcopyrite. No pyrite was detected. Limonite/goethite coatings on particle surfaces were common in five of the six samples and the samples were found to be predominantly comprised of clay/mica and quartz minerals, which made up 65 to 92 per cent by weight of the gangue minerals in the samples. XRD indicated that crystalline gypsum was present in all but one of the samples and that crystalline jarosite was present in only one sample. SEM testing found that sulfide surfaces in four of the six Site 2 samples analysed were heavily coated with relatively thick layers of iron hydroxides. The other two samples had iron hydroxide coatings on some of the sulfide surfaces, but also had exposed reacting surfaces as well.

Figure 7 compares the total EDTA-extractable cations[†] (includes cations such as Ca, Cu, Fe, Mg, Mn, Ni and Zn) of selected samples from Site 1 and Site 2, ranked from highest to lowest concentration and split by site. The blue and aqua areas of the stacked bar chart represent the portion of the total extracted cations that were water-soluble and the red and brown dotted areas represent the portion of the total extracted cations that were EDTA extracted.

[†] Total EDTA Cations includes water-soluble cations and cations extracted by EDTA.

EDTA (ethylenediaminetetraacetic acid) is a complexing agent that binds very strongly to cations and therefore transfers them into solution from the surfaces of particles. As EDTA is selective against sulfide forms of metals but readily dissolves oxides and hydroxides, it is a very good indicator of the extent of oxidation product contained in a waste rock sample. In addition, because EDTA extracts both water soluble and surface bound oxidation products, a deionised water extraction is also conducted to indicate those elements that are elevated in the EDTA extract.

An important factor that needs to be noted is that because the EDTA test procedure is a surface chemistry method, only the fine fraction of samples were used in the test. Therefore, results do not apply to whole samples, but are indicative of what oxidation products are on the surfaces of the finer particles.

The results show that the total EDTA-extractable cation concentration from Site 2 is at least three times higher than that of Site 1. Figure 7 also shows that in the majority of the Site 2 samples, more than half of the total extracted cations were water-soluble. This contrasted that of the Site 1 samples where generally less than half of the extracted cations were water-soluble.

The large differences in the total concentration of cations extracted from both sites is supported by scanning electron microscopy photomicrographs (see Figure 8 and Figure 9), which show a high degree of armouring (oxidation products) on the surfaces of the Site 2 samples, whereas armouring of the Site 1 samples was present but not to the extent of that observed in the Site 2 samples.

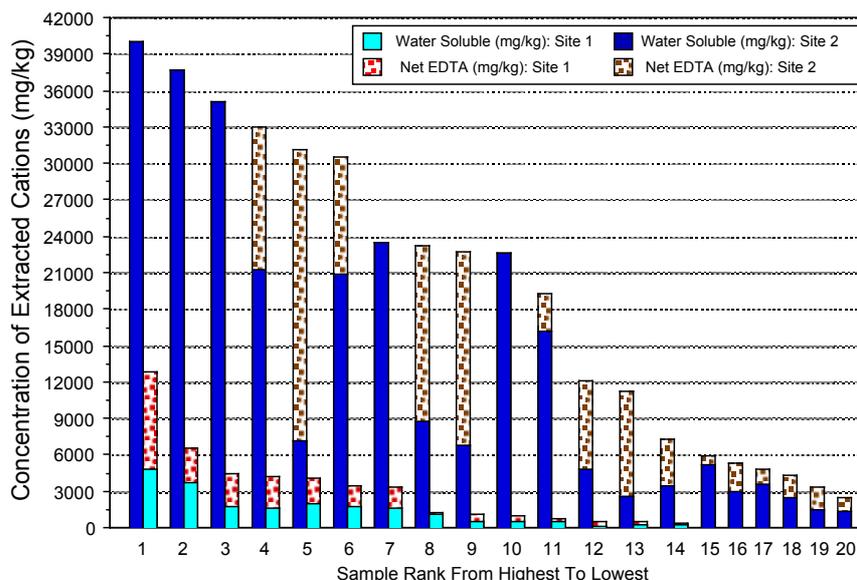


FIG 7 - Comparison of the total extractable, water-soluble and EDTA extracted cations for selected samples from Site 1 and Site 2.

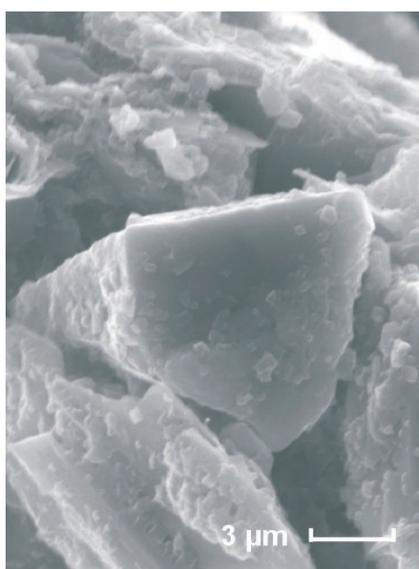


FIG 8 - Minor oxidation products observed on surface of particles from Site 1 sample TP23GS5x. Goethite/limonite coatings on gangue minerals and secondary jarosite was observed in this sample.

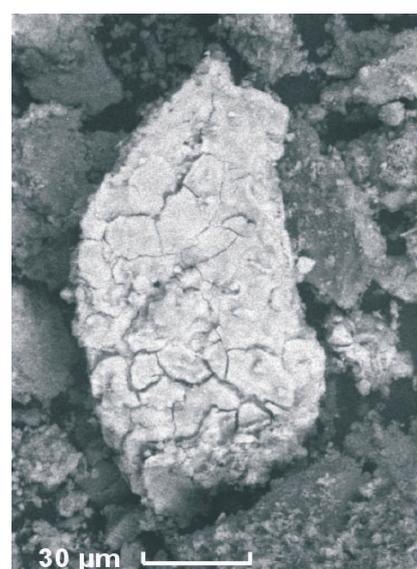


FIG 9 - High concentration of surface oxidation products observed on particles from Site 2 sample TP12GS2. This sample contained goethite coatings and surface layers (some as free sheets) of iron hydroxides.

The results indicate that flushing of the waste rock at Site 2 may have been limited, therefore making the storage of oxidation products at Site 2 more prevalent than at Site 1.

RELATIONSHIP BETWEEN GEOCHEMICAL AND PHYSICAL CHARACTERISTICS

At this time, comparisons between the geochemical and physical interactions at Site 1 and Site 2 are only in the initial stage. Therefore, only key, preliminary results from comparisons are presented in this section.

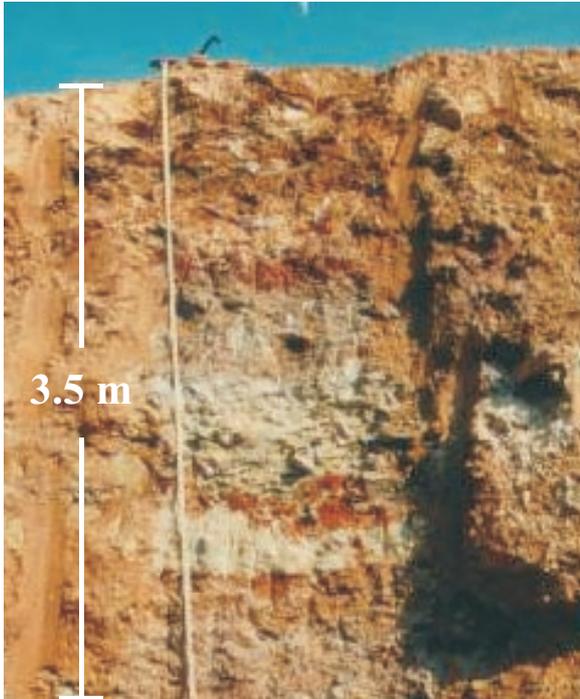


FIG 10 - Test pit 15 at Site 1. Sand to clay sized particles predominant with a few coarser particles in matrix material.

Physical testwork was carried out by Pamela Fines (Fines *et al*, 2003). A major finding of the physical testwork was that waste-rock particle sizes from the two sites contrasted significantly. At Site 1, sand to clay particles derived from sedimentary protoliths were predominant, whereas at Site 2, cobble to boulder sized particles were characteristic of the igneous waste rock. The photographs below highlight the contrasting grain sizes at the two sites.

As previously stated, the EDTA test procedure is a surface chemistry method and therefore results are only indicative of the oxidation products on the surfaces of fine particles.

Figure 12 presents the D_{50}^{\ddagger} particle-size range compared against the percentage of water-soluble § oxidation products from the Site 1 and Site 2 samples.

\ddagger D_{50} particle size is the size fraction through which 50 per cent of the particles in a sample pass through.

\S Per cent of Water-Extracted Cations = (Water Extracted Cations ÷ Total EDTA-Extracted Cations) × 100 per cent.



FIG 11 - Test pit excavation at Site 2. Large cobble to boulder sized particles typical of waste rock with small fraction of fine particles in matrix material.

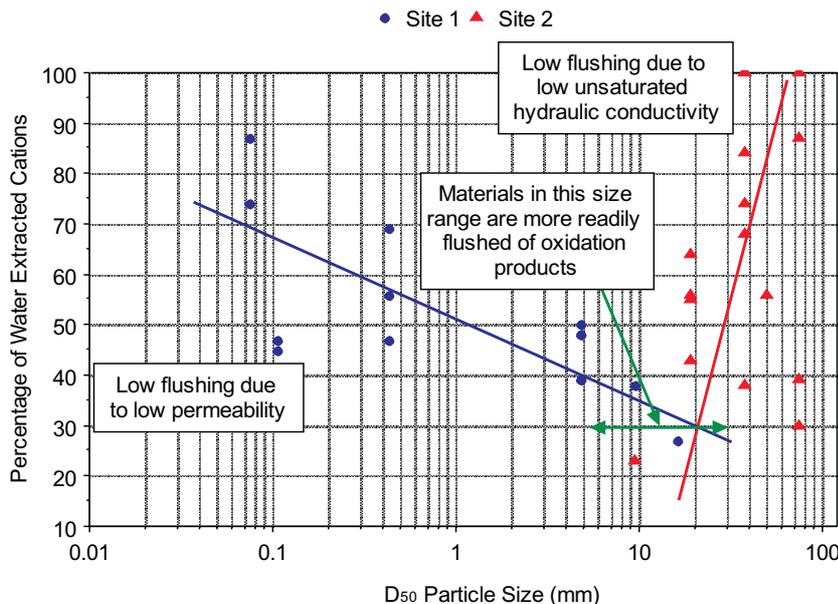


FIG 12 - D_{50} particle size fractions compared against the per cent of water-extracted cations from Site 1 and Site 2.

The results show that samples that have a $D_{50} < 1$ mm have a higher percentage of water-extracted cations that remain on the surfaces of those particles than do samples with a $D_{50} > 1$ mm. This indicates that finer samples do not undergo as much flushing by infiltrating rain water at Site 1. Because of the general relationship between particle size distribution and hydraulic conductivity, these results may be due to the relative hydraulic conductivities of these materials.

In addition, Figure 12 suggests that the fine particle size fractions in coarser materials that have a $D_{50} > 30$ mm also do not undergo any significant flushing. This is indicated by the high percentage of water-extracted oxidation products observed for these waste rock samples. The lower water flux implicated by these observations is consistent with the unsaturated conditions, which are prevalent in the coarse-grained portions of the dump at Site 2.

However, there is an overlapping particle-size range from both of the mine sites, D_{50} between 5 mm and 30 mm, where the waste rock appears to be more regularly flushed. This is indicated by the lower concentration of water soluble oxidation products that were extracted.

The results therefore suggest that the waste rock dumps at both Site 1 and Site 2 have preferential water pathways, which lead to the storage of oxidation products in some materials and the leaching of oxidation products in others.

CONCLUSION AND RECOMMENDATIONS

The results from geochemical and mineralogical testing indicated that waste rock from Site 1 are weathered, with the majority of the samples containing no acid buffering capacity and a low total S content. The waste rock at the site is believed to be relatively advanced in the ARD evolution trend.

In contrast, the waste rock from Site 2 is indicated to only be in the initial stages of acid rock drainage evolution, with samples still containing a considerable amount of reactive sulfides.

EDTA and deionised water extraction tests revealed that a large concentration of water-soluble oxidation products were being stored in the Site 2 waste rock dump. This has implications for the management of water quality at the site, as any flushing of the dump materials would lead to a high proportion of elements reporting to the loading of seepage.

In addition, different particle-size fractions were observed to have an impact on the concentration of oxidation products at each site. Waste rock which contained a large proportion of fine particles (< 1 mm) appeared to undergo less leaching probably

due to low saturated hydraulic conductivities of the materials and therefore predominantly stored oxidation products. Also, coarse materials (> 30 mm) experienced limited flushing due to the low unsaturated hydraulic conductivity of those materials. This too led to the storage of oxidation products. However, the portion of materials that had a D_{50} particle size in the range of 5 mm to 30 mm appeared to have been more regularly flushed, as these materials had lower extractable concentrations of water-soluble oxidation products.

The conclusion drawn from this project is that the dump internal structure strongly influences the geochemistry of waste rock contained within a dump. Recommendations for improved disposal practices to control ARD generation include:

- Once the mining block model has been completed or production schedules are known, blasting of overburden and ore can be conducted selectively. For instance, if it is known that areas of PAF and/or contaminating materials will be encountered, then the materials should be blasted so that they remain coarse. This selective blasting and placement of PAF materials will hopefully control the flow of water away from layers that contain these materials.
- If however, NAF and/or non-contaminating materials will be encountered during blasting, then the materials should be blasted so that they are fine grained. During placement in the dump, these materials may then be confined to layers which transport water.
- Controlled placement of fine-grained (NAF) and coarse-grained (PAF) material within the dump could significantly reduce the overall ARD load. Storage of oxidation products at the mineral surface will also slow the oxidation rate due to mineral surface armouring.

REFERENCES

- Fines, P, 2000. Personal communication. February.
- Fines, P, Wilson, G W, Williams, D J, Tran, A B and Miller, S, 2003. Field characterisation of two full-scale waste rock piles, in *Proceedings Sixth International Conference on Acid Rock Drainage*, pp 903-910 (The Australasian Institute of Mining and Metallurgy: Melbourne).
- Miller, S D, Jeffery, J J and Wong, J W C, 1991. Use and misuse of the acid-base account for AMD prediction, in *Proceedings Second International Conference on the Abatement of Acidic Drainage 1991*, pp 489-506 (Mine Environment and Neutral Drainage: Canada).
- Tae, M, 1999. Species selection for vegetating an engineered pit cover in the Sudbury area, in *Proceedings Sudbury '99 Mining and the Environment II 1999*, pp 561-570 (CANMET: Ottawa).

