Ongoing Evaluation of Tailing Geochemistry: An Integral Component of Mine Closure Planning

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Abstract

This paper presents a case history demonstrating improved understanding of geochemical aspects of mine tailingthrough ongoing evaluation at a base metal mine located in a semi-arid area of Western Australia. The tailing is currently stored at an above-ground valley fill Tailing Storage Facility (TSF) and options for long term management under consideration include backfilling the open pit or leaving the tailing*in situ* at mine closure and covering using the concept ofan enhanced "store and release" cover system.

Geochemical and mineralogical studies over the last decade have found that the geochemical behaviour of the tailing in the TSF is more benign than initially predicted. The sulfide content of the tailing is primarily pyrrhotite, which can be acid-forming, acid-neutral or acid-consuming depending on a number of factors including redox conditions. Tailing pore water below the surface hardpan is pH neutral with excess alkalinity, low concentrations of dissolved metals, and elevated sulfate concentration.

Recent geochemical tests on tailing indicate that a reduction in the Acid Potential (AP) and an increase in the Neutralising Potential (NP) of the tailing, through partial removal of pyrrhotiteand concentration of magnesium silicates at the processing stage, has the potential to further reduce the long-term risk of potential impact to the environment from any TSF seepage. The current work program investigates whether partial pyrrhotite removal has merit as one of several options being considered to produce a cost effective and sustainable outcome at mine closure.

Key Words: geochemical characterisation, tailing, prediction, pyrrhotite, acid drainage, mine closure

Introduction

The need for geochemical studies for planning, operating and eventually closingsulfidicmine waste storage facilities around the world is now generally well accepted (Parker and Robertson, 1998; Robertson *et a*l., 2009 and 2011). These studies form an integral component of a broader set of studies, which must be completed to meet sustainable development principles as well as mining and financial industry guidelines and standards (World Bank, 2007). Successful completion of geochemical studies and implementation of appropriate environmental management strategies can significantly reduce the risk of Acid and Metalliferous Drainage (AMD) generation and associated environmental impacts.

Acquisition of timely geochemical information on the nature of mine waste materials can be used to develop innovative design solutions, limit the potential for environmental impacts, and promote sustainable closure (DITR, 2007; INAP, 2009 and Wilson, 2011). During the mine planning and regulatory approvals stage, there may be a limited amount of geochemical information available on the long term behaviour of mine waste materials. This knowledge gap can lead to the development of mine waste management design solutions and prescriptive approval conditions, which may not be the best way to deliver acceptable environmental outcomes. It is beneficial that a proponent have some flexibility to improve mine closure plansduring the mine operational phase based on improved geochemical knowledge and experience gained throughout the mine life.

Geochemical Testing

Geochemical testing of mine waste materials is generally divided into two categories: static and kinetic tests. In Australia, technical guidelines for static and kinetic geochemical testing of mine waste materials have been developed (AMIRA, 2002), although it is important to consider the individual characteristics of sites and waste material types when selecting test methods to use.

Static tests generally involve screening a relatively large number of samples at the start of a project to determine their fundamental geochemical characteristics (*eg.* pH, salinity and potential for acid generation). Following screening, a subset of these samples is subjected to multi-element tests for total metals and also soluble metals contained in water extracts. Kinetic tests are typically time-series tests designed to determine the effects of oxidation of a sample over time. Kinetic tests are generally reserved for a smaller number of samples due to higher cost and may not provide useful data for months or years.

The information acquired from static and kinetic geochemical tests can be very useful. However, due to scale-up and other factors such as the heterogeneity of the mine waste materials, simplistic direct comparison of this information with existing soil and water quality guidelines should be treated with caution. Where uncertainty exists, modelling is often used to assess the complex behaviour of mine waste materials and potential impacts from mine waste storage facilities (Mayer *et al*., 2003). Mineralogical studies can also be used to complement geochemical studies, especially where some uncertainty remains over the long term geochemical nature of mine waste materials.

Project Background

The case study presented in this paper focuses on the geochemical characteristics of tailing materialgenerated from a base metal mine in the Kimberley region of Western Australia (WA). The mine located in a semi-arid to sub-tropical climate, with average annual rainfall of approximately 557 mm (ranges from 280 to 1,310mm) and average annual evaporation of approximately 3,200 mm. Rainfall variability is moderate, with most rainfall occurring in the hot summer months between December and March.

The mine commenced in 2005 as an open pit operation, but is now an underground operation and tailing generated from processing ore is currently disposed of as a cement based backfill underground or stored at an above-ground valley fill TSF. The existing mining approval requires the mine operator move the tailing from the conventional valley fill TSF into the open pit at the end of mine life. Approximately 3.5 million tonnes of tailing has been placed in the TSF.Due to ongoing exploration success, the mine operator is now assessing options for the long term management of tailing at the operation to match revised life of mine ore reserve estimates. One option under consideration is leaving the tailingin situ at mine closure and covering the TSF using the concept ofan enhanced “store and release” cover system. The high evaporation to rainfall rate (approximately 4.5:1) essentiallypreclude the use of a water cover system for tailing. It is proposed that the cover system utilise geochemically benign waste rock adjacent to the TSF as part of this closure option for the TSF, and would be designed to store at least some of the incident rainfall and then release this moisture through evapo-transpiration during dry periods. The cover design does not aim to stop all moisture infiltrating through the cover profile, and modelling to determine net percolation rates has assumed a ‘bare’ surface (*ie.* no vegetation).

Geochemical information presented in the original approvals documentation in 2002 predicted that the tailing would be Potentially Acid Forming (PAF) and would be likely to pose a significant long term risk to the environment from potential seepage. Based on the geochemical assessment information presented at the time, Regulators took a conservative approach and made the return of tailing material to the open pit void at end of mine life a condition of consent. The condition of consent was made without knowledge of potential advances in the role and success of “store and release” cover systems for above ground tailing

storage facilities in arid parts of Australia. Ongoing geochemical characterisation and assessment of the tailing was also a condition of consent and relevant information has been collected and reviewed since the mine was commissioned. However, in 2007 it became clear that whilst the tailing remains classified as PAF, itsgeochemical natureis much more benign than initially predicted whenstored at the TSF.

Since 2007, the mine operator has engaged a team of technical specialists to develop a long-term alternative tailing storage strategy for closure. The specialist team has completed a number of broader studies associated with geotechnical stability, cover design/modelling, landform erosion modelling, tailing geochemistry andmineralogy, surface water and groundwater hydrology, solute transport modelling, ecotoxicological assessment, and ecological assessment of downstream aquatic fauna.The project has been completed in consultation with relevant stakeholders, including State Government agencies,some of whom have taken time to accept the veracity of the technical studies that support a significant change in the interpretation of the geochemical characteristics of the tailing material.

Based on the results of these technical studies,the long-term risk of significant impact to the environment due to TSF seepage is lower than originally predicted. The mine operatornow has a much improved understanding of the geochemical nature of the tailing material, environmental risksand any potential to impact the environment as it evaluates several possible closure options for tailing moving towards mine closure. Notwithstanding, the mine operator has recently commissioned additional geochemical tests on tailingmaterial to assess the effect of partial removal of pyrrhotite from the tailing at the mineral processing stage. Results indicate that this can reduce theAP(by removal of most of the pyrrhotite) and increase the NP(by concentration of magnesium silicates) of the tailing, which has the potential to further reduce the long-term risk of potential impact to the environment from any TSF seepage. The current work program investigates whether partial pyrrhotite removal has merit, compared to alternative tailing management options, to produce a cost effective and sustainable outcome at mine closure.

Geochemical Characteristics

A series of static and kinetic geochemical studies have been completed on tailing materialsfrom the project site since 2005. An independent peer review of the long-term tailing storage strategy at the site in 2008 found that ‘actual’ tailing generated at the project is much less reactive than originally indicated for a simulated tailing in 2002. The current tailing contains less sulfide and more neutralising capacity than predicted,but is still classified as PAF by static geochemical classification methods. At the TSF surface, the tailing forms a trafficable hardpan surface (about 3 cm thick) and remain relatively fresh/unoxidised (pH neutral with excess alkalinity and low concentrations of soluble metals/metalloids) below the hardpan surface (Figure 1). At this stage, the oxidation front has not progressed beyond the hardpan layer.

Figure 1. Trafficable tailing hardpan surface at TSF

Several authors have found that the rate of pyrrhotite oxidation slows when a hardpan layer is present on tailing under both dry and saturated cover conditions (Gilbert *et al*. (2003)). McGregor and Blowes (2002) suggested that a TSF hardpan layer can act as a hydraulic and diffusive barrier against the migration of rainfall infiltration and oxygen. The authors presented a case study forpyrrhotite tailing at a TSF in Canada (Fault Lake), and highlighted that the hardpan layer had grown to 20 cm and the oxidation front had migrated only an additional 18 cm after 25 years of exposure to atmospheric conditions. Further numerical simulations of the Fault Lake tailing concluded that over a time period of 1,000 years only the top three metres of tailing would become oxidised (Romano *et al*, 2006), which aligns with earlier tailing modelling work which indicated that the overall rate of oxidation of the near surface tailing was eventually controlled by the diffusion of oxygen into the tailing mass rather than by the reaction kinetics in the tailing (Elberling*et al*, 1994). Both of the references from Fault Lake tailing were used to illustrate the characteristics of a tailing surface hardpan and clarify the expected rate of progression of the oxidation front into the bulk tailing material over time at the Savannah Project. No information on water quality was presented in either of these references.

At the current case study project in WA, the tailing forms a surface hardpan, which also appears to limit oxygen diffusion and retains the bulk tailing in a mostly reducing/anoxic environment. This has been confirmed by recent work completed on the operation's tailing by the University of South Australia, which indicates a slow and comparable rate of progression of the hardpan layer and oxidation front into the tailing (approximately 1cm per year if the tailing are maintained above 75% saturation). Another attribute of the project tailing is that it contains significant amounts of potentially acid-neutralising gangue silicate minerals (*eg*. anorthite, enstatite and chlorite), which can provide both short- and long-term neutralisation of acid generated through pyrrhotite oxidation (Ciccarelli*et al*, 2008; Miller *et al*., 2008).

Soil-atmosphere modelling results associated with the proposed final cover design for the TSF demonstrate that a saturation level of 75 % in the tailing below the cover material is likely at depths of 5m or greater below the tailing-cover interface. At shallower depths in the tailing profile, a reduced level of saturation is expected, although at a depth of 1m, a saturation level in the range 62 to 68% is still likely. This modelling takes no account of the surface hardpan maintaining higher levels of saturation in the bulk tailing. Hence the predicted level of saturation, together with the surface hardpan, will serve to significantly slow the pyrrhotite oxidation rate at TSF1 to a rate that is likely to be matched by the magnesium silicate dissolution ratewithin the bulk tailing.

Several geochemical and mineralogical studies in the laboratory and in situ at the TSF completed from 2008 to 2011 have found that tailing stored at the TSF is significantly less reactive than expected. In particular, *in situ*tailing samples taken from depth at the TSF and groundwater monitoring data indicate that TSF seepage water is typically pH-neutral, with excess alkalinity, andelevated electrical conductivity, mostly attributable to dissolved sulfate, calcium and magnesium and the concentration of trace metals/metalloids is low. The main water quality parameter that has a consistently elevated concentration is soluble sulfate, which may be attributable to a number of factors including the oxidation of near-surface tailing stored in the TSF and recycling of sulfate rich water from dewatering of underground workings at the mine.

Figure 2 illustrates pH data obtained fromthree long term kinetic leach column (KLC) tests being completed for the tailing material with and without cover materials. The KLC tests were completed using a mining industry standard method as a framework (AMIRA, 2002), but were operated on a larger scale (25kg of sample per column) as previously described elsewhere (Robertson *et al.*, 2009). The columns were initially operated under oxic conditions for eight months and then converted to anoxic conditions for the remainder of the test period simply by adding excess water. Sampling was initially undertaken on a monthly basis for three months and then quarterly for the remainder of the test period with water sampled

from the bottom of the columns replaced with fresh water at the top following each sampling event. The results clearly illustrate that under freely oxidising conditions (as in the surface hardpan) the tailing has the potential to generate acid conditions after about nine months. However, when oxygen access is restricted (as in the bulk tailing) the tailing is likely to generate pH neutral to slightly alkaline conditions. This reflects the situation for seepage from the bulk tailing at the project site which is pH neutral, has excess alkalinity and low concentrations of dissolved metals/metalloids. The seepage does however have elevated electrical conductivity values caused by elevated sulfate concentration.

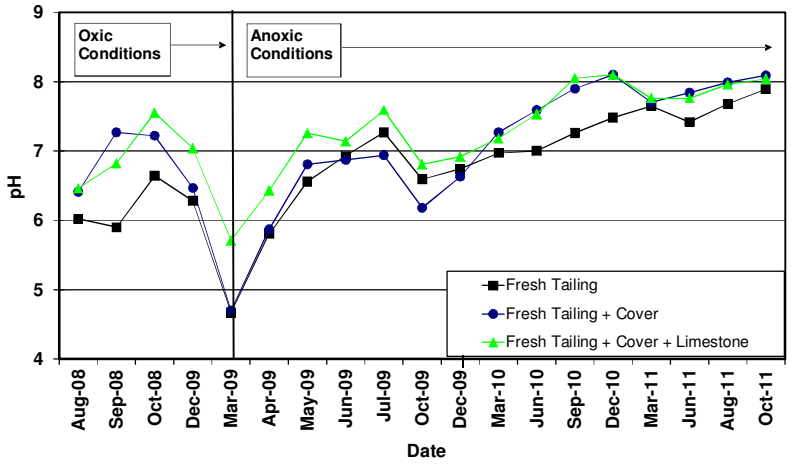

Figure 2.pH trend for KLC tests on fresh tailing samples under oxic and anoxic conditions

Mineralogical Characteristics

The relatively benign nature of the tailing solids at the TSF is unusual as this material typically contains over 8-9 % total sulfur. Mineralogical investigations indicate that most of the sulfur is present in the monosulfide form (*i.e.*pyrrhotite) in a gangue of mafic-silicates, with only trace amounts of carbonate. Pyrrhotite, rather than pyrite, is the main sulfide gangue mineral usually associated with nickel sulfide deposits, but this geochemical difference has not been recognised in standard testing of wastes from these deposits (Schipper*set al.*, 2007, Heikkinen and Räisänen, 2008; and Robertson *et al.*, 2011). In particular, it is not widely recognised that pyrrhotitecan follow a number of reaction pathways that can be acid forming, non-acid forming and in some circumstances, acid consuming (Thomas *et al.*, 2001).The dissolution behaviour of pyrrhotite is less studied than that of pyrite, however a number of studies from both laboratory and field investigations have been published (eg. Belize *et al.*, 2004; Thomas et al. 1998, 2000; Nicholson and Scharer, 1994).The two main reaction pathways which are considered to potentially operate within the tailing are provided below.

Reaction Pathway 1

$Fe_{(1-x)}S + 3(1-x)/4O_2 + (1-x)/2H_2O \rightarrow (1-x)FeOOH + S^0$ (1)

Pyrrhotite + Oxygen + Water → Goethite + Elemental Sulfur

Reaction Pathway 2

$Fe_{(1-x)}S + 3(3-x)/4O_2 + (3-x)/2H_2O \rightarrow (1-x)FeOOH + H_2SO_4$ (2)

Pyrrhotite + Oxygen + Water → Goethite + Sulfuric Acid

Site evidence for sulfur formation in the bulk tailingwas quantified by extraction of the solids with acetone followed by analysis of the extract by High Performance Liquid Chromatography (McGuire and Hamers, 2000). The presence of elemental sulfur suggests that pyrrhotite oxidation has occurred at least to some extent according to Reaction Pathway 1, where iron is principally converted to goethite or similar amorphous iron oxyhydroxides, and sulfide is primarily oxidised to produce elemental sulfur under

conditions of less oxygen and water than Reaction Pathway 2 and does not involve any acid generation. In contrast, pyrrhotite oxidation under Reaction Pathway 2 alsoinvolves iron conversion to goethite, but in this situation sulfur is fully oxidised to produce sulfuric acid. It is interesting to note that no reduced sulfur species (such as sulfite) were found in the bulk tailing pore water at depth and iron concentrations were very low suggesting that the potential for latent acidity to occur in seepage from bulk tailing at the TSF is low.

Whilst both reactions described above could be occurring in the tailing at the TSF, the KLC results, tailing at depth assessment, and seepage and groundwater quality observations downstream of the TSF suggest that although pyrrhotite may be acid generating to some extent in the hardpan tailing material, it is acid neutral or NAF in the bulk tailing material. The presence of elemental sulfur in the bulk tailinghardpan and at depth, and lack of oxygen below the tailing hardpan surface (dissolved oxygen was measured in the tailingporewater during a drilling and sampling program at the TSF) suggests that Reaction Pathway 1 is likely to be favoured.

Another alternative adding to the complexity of interpretation, is that some acid may be generated according to Reaction Pathway 2 and then neutralised by alkalinity from residual lime from the tailing or from mineral dissolution reactions or both. Recent mineralogical assessment work by the University of South Australia has established that the tailing contains enstatite, a magnesium silicate that has dissolution rate comparable to the measured oxidation rate of pyrrhotite in near saturated tailing and provides a source of alkalinity at a rate comparable to the acid generation rate from pyrrhotite oxidation. This results in pH neutral drainage with excess alkalinity and very low levels of dissolved metals as well as elevated salinity from sulphate, calcium and magnesium. These results are consistent with observations reported in the literature regarding other pyrrhotite-bearing tailing wastes.

Pyrrhotite Removal

Additional geochemical tests (KLC tests) on tailingmaterial to assess the effect of partial removal of pyrrhotite from the tailing at the mineral processing stage are currently being completed. Initial results indicate that this can reduce theAP and increase the NPfor the tailing, which has the potential to further reduce the long-term risk of potential impact to the environment from any TSF seepage. Figure 3 illustrates the pH of leachate derived from fresh tailing and well as pyrrhotite concentrate and reduced pyrrhotite tailing material generated through an additional laboratory scale flotation process.

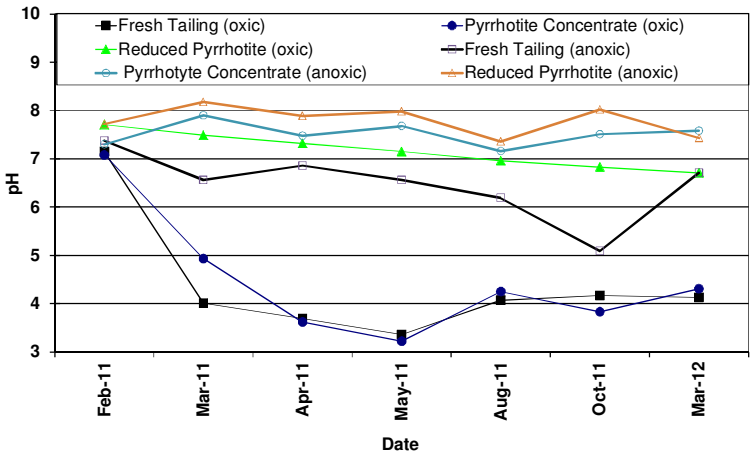

Figure 3.pH trend from KLC tests on fresh tailing, pyrrhotite concentrate, and reduced pyrrhotite samples

The results illustrate that under oxic conditions both the fresh tailing and pyrrhotite concentrategenerate

acid conditions after only a few months. In contrast, the two reduced pyrrhotite tailing samples remain pH neutral throughout the initial 14 month test period under both oxic and anoxic conditions. The pyrrhotite concentrate sample also remains pH neutral throughout the test period under anoxic test conditions. The fresh tailing has a slightly reduced pH value under anoxic conditions, but has returned to the neutral pH range at the end of the14 month test period. The quality of leachate derived from the reduced pyrrhotite tailing material under both oxic and anoxic test conditions, and from the fresh tailing and pyrrhotite concentrate samples under anoxic conditions is significantly better than that of the fresh tailing and pyrrhotite concentrate under oxic conditions. In particular, the electrical conductivity and sulfate concentration in leachate from the reduced pyrrhotite tailing under both test conditions is an order of magnitude less than that of fresh tailing and pyrrhotite concentrate under oxic conditions.

Further Work

The mine owner has commissioned additional geochemical and mineralogical test work on tailing material to look at fundamental reaction pathways and rates of reaction for both pyrrhotite and neutralising minerals in the tailing material. In addition, the feasibility of magnetic separation of pyrrhotite from the tailing material is being investigated as removal through flotation at the processing plant may be uneconomic. The results of this program of work will be usedto investigate whether partial removal of pyrrhotitefrom tailing is necessary to produce a significantly better outcome at mine closure.

Conclusions

Mine waste characterisation studies are an essential pre-requisite component of the total information package required to correctly design, operate and close sulfidic mine waste storage facilities to the standard required by international mining industry best practice. However, some flexibility should remain during the operational mining phase to develop and enhance mine rehabilitation and closure plans based on new geochemical, mineralogical and other knowledge and experience gained throughout the mine life. Decisions made by stakeholders during the planning stage should not preclude innovation and change during operation and towards closure as ongoing investigations uncover new information.

A case study has been used to illustrate the complexity of the geochemical and mineralogical processes associated with tailing material at a base metal mining operation in Australia. Whilst detailed and targeted geochemical studies in the early stages of mine feasibility and planning can provide important information of the characteristics of mine waste materials, this paper illustrates that ongoing study is required throughout the life of mine to ensure that the most appropriate operational and closure options are developed and implemented for mine waste storage facilities.

The results of the case study indicate that there is now a very good understanding of the geochemistry and mineralogy of tailing material at the site based on a number of studies by recognised experts, where field evidence at the TSF matches predicted geochemical behaviour over time. The downward movement of the surface hardpan and oxidation front into the bulk tailing at the TSF is very slow and predicted to remain so even without a cover system in place. The final cover design for the TSF predicts a high level of saturation in the bulk tailing below the cover material, but does not take into account the positive effects of the surface hardpan on maintaining the tailing saturation level. Mineralogical studies show that the rate of pyrrhotite oxidation is likely to be matched by the magnesium silicate dissolution rate within the tailing. This results in pH neutral drainage with excess alkalinity and very low levels of dissolved metals as well as elevated salinity from sulphate, calcium and magnesium.

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List of Acronyms

NAF	Non-Acid Forming	KLC	Kinetic Leach Column
PAF	Potentially Acid Forming	ANC	Acid Neutralising Capacity
AP	Acid Potential	TSF	Tailing Storage Facility
NP	Neutralising Potential	AMD	Acid and Metalliferous Drainage