An integrated mineralogy-based modelling framework for the simultaneous assessment of plant operational parameters with acid rock drainage potential of tailings

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Abstract

An integrated process modelling framework, underpinned by mineralogy, is under development at the University of Cape Town as a holistic approach towards addressing the multifaceted challenges currently faced in mining. This paper demonstrates application of this approach for the case of a polymetallic base metal sulfide flotation circuit. In this case study, the effect of potential design strategies and feed ore variability on net acid producing potential of the resulting tailings is assessed. The framework is underpinned by mineralogical calculations of acid potential and neutralising potential. Application of the framework allows for the identification of potential opportunities towards more sustainable mining practice.

Keywords: mineralogy, framework, ore variability, flotation

Introduction

The minerals industry is facing numerous multifaceted challenges ranging through the techno-economic, environmental and social domains, including increased ore variability, lower grade and more mineralogically complex ores, rising operating costs and lower profit margins, increased awareness and accountability of the environmental footprint of mining operations and the growing need to obtain and maintain a social license to operate. The generation of acid rock drainage (ARD) and the associated consequences of this heavy metal bearing, sulfate rich, acidic leachate on the surrounding environment is the key concern here. In order to address these challenges effectively and collectively, a holistic approach is required. In such an approach, the ability to compare scenarios, evaluating the various trade-offs between the techno-economic, environmental and social indicators, is needed (Tuazon et al. 2012).

Given the key role mineralogy plays in both valuable and deleterious metal deportment, metallurgical process design and optimisation and consequent environmental effects (Skinner 1976; Hochella 2002; Broadhurst et al. 2007; Becker 2018), it is an essential component in the design of the framework. In the context of ARD, it is the relative abundance of both acid forming and neutralising minerals, their mineral chemistries and the textural inter-relationships that play a pivotal role in determining whether ARD is generated, how much is generated, what is its composition and what are the relative time scales of the reactions.

The development of an integrated modelling framework is under development by researchers at the University of Cape Town which gives recognition to the critical role of mineralogy in the design of environmentally and socially responsible primary mineral beneficiation processes. The initial development of this modelling framework focused on a case study of a polymetallic sulfide ore flotation circuit (Ntlhabane et al. 2018). The circuit sequentially recovers the different metal sulfides to produce Cu (chalcopyrite), Pb (galena) and Zn (sphalerite) concentrates respectively. The final tailings are sent either to the tailings dam or used as backfill when required. This initial work focused on setting up a unique ore-specific element-to-mineral conversion (EMC) recipe to calculate mineral grades from chemical assays (Whiten 2008). Thereafter, a set of mineral distribution functions were developed for modelling and prediction of mineral grades across the flotation circuit under different scenarios. Mineralogical calculations of acid potential and neutralising potential were then performed to determine a theoretical 'mineralogical' net acid producing potential of the final tailings.

The objective of this paper is to further demonstrate the application of the integrated framework using the case study of Ntlhabane et al. (2018) on several different operating scenarios. Complementary static chemical tests are used to validate the mineralogical predictions of the acid producing potential of the tailings sample.

Methods

Full details of the initial sampling of the case study flotation circuit and associated chemical and mineralogical characterisation are provided in Ntlhabane et al. (2018). Mineralogical predictions of acid potential (APmin) and neutralising potential (NPmin) were calculated using the concepts of the approaches behind Paktunc (1999) and Lawrence and Scheske (1997). Laboratory chemical tests following the methods of Weber et al. (2004) and Miller et al. (1997) were used to determine the acid neutralising capacity (ANC) and net acid generation (NAG). Maximum potential acidity (MPA) was calculated from the Leco S assay after which the net acid producing potential (NAPP) was calculated.

A model describing the base case operations of the polymetallic base metal sulfide flotation circuit considered in this study was developed (Ntlhabane et al. 2018). HSC Chemistry 8 software was used as the platform to develop the integrated framework. Scenarios aimed at predicting the effects of improved concentrate recovery and the impact of ore variability on final tailings acid rock drainage potential were analysed. Monte Carlo simulation was used to evaluate each scenario.

Results and Discussion

The mineralogical composition of the sulfide ore to the flotation circuit and the final tailings as calculated using the EMC recipe of Ntlhabane et al. (2018) is given in Table 1. It is a massive magnetite - sulfide ore consisting of notable amounts of chalcopyrite, galena, sphalerite and pyrrhotite. Pyrrhotite is the dominant acid producing sulfide mineral with very minor pyrite present. The limitations of the EMC method are that the grades of both pyrite and pyrrhotite cannot be simultaneously calculated using solely chemical assays and therefore only pyrrhotite is reported. Quartz, biotite, garnet and magnetite are the dominant gangue minerals. No carbonate minerals are present. Following separation and concentration of chalcopyrite, galena and sphalerite by flotation, the tailings consist of only minor economic sulfides (0.6 wt. % in total), but with significant pyrrhotite (3.8 wt.%) with the potential to form ARD.

***Table 1** Mineralogy of the feed and final tails calculated using EMC (see Ntlhabane et al. 2018)*

Minerals (wt. %)	Feed	Final tails
Chalcopyrite	2.3	0.2
Galena	5.1	0.2
Sphalerite	5.3	0.2
Pyrrhotite*	4.1	3.8
Garnet**	8.6	9.9
Biotite***	2.9	3.3
Quartz	21.1	24.3
Barite	0.9	1.0
Magnetite	49.6	57.2

* includes pyrite, ** almandine, spessartine and pyroxmangite, *** annite and chamosite

Based on both the knowledge of the mineral grades and chemistry, a theoretical acid producing potential (APmin) and neutralising potential (NPmin) can be calculated (Table 2). The AP is calculated directly from the sulfide mineral grades as 94.8kg H_2SO_4/t for the feed, and 47.4kg H_2SO_4/t for the final tails. Calculation of the NP considered all minerals with the potential to provide neutralising capacity, specifically those that are fast, intermediate or slow weathering, i.e. garnet, biotite and chlorite. This ore, however, has a notably strong Fe-Mn tenor which is reflected in the mineral chemistry of the silicates (Fe-rich biotite, Fe-rich chlorite, Fe-Mn-rich garnet). Consequently none of these silicate minerals were considered to provide neutralising capacity due to the presence of oxidisable cations and the NPmin was estimated at zero for both the feed and tailings. Both samples are classified as potentially acid forming based on their mineralogy.

The MPA calculated using the conventional approach (Table 2) directly from the S assay is considerably higher than the APmin. This is attributed to the assumptions of the standard method that the dominant sulfide is pyrite (a disulfide) and not pyrrhotite (a monosulfide). In this case the APmin is considered a more reliable estimate suitable for input to the modelling framework. The experimentally derived ANC indicates a potential neutralising capacity of 31 kg H_2SO_4/t. It is however recognised, that the harsh and aggressive chemical conditions of the ANC tests may overestimate neutralisation capacity. In this case the presence of silicate minerals containing oxidisable metal cations (Fe, Mn) are unlikely to provide any real long term neutralising capacity. The overall NAPP and NAG pH indicate both samples are classified as potentially acid forming.

Analysis of the base case based on measured plant data (Ntlhabane et al. 2018) showed a recovery of chalcopyrite of 77% with a mineral grade of 67 wt. % in the Cu bank. The copper (chalcopyrite) concentrate showed moderate dilution with pyrrhotite (26 wt. %), and minor dilution by sphalerite (2 wt. %) and galena (3 wt. %). Sphalerite (zinc) and galena (lead) achieved higher recoveries over 90% in the Zn and Pb banks, respectively. The following observations of the base case

Table 2 *Summary of the chemical and mineralogical ARD characteristics.*

Parameter (units)	Plant feed	Final tails
Total S (wt. %)	4.7	2.3
MPA (kg H2SO4/t)	143.8	70.4
ANC (kg H2SO4/t)	30.5 ±5.8	32.5 ± 7.1
NAPP (kg H2SO4/t)	113.5	37.9
NAG pH	2.88 ± 0.01	2.83 ±0.01
AP min (kg H2SO4/t)	145.3	47.4
NP min (kg H2SO4/t)	0	0
ARD classification	Potentially acid forming	Potentially acid forming
ARD classification (min)	Potentially acid forming	Potentially acid forming

plant operation were key to formulating two scenarios for further investigation (see Figure 1): (a) The payable metal content of the Cu concentrate was only 95% due to significant dilution by pyrrhotite. An opportunity existed to further upgrade the concentrate and increase the payable metal content. (b) The final tailings consisted of over 50% magnetite and could be explored as a possible saleable magnetite product. The active intervention in formulating scenario I is the addition of an appropriate flotation reagent to depress pyrrhotite so it is recovered to the tailings instead of concentrate (chemical intervention). The active intervention in formulating scenario II is the installation of a magnetic separator to the final tailings of the existing circuit (Figure 2) to generate a magnetic fraction and a non-magnetic fraction (physical intervention). In both scenarios, the grade of pyrrhotite to the final tailings would be affected having a direct consequence on the estimated APmin of the final tailings. A sensitivity analysis was also conducted to assess the effect of feed ore variability on the two scenarios.

When running the simulations it was assumed that: (a) recovery of pyrrhotite to the copper concentrate and consequent dilution of concentrate grade was not due to poor chalcopyrite liberation (recovery of com-

Scenario I:	Scenario II:
Improve Cu concentrate quality through **pyrrhotite flotation rejection** (pyrrhotite depression)	Improve Cu concentrate quality through **pyrrhotite flotation rejection** (pyrrhotite depression) & **install magnetic separator** on final tailings

Sensitivity analysis

Variability in pyrrhotite feed grade

Figure 1 *Matrix of the different scenarios considered.*

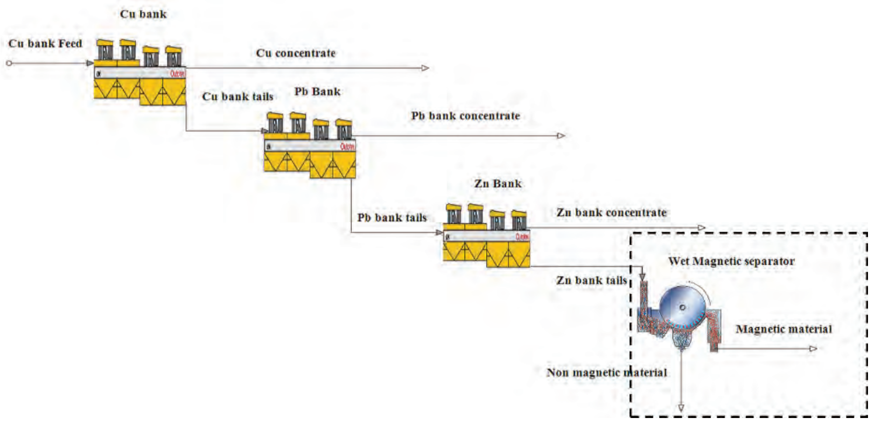

Figure 2 *Flotation circuit configurations considered for the scenario analysis. Boxed inset illustrates the circuit modification for scenario II.*

posite pyrrhotite-chalcopyrite particles) and (b) the pyrrhotite present was magnetic 4C pyrrhotite (Becker et al. 2010) that could be simultaneously recovered with magnetite using a wet magnetic separator. The sensitivity analysis only considered changes in pyrrhotite feed grade to the flotation circuit and other mineral recoveries remained constant.

The results of scenario analyses are illustrated in Figure 3. In scenario I, the effect of improving Cu concentrate grade by rejecting pyrrhotite to the tailings, resulted in a decrease in pyrrhotite recovery to the concentrate and a consequent increase in pyrrhotite tailings grade up 4.5 wt. % corresponding with an APmin of 53 kg H_2SO_4/t. In scenario II, where pyrrhotite is rejected to the flotation tailings and thereafter recovered by magnetic separation, resulted in a minimum APmin to 15 kg H_2SO_4/t for the final tailings (non-magnetic fraction). The sensitivity analysis of scenario I where pyrrhotite feed grade was varied (up to 8.1 wt. % in feed) resulted in an increase in pyrrhotite tailings grade corresponding with an increase in APmin to a maximum of 88 kg H_2SO_4/t. The sensitivity analysis of scenario II (up to 8.1 wt. % in feed), resulted in an overall decrease in pyrrhotite tailings grade with a maximum APmin of 29 kg H_2SO_4/t for the final tails (non-magnetic fraction).

Comparison of the absolute differences in APmin for the two scenarios and their sensitivity analyses (Figure 3) shows that the variability in pyrrhotite feed grade has the greatest effect on the modelled APmin. Ore variability therefore represents a significant challenge in both the processing of this ore and tailings management. Upfront knowledge of this variability on the scale of the geometallurgical block model ahead of mining and processing represents a significant opportunity of managing this variability and its consequent techno-economic and environmental effects (Wil-

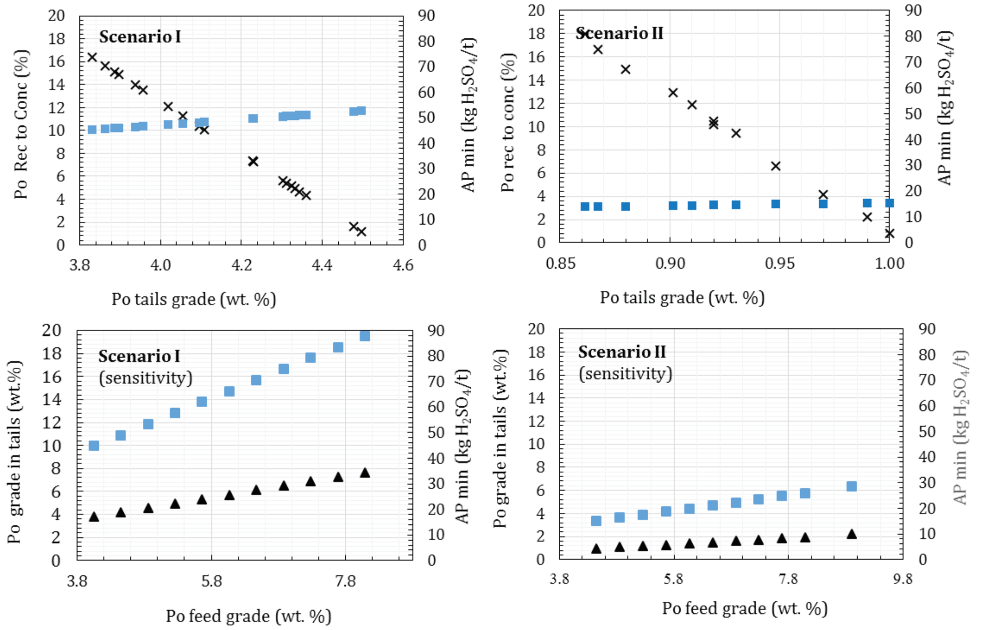

Figure 3 *Modelled AP min for the two scenarios analysed with their associated sensitivity analysis (see text for detail). ☐ indicates AP min, X indicates pyrrhotite (po) tails grade and Δ indicates pyrrhotite feed grade.*

liams and Richardson 2004). The consequence of upgrading payable metal content of the copper concentrate, by rejecting pyrrhotite to the flotation tailings has a notably smaller effect on the modelled APmin. With the installation of a magnetic separator in scenario II this could be partially alleviated. The viability of scenario II however, relies on two tailings products: a magnetic fraction containing both pyrrhotite and magnetite and a non-magnetic silicate rich product. With further processing the magnetic fraction could potentially be amenable for sale as a magnetite by-product, and the non-magnetic fraction could possibly become non-acid forming. In the case of scenario II, such a concept is consistent with a cleaner production approach similarly to that demonstrated by Hesketh et al. (2010) and Harrison et al. (2015).

Conclusions

This paper has demonstrated the first-order application of an integrated modelling framework to a polymetallic base metal sulfide ore. Mineralogical information provided a powerful input to the framework allowing the effect of ore variability and plant operating parameters on the acid potential of the resulting tailings to be evaluated.

The scenario analyses highlighted the opportunity to reduce the acid potential of the flotation tailings by actively rejecting pyrrhotite during flotation, and installing a magnetic separator to the final tailings. In both cases, a potential techno-economic advantage exists – to increase the payable metal content of the copper concentrate, and to produce a magnetite concentrate by-product. Further investigations should explore the viability of such interventions. The sensitivity analyses indicated that changes in pyrrhotite feed grade to the flotation circuit have a significant effect on the modeled acid potential of the tailings (almost double the APmin relative to the base case). Upfront knowledge of this variability ahead of mining provides an opportunity to manage these effects.

Development and application of such an integrated framework provides a new approach to addressing the multifaceted challenges faced as the industry strives for more sustainable mining practice.

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