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TECHNICAL ARTICLE

The Effect of Particle Size on Mine Waste Sulfide Oxidation Rates and Conceptual Treatment Costs

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Abstract

Acid and metalliferous drainage (AMD) oxidation reaction rates were determined using oxygen consumption rates in a high sulfur overburden rock from the Australian Latrobe Valley coal provinces, and a mid to low range sulfur waste rock from a porphyry copper deposit in Papua, New Guinea. Nine grain sizes were tested, ranging from material retained by a 0.038 mm sieve through to a 40 mm sieve. Oxygen consumption rates in sealed cells were measured to establish pyrite oxidation rates (POR) in each sample. The oxygen consumption rates displayed a strong exponential reaction correlation with particle size for the material. The POR was found to range from 0.28 to 10.90 wt%/year FeS_2 for the materials tested. A relationship between particle size and POR was established for comparative purposes. The smaller grind sizes included in this study extend the AMD/POR particle size data set available in the literature and will assist with geochemical engineering for designing tailings storage facilities. The potential economic and mine design ramifications of additional reactivity of fine mine materials is assessed and discussed using a unit cost framework for applying neutralizing materials.

Keywords Acid mine drainage · Surface and groundwater · Oxygen consumption · Pyrite oxidation rate · Mine closure

Introduction

The optimum particle size to adopt for mineral processing, particularly for sulfidic ores, is a complex question for the mining and resources sector (Runge et al. 2013). Mine profitability requires optimization modelling of many variables during the feasibility stage of mine design, based on balancing the cost of operations against the cost of mine closure. Interacting variables include: the current and future value of mined minerals and metals, recovery rates of processing technology, the geochemical interactions between the host rock geochemistry and the target mineral or metal during processing and closure, the cost of mining, crushing and milling technology, the transport of milled product and waste rock, the cost of environmental containment of waste rock and mine tailings, and providing ease of access to waste products for potential future re-mining (Chadwick 2009). The focus of this paper is on sulfide geochemical interactions and the influence of mineral processing, tailings, and waste rock particle size on the final reactivity of mining waste.

Acid and metalliferous drainage (AMD), or acid rock drainage (ARD) develops when sulfide materials, such as iron pyrite (FeS_2), oxidize when exposed to the atmosphere (EA 1997). The acidity dissolves the metals in soil/rock, which can create toxic conditions for fish and aquatic ecosystems and can potentially damage corporate reputations (DITR 2007). There is a need to better understand, predict, and control the rates of AMD production at both existing and legacy mine sites (US EPA 1994). Information on particle size and AMD reactivity is particularly important for long term geochemical stability of mining wastes post closure, and for minimalizing cost transfer from mine waste management during operations to the closure phase. Future environmental liability is related to particle size, as increases in reactive area can contribute to AMD production in the waste tailings that remain. Therefore, there is a trade-off between the particle size generated by mineral processing that optimizes product recovery and the potential for AMD from the waste tailings. Designer tailings are therefore created by balancing returns on processing of the milled ore bearing rock

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against the increased reactivity and long-term management requirements of the more reactive milled pastes.

It is a well-established that solubility (Stumm and Morgan 1981) and sulfide oxidation rates (Hollings et al. 2000) increase with decreasing particle size due to increases in reactive surface area. This effect was described by Apello and Postma (2007), who illustrated the relationship between surface area and particle size for a range of soils and smooth spheres. An increase in available surface area increases the molecular amount of reactive chemical available for reaction to gases and liquids coming in contact with the surfaces (Fig. 1). Therefore, reactive surface area and particle size are key parameters for geochemical modelling.

Measurement of reactive surface area has advanced greatly in the last 10 years. New measurement methods, primarily to support geochemical modelling, include the Brunauer–Emmett–Teller surface area determination (BS 4359-1) and temperature-programmed desorption (Schroeder and Gottfried 2002). However, the effect of particle size on the AMD reaction is complex and requires further examination. Studying the effects of particle size on AMD reaction rates requires the careful selection of geochemical testing methodology. Most current static and kinetic geochemical AMD tests, such as humidity cells, are based on measuring the maximum potential acidity generation (Maest et al. 2005; US EPA 1994). These methods typically rely on sulfate production to report oxidation, which may confound results if sulfate within the rock or soil sample is released during kinetic testing procedures (US EPA 1994). Advanced rate-based AMD kinetic testing based on oxygen consumption measurement was identified as a potential way to examine sulfide oxidation reaction rates while avoiding the use of sulfate as an indicator. This method has recently been deployed successfully in AMD risk studies (Hollings et al. 2000; Schmieder et al. 2012). A great deal of work has been undertaken on AMD geochemical characterization, but few studies have focused on AMD and particle size relationships using oxygen consumption techniques (Davis et al. 2014; Hollings et al. 2000) Several studies have also examined particle size relationships using conventional column leach and/or humidity cell analysis (Brough et al. 2017; Elghali et al. 2018, 2019; Erguler et al. 2014; Erguler and Erguler 2015; Lapakko et al. 2003, 2006).

The limited number of published particle size studies with AMD materials is perhaps due to the confidential nature of many mining activities, and possibly slow uptake of the new kinetic AMD characterization techniques, such as oxygen consumption testing. Current methods use geochemical characterization of exploratory drill core rock samples crushed to 15 mm, primarily for process metallurgy requirements, and is based on a process that includes minor amounts of fines, but insufficient to fully represent tailings particle size ranges after mineral processing (Runge et al. 2013). The AMRIA (2002) guideline suggests a sample grind size of 4 mm and < 0.75 mm. A review of published studies including AMD and particle size relationships showed limits to material particle sizes from 25 to 0.1 mm, including Erguler and Erguler (2015) and Erguler et al. (2014). Lapakko's (2013) study examined < 0.053 mm for two mine materials. Runge et al. (2013) suggested that for many process metallurgy requirements, the tailings sizes are indeed much smaller than 15 mm, with several common grind sizes below 0.1 mm (Fig. 2).

The new oxygen consumption techniques for measuring AMD production rates offers accurate results, but the current dataset for oxygen consumption based pyrite oxidation rate (POR) analysis needs to be extended across a wide range of geochemical conditions and parameters (Hollings et al. 2000). The smaller grind sizes included in this study extend the current AMD/POR particle size data set available in the

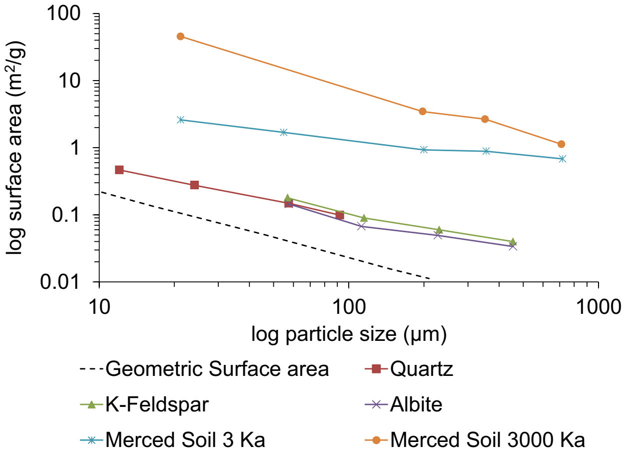

Fig. 1 Relationship between surface area and particle size (after Apello and Postma 2007)

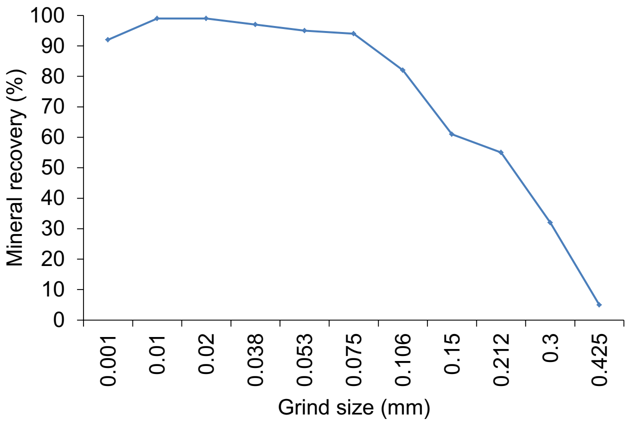

Fig. 2 Example grind size and expected mineral recovery for copper flotation process (Runge et al. 2013)

literature and will assist with geochemical engineering for tailings storage facility (TSF) design.

The main objective of this study was to understand the dependency of reaction rate of AMD mine materials on particle size to assist environmental managers such as mining companies and regulators with focused information to manage risk after sulfidic material oxidizes, such as when exposed to the atmosphere for the first time. Identification of chronological phases of AMD management requirements are seen as being beneficial to mine design and cost minimization (DITR 2007; US EPA 1994). We also sought to model conceptual cost variations based on a more accurate assessment of AMD risk.

Methodology

Sample Collection and Particle Size Fractionation

20 kg of sulfidic rock samples were collected from both an open cut brown coal mine in the Latrobe Valley, Australia (OB) and a porphyry copper deposit in Papua New Guinea (WR). The Latrobe Valley sample was a “brassy top” marcasitic rock, similar to that associated with the Greta seam of the Sydney basin, where marine incursions during the Late Permian allowed bacterial hydrogen sulfide to combine with dissolved iron in the seawater to form pyrite (Blewitt 2012). The Latrobe Valley coal is overlain in many places by a marine succession that formed brassy top between the coal seams. The Papua New Guinea waste rock porphyry consists of hydrothermally altered deposits of magnetite and sulfide in Cu-Au skarn formed in sedimentary mudstone. The porphyry consists of complex layering of alteration and mineralization derived from multiple hydrothermal events developing magnetite and Cu-Au (among other minerals) within quartz veins to form quartz-magnetite-sulfide veins (Corbett 2009). Both the brassy top and Cu-Au porphyry derived waste rock contain sulfides. A Gold float process tails material was also used as an additional particle size distribution to show the impact of similar grind size materials, based on data from Runge et al. (2013).

The rock samples were then representatively sub-sampled, ground, and separated into particle size fractions. Sieve sizes included 0.038, 0.075, 0.106, 0.425, 1, 2, 4.75, 19, and 40 mm to provide a range of smaller grain sizes similar to that created by grinding circuits for flotation recovery of porphyry copper (Fig. 2, Runge et al. 2013). The OB material was ground to < 0.038 mm, < 0.106 mm, and < 1 mm, while the WR was ground to < 0.075 mm, < 0.425 mm, < 2 mm, and < 40 mm. To extend our understanding of the relationship between particle size and reaction rates over a wider range of particle sizes than currently available in the literature, the samples were sieved to two sizes below 0.1 mm, including 0.075 mm and 0.038 mm sieves.

Oxygen Consumption Rates

The Earth Systems Ltd. OxCon testing technique (Davis et al. 2014; Schmieder et al. 2012) was used on each of the particle size samples to determine oxygen consumption rates, which were then used to estimate POR. The oxygen consumption technique has been successfully used by several studies (Anderson et al. 1999; Bourgeot et al. 2011; Davis et al. 2014; Elberling and Nicholson (1996); Elberling et al. 1994; Schmieder et al. 2012; Tibble and Nicholson 1997). The technique involves oven drying the specific grain size sample at 105 °C for 24 h, wetting until the required gravimetric moisture content of 10–15% is attained, and then reweighing and placing the sample in a sealed OxCon cell (Fig. 3). The oxygen meter was calibrated for accuracy against atmospheric O_2 and using a calibration gas with 10% O_2, and 99.99% N_2. Oxygen consumption of the ground rock sample was then measured for 72 h to determine the POR. Sulfide oxidation rates were then evaluated by normalizing the observed oxidation rate against the sulfide content of the samples. This was undertaken using the pyrite equivalent content, which assumes all sulfide is present as pyrite, and was expressed as POR in units of weight percent of remaining pyrite (equivalent) that will oxidize to form sulfuric acid (equivalent) acidity per year (wt% Py/year). Additional Bureau of Metrology (2017) atmospheric pressure data was collected during the test and compared to chamber pressure to verify the chamber accuracy (Fig. 3).

Pressure in the chamber did not vary with atmospheric pressure, which indicates minimal leakage. Temperature was kept relatively constant (from 25.0 to 25.8 °C) over the 26 day test. These test conditions were maintained for each

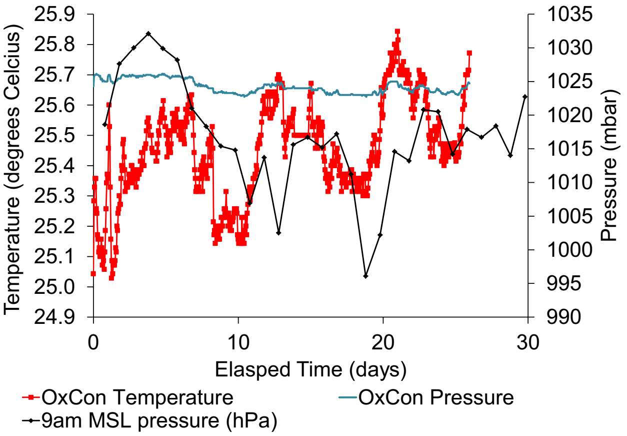

Fig. 3 WR 4.75–40 mm Ox Con chamber error checking data

particle size sample tested for oxygen consumption. The OxCon apparatus is shown in Fig. 4.

Sulfur Content in Samples

Sulfur content in the samples was examined to determine if reactivity is related to sulfur content. Three representative sub samples of each grain size batch were analyzed for total sulfur (S) and extractable S as per ASTM E1915-13 (2013). Total S was determined using a Leco sulfur analyzer. The Leco process involves heating the sub sample in an induction furnace while passing a stream of oxygen through the sample. Sulfur dioxide released from the sample is then measured by an infrared detection system, which yields the total sulfur content. The HCl extractable S results were determined by heating the prepared sub-sample with dilute HCl for 30 min. Silica and any acid-insoluble materials were removed by filtration and ferric iron was reduced to ferrous iron by the addition of hydroxylamine hydrochloride. The sulfate in the resulting filtrate was then precipitated with barium chloride in a dilute HCl medium. The barium sulfate precipitate was then filtered, ignited, weighed, and calculated as %S (of the HCl-leachable sulfate) in the original sample.

Results

Particle Size

This study extends the particle size data below < 0.1 mm by providing data on < 0.075 mm and < 0.038 mm grain size materials, to provide additional oxygen consumption derived AMD reaction rates for the smaller particles expected in a TSF. The sieve sizes used to create consecutively smaller particle sizes are shown in Fig. 5, along with the apparent sieve sizes used by Hollings et al. (2000).

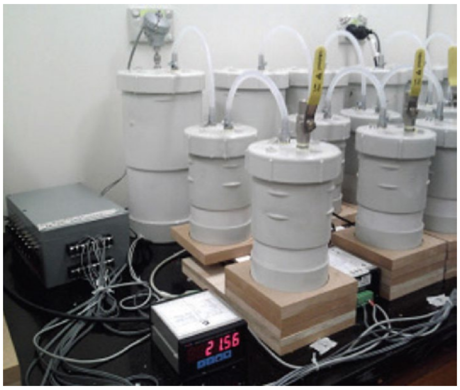

Fig. 4 Earth Systems OxCon Apparatus in action for kinetic POR determination (Schmieder et al. 2012)

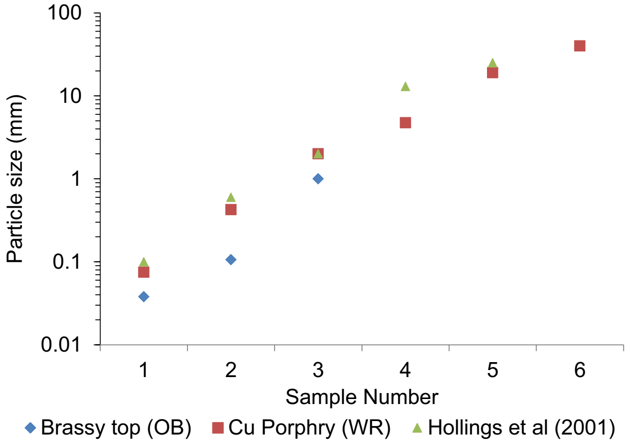

Fig. 5 Particle sizes used for particle size separation in this study and that of Hollings et al. (2000)

Confirmation of Optimal Oxidation Conditions using OB Material

Oxygen consumption testing was completed on the OB and WR materials passing a 2 mm sieve, for a range of adjusted moisture contents to determine the effect of moisture on POR. The range of moisture was adjusted from residual moisture, where absorbed moisture is dominant and effective porosity is large, through to approaching saturation. These tests were used to confirm optimal median moisture content to provide high rates of AMD/POR sulfide oxidation. These conditions were maintained to ensure high POR rates and less variability, so these factors would have minimal influence on the study, as suggested by Hollings et al. (2000).

Figure 6 shows that POR was sharply reduced at low moisture contents (< 4 wt%) due to a lack of available

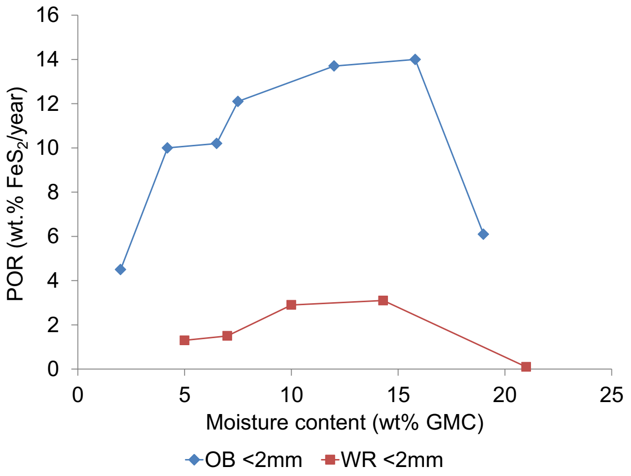

Fig. 6 OB POR vs. gravimetric moisture content (GMC) the green area is the optimal oxidation moisture content

moisture for pyrite oxidation, and also at high moisture contents (> 16 wt%) due to low effective porosity and associated low soil gas (oxygen) diffusion rates. The median moisture contents (10-15 wt%) were identified for both the OB and WR material as having high and relatively stable POR rates (the green zone in Fig. 6). These optimal moisture content values (10–15%), temperature (20–21 °C), and atmospheric pressure were maintained for subsequent oxygen consumption testing on sieved material, as per Hollings et al. (2000) for optimal oxidation of both the OB and WR samples.

The OB samples were oven dried prior to wetting to the target moisture content to minimalize biological activity during the testing period, and the oxygen consumption chamber was gas sealed to prevent oxygen leakage during testing.

Sulfur Content

Results for total S (%) in the WR and OB sieved samples are shown in Fig. 7, with the total S content in OB rock (25–35%) being significantly greater than in the WR (0.5–5%). The data for total S shows the increased variability of sulfide content as particle size increases, and the converse, which is a much smaller difference in total S content as particle size decreases. The WR sample with the large particle size of > 19 mm supports this finding, showing the most variation with one sample with more than 5% total S and the other two sub samples yielding less than 1% total S.

In the WR sample, the highest total sulfur content was found in the 0.075–0.425 mm sample rather than in the finer < 0.075 mm. This may be due to the natural crystallization size of the sulfide materials, since this effect did not occur in the OB sample. The HCl extractable sulfur is an indicator of completed sulfide oxidation and was useful for normalizing the oxygen consumption data to show a relationship between reaction rate and grain size (Fig. 8). The WR samples were low in extractible sulfur, which may indicate that less oxidation occurred in these materials, while the OB samples were higher in extractible sulfur, but with more total sulfur, which may have remaining oxidizing potential. This was investigated in further analyzes of particle size and total and extractible sulfur below.

The WR and OB samples were plotted for grain size against total and extractable HCl sulfur content (Figs. 8, 9). Figure 9 shows that the WR samples contained less extractible sulfur and were less variable in content than the OB samples.

While the WR samples showed a slight (1–2.5%) change in the fraction of extractible S compared to total S, the OB samples showed a large increase in the fraction of extractible S with decreasing particle size, again demonstrating potential reactivity and the benefits of milling ore prior to processing. The OB samples contain relatively high total S (25–30%) and higher extractable S (0.75–3%), compared to the WR sample, which had less total S (0.5–4.5%) and less extractable S (≈ 0.05–0.1%).

Oxygen Consumption and Pyrite Oxidation Rates

The oxygen consumption results were used to predict the POR, which was used as the indicator of the AMD reaction rate in this study. The POR were sample size adjusted (as wt%/year FeS_2) for each grain size sample and median total and extractible S (Table 1).

The oxygen consumption results for the WR 4.75–40 mm particle size are highlighted to show the influence of particle size for the larger particles, with relatively little oxygen

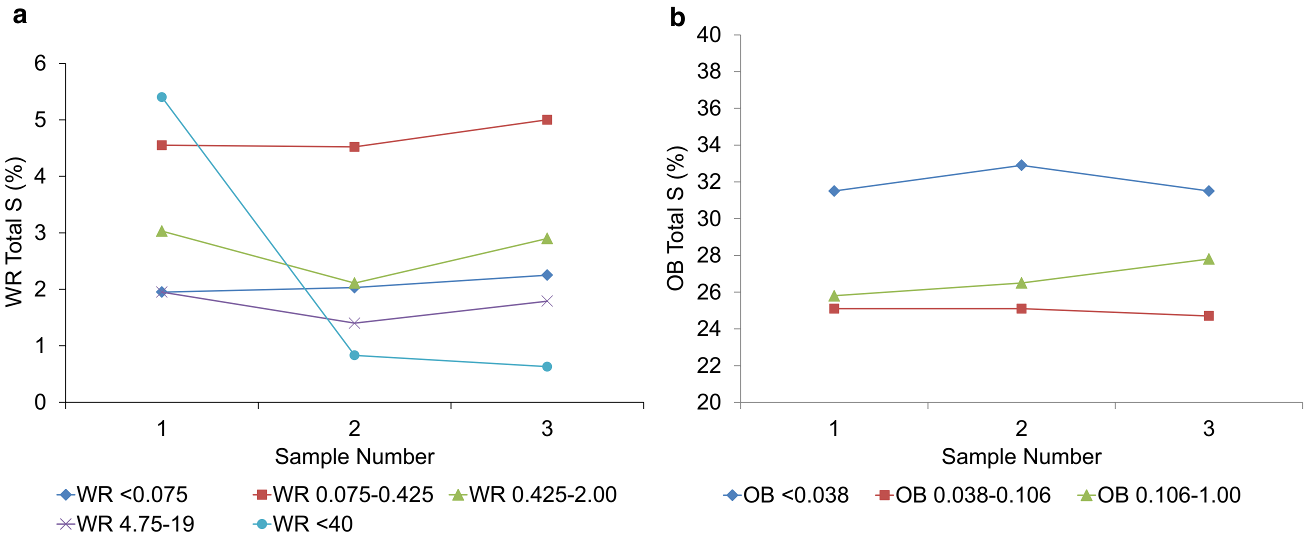

Fig. 7 Total S (%) results for the WR and OB samples

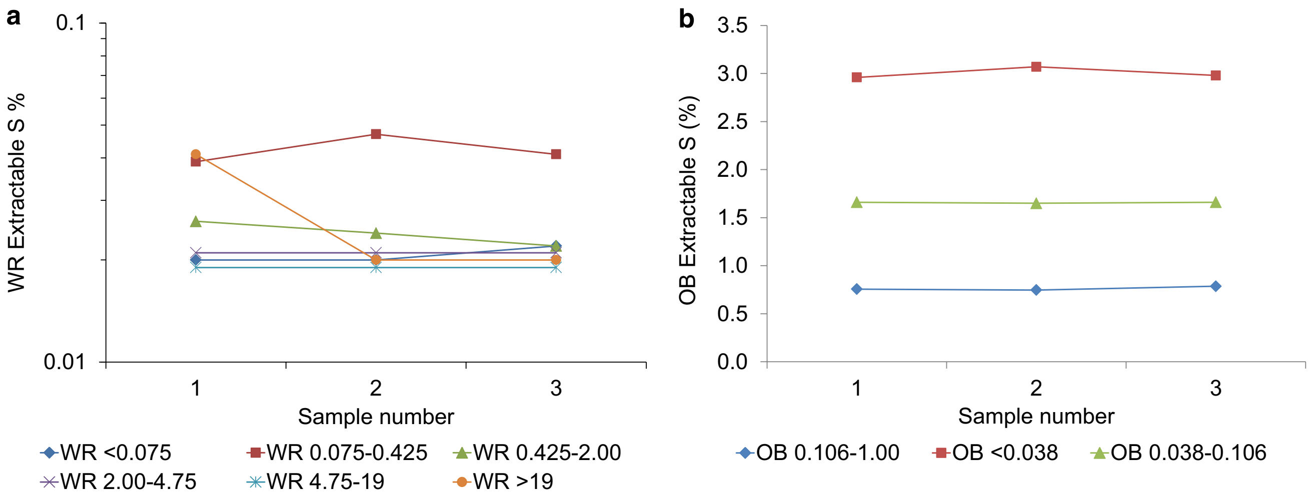

Fig. 8 HCl Extractable S (%) results for the WR and OB samples

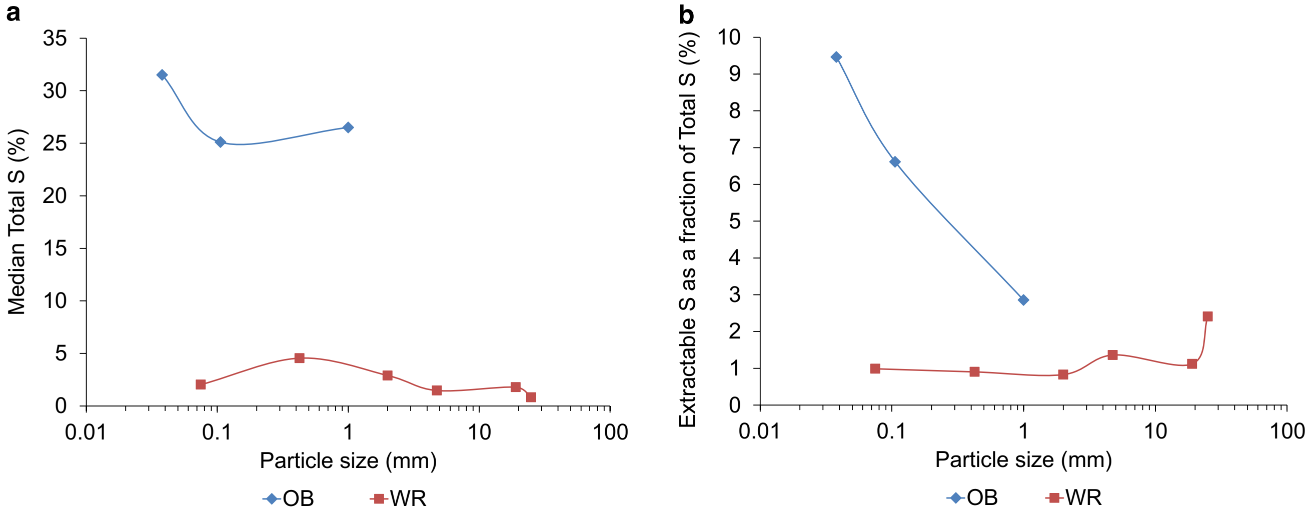

Fig. 9 Particle size vs. median total S (%) and particle size vs. extractable S as a fraction of total S (%)

Table 1 Particle size, total and extractable S, and POR results

Material	Particle/grain size (mm)	Median total S (%)	Median extractable S (%)	POR (wt %/year FeS2)
OB	< 0.038	31.5	2.98	117.02
	< 0.106	25.1	1.66	71.16
	< 1	26.5	0.756	14.01
WR	< 0.075	2.03	0.02	10.51
	< 0.425	4.55	0.041	4.42
	< 2	2.9	0.024	2.12
	< 4.75	1.47	0.02	1.09
	< 19	1.79	0.02	0.26
	< 40	0.83	0.02	–

consumption over 30 days due to few available sulfide oxidation sites. Oxygen concentration in the OxCon cell over the testing period is shown in Fig. 10.

The Ox Con O_2 concentration (%) reaction trace for each of the sieved WR and OB materials is shown in Fig. 10. Comparing the oxygen consumption of the various size grades of the OB and WR material, it can be seen immediately that the OB material was more reactive, with each size grade consuming all of the available oxygen in the cell in less than 14 days. The WR material showed a strong reaction gradient with smaller particles being more reactive than larger particles, as one would expect. However, the WR material was less reactive than the OB material with only a 4% reduction in O_2 concentration over 25 days.

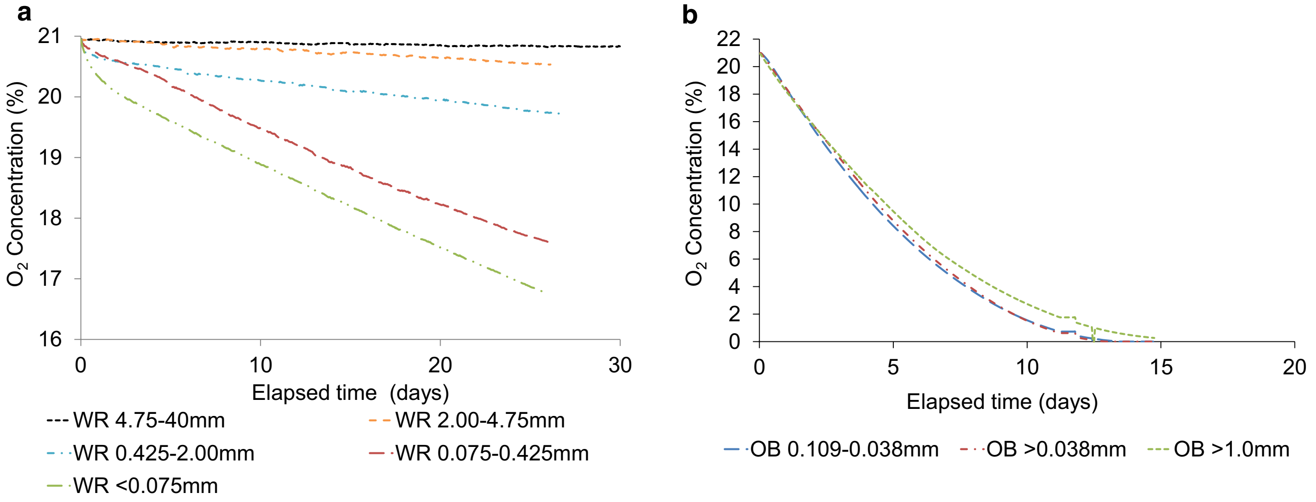

Fig. 10 Ox Con O_2 (%) concentration in WR and OB samples over time

Finally, the results of the POR were then graphed against particle size to demonstrate the relationship between particle size and reactivity (Fig. 11). For both materials, the relationship was exponential: as particle size decreased, reactivity increased exponentially, confirming that particle size influences reaction rate.

The OB and WR data fit to a power relationship shows an R^2 of 0.99 and 0.97, respectively. The highly exponential behavior of POR compared to particle size, particularly in material below 1 mm in size, confirms that decreasing particle size increases reactivity. Comparing the strength of this reactivity effect between the low total S (WR) and the high total S (OB) material, it can be seen that the OB material displays a more strongly exponential behavior. Particle size increases acidity generation exponentially and this effect is likely to increase further with greater sulfur content. In the next section, the particle size and reactivity functions derived in Fig. 11 will be used to derive treatment costs for a geochemically stable mine closure.

Mine Rehabilitation Costs for Three Different Mine Wastes

A conceptual calculation of mine rehabilitation costs was conducted to illustrate the AMD management costs to provide geochemical stability for three different mining wastes: (1) the WR material, (2) the OB material and (3) a gold float tailings material. Particle size data for similar mine wastes types was applied to the material POR data to provide three

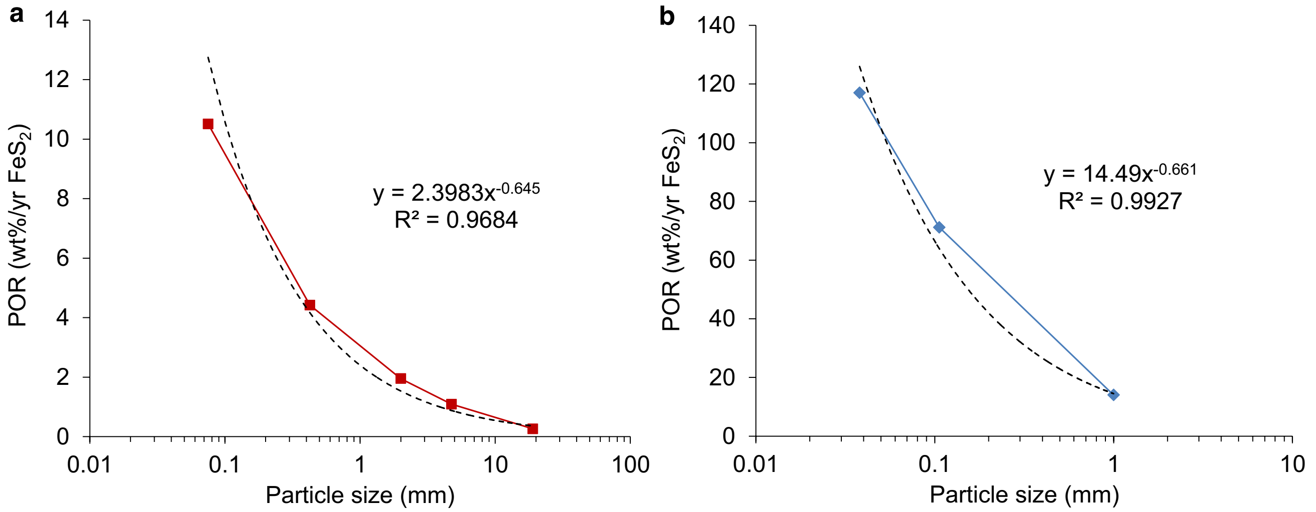

Fig. 11 Pyrite oxidation rate and particle size in the OB (left) and WR (right) samples

AMD management scenarios, including a copper float tailings particle size analysis (PSA) for the OB, a heap leach grind size for the WR, and a gold float PSA for the gold float tailings material. The assumptions of the modelling include:

- Rehabilitation requires addition of neutralizing materials to achieve geochemical stability for closure.
- The same unit price and reactivity (neutralizing potential) for neutralizing materials at each mine site.

Table 2 illustrates a simple methodology showing how PSA-based AMD costs can be calculated conceptually using the PSA/POR data from this study. The geochemical engineer undertaking the neutralization process design in tailings or waste rock will need to conduct some further inexpensive studies to investigate the reactive surface area/particle size relationship of the neutralizing material to determine the ultimate neutralizing potential per unit of material.

The calculated cost of geochemical treatment for the three mine materials are presented in Fig. 12. Figure 12a shows the reactivity of each particle size group for each mine material, with fine materials displaying more reactivity, even in the least reactive WR material. Figure 12b provides data on the relative mass of each material based on the PSA; most of the OB material (60%) is grind size 0.106 mm, the more reactive 0.038 mm material is only 10% by weight, while the unmilled material is all the same material (100%). Most of the WR material is 1 mm in size, while the gold float process tailings is at the other end of size spectrum, with most (70%) being less than 0.038 mm. Figure 12c shows the relative amounts of neutralizing material required by mass for each material and grind size and a comparison to the unmilled ore. While the 1 mm component is greater by mass, its lower reactivity requires less neutralizing material, while the 0.038 mm material requires more.

The final AMD treatment cost is shown in Fig. 12d, which illustrates the possible potential error of basing a conceptual mine design on the unmilled ore geochemistry alone. Treatment costs based on a PSA/POR-based reactivity analysis is about four times greater for OB material than predicted by simple POR testing of the unmilled ore sample. The gold float tailings treatment cost was about seven times greater than the unmilled ore. On the cost saving side of the balance sheet, the WR materials cost less to treat than the unmilled ore materials, indicating that all materials should be tested for POR prior to commencing geochemical stabilization design work as a potential cost saving.

Similarly, all potential neutralizing materials available at the mine site should be evaluated for use as treatment material; this can represent a major cost saving to mine design when enough neutralizing materials are available at the mine site.

Discussion

The results show that particle size distribution can strongly influence total mine tailings processing costs. The ramifications of this for practitioners designing mine waste storage facilities, such as a TSF with particles in the silt to sand range, should be obvious. Modelling of mine rehabilitation costs shows that to accurately predict AMD generation during operations and closure phases, mine designers must accurately determine the sulfide reactivity rate for each representative mill grind size. Undertaking the PSA/POR test detailed in this study for five grind sizes is estimated to cost less than $50,000 (US) commercially, which is insignificant relative to total processing or mine development costs.

It is important to note that Erguler et al. (2014) found that reducing particle size can reduce hydraulic conductivity for some situations and materials, which may reduce AMD development, but this is likely site specific and applies to undisturbed mine wastes. There is also a possibility that reducing hydraulic conductivity will reduce the rate of oxidation but will not prevent the completion of the process. When mine wastes are moved (for rehabilitation or uncontrolled placement), it is thought that a decrease in particle size and increased reaction is likely, but careful modelling of available neutralizing material and soil gas transport is required to pursue treatment savings that may be derived from reducing hydraulic conductivity (AMIRA 2002).

The greater variation in total S in the larger WR particles illustrates why mine ore is crushed and milled prior to processing, not just to provide for greater ore recovery

Table 2 Example of a PSA-based AMD-load conceptual cost calculation for OB materials

Particle size (mm)	POR (wt%/year FeS2)	PSA percentage (wt%)	Neutralizing material (units)	Conceptual cost (per unit)
< 0.038	117	10	12	59
< 0.106	71	60	43	213
< 1	14	30	4	21
			Total	293
Unmilled ore	14	100	14	70
			Total	70

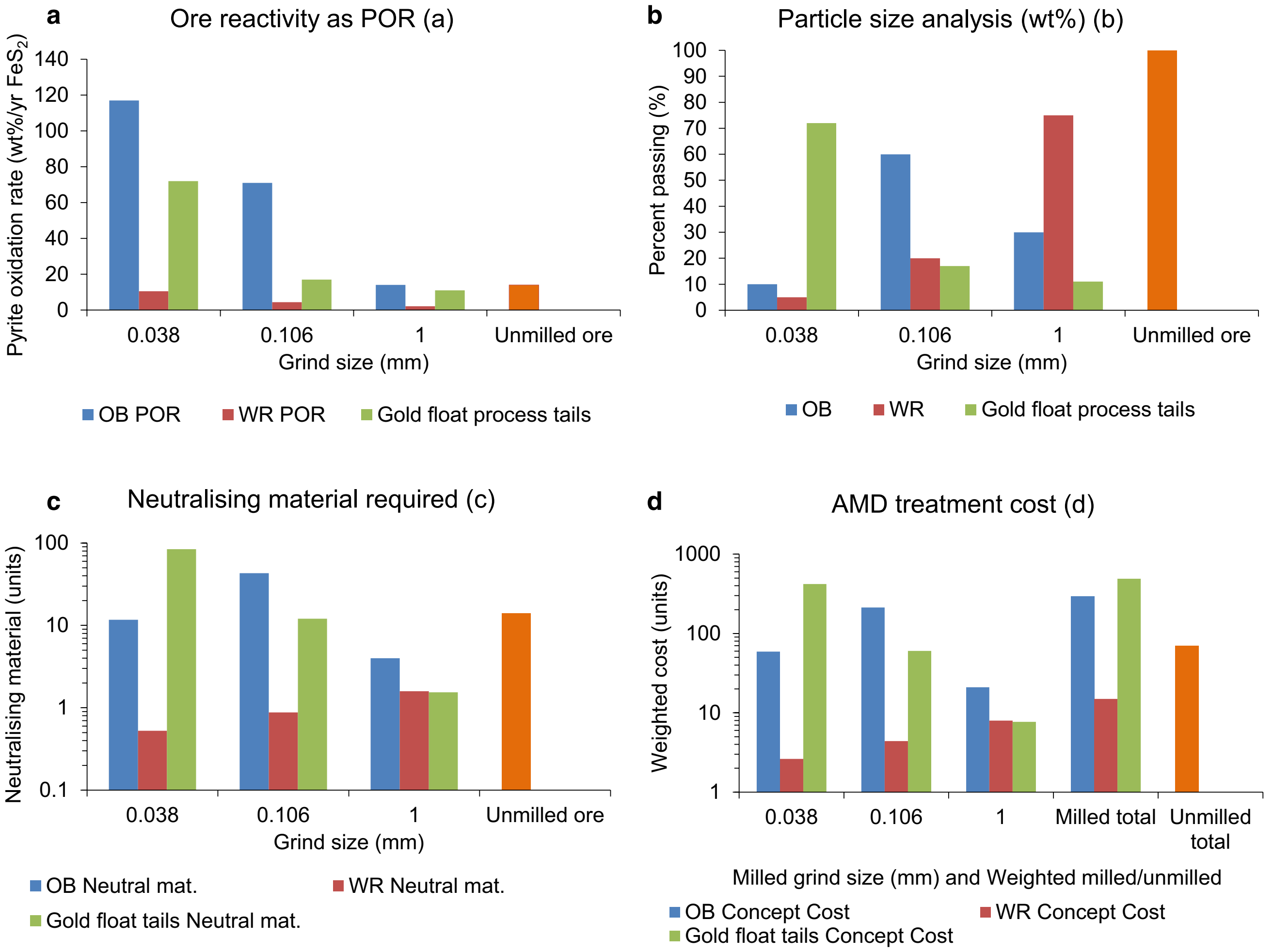

Fig. 12 Conceptual geochemical stabilization cost of considering unmilled ore compared to PSA/POR method for OB, WR, and gold process float tailings

but to ensure reliable extraction rates. Well mixed, fine grained materials will generally display less variation in content from the same source materials.

Total acid load has to be calculated over the period of mining life and after closure for inclusion in acid–base accounting calculations (DITR 2007). In this study, for the materials tested, the volume of particles below 1 and 0.1 mm in size were capable of delivering 6–10+ times the acidity load by mass of the larger materials in the waste rock and ore materials after blasting and crushing.

The mine process designer should estimate the return in ore from the milled product and compare that to the long-term cost of ensuring geochemical stability of the tailings before deciding on an optimal particle size. Developing similar particle size to POR relationships is recommended during geochemical assessment of the ore in the exploration phase to help determine the final reactivity and POR of the anticipated wastes (tailings and waste rock).

The results of this study indicate strongly that very fine-grained materials increase the cost of maintaining geochemical stability of the processed mine wastes in AMD mine materials. Oxygen diffusion inhibiting covers may reduce the rates of pyrite oxidation, but unless the mine is in a high rainfall area, this oxidation cannot be prevented during closure. Geochemical stabilization of waste rock and tailings will very likely require additional neutralizing materials. The neutralization material or treatment required should be calculated based on the volumes of various grain size fractions stored in the TSF/WRD to correctly account for exponential acidity production by the finer grain sizes.

While this sounds like a case for permanent water covers, wet clay-GCL caps, and other oxygen diffusion limiting technologies, there are at least three potential issues that require investigation before these technologies can be an acceptable solution: (1) weathering and natural soil heaving and slumping will cause wet clay-GCL caps to become permeable within 4–5 years of commissioning (Benson 2014); (2) very fine grained materials can become mobile in the porous media of the TSF/WRD liner, seepage groundwater, and surrounding geology, especially if pyrite oxidation and acidity changes the porosity of the liner system (Naka et al. 2014); and (3) seismicity of the TSF location may limit the design life of the TSF structure (and many existing TSFs are built to have a short design life due to planned AMD management during closure) and require geochemical stabilization to prevent environmental harm in the case of structural failure (Zardari 2011). These three issues virtually mandate the creation of geochemically stable mine tailings and waste rock at least at closure, but preferably during operations. These issues should be dealt with at an early phase by mine designers and geochemical engineers, for instance by adding sufficient neutralizing material to deal with all of the potential acidity before final deposition in the TSF. Government EIA/EIS procedures and guidelines for the mining sector should be updated to include similar procedures for evaluation of reactivity risk to increase the likelihood of sustainable outcomes for the mining sector.

Conclusion

The study demonstrated that grain size is a principle factor affecting POR and reactivity within AMD materials in waste rock and tailings materials generated from mining processes, using materials from a highly sulfidic overburden from the Latrobe Valley coal provinces, and a moderate-to-low sulfidic rock material from a porphyry copper deposit in Papua, New Guinea. The AMD POR reactivity was found to exponentially increase as grain size decreased, with the effects particularly marked for materials less than 1 mm in size. This exponential reaction relationship for small particles is important to understand if a mine waste structure, such as a TSF or waste rock dump, is to achieve environmentally sustainable mine closure requirements.

This study extends previous geochemical reaction rate studies using oxygen consumption techniques on AMD/PSA-based reactive materials and shows that particle size is a clearly an important mine design parameter that needs to be considered, along with its associated geochemical reactivity. Mine waste managers seeking designer tailings with no net environmental risk, are advised to undertake geochemical reactivity testing on all mine site materials, at several moisture contents and grain sizes representing the proposed milled material grain size for mineral processing. The results of the grain size reactivity analysis should be included in the mine's acid base accounting assessment so that a fair and reasonable assessment of risk can be apportioned for both mining bonds and mine closure costs. Some mine site materials will be determined to have neutralizing capacity, which is an important potential cost saving for the geochemical stabilization mine waste management system.

The implications for AMD material treatment effects on a theoretical closure costs have been carefully evaluated for three different mine wastes. The scenarios demonstrate both underestimation and overestimation of the closure cost, when insufficient kinetic testing results are available. Final theoretical AMD treatment costs were shown along with the potential error in basing concept mine design on geochemistry results from unmilled ore geochemistry alone. Treatment costs based on PSA/POR based reactivity analysis was between 4 and 7 times higher for the ground ore materials than for the same conceptual design cost to treat unmilled ore.

The cost of the studies to undertake this work and the geochemical engineering design required should have a negligible effect on project profitability and represents project insurance for companies facing the risk of an AMD legacy. Long term costs will be dramatically reduced, especially during closure, when treatment and mitigation costs without such considerations is likely to be ten times higher, and ore is no longer available to help pay for water treatment.

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