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Multi-scale quantification of leaching performance using X-ray tomography

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ABSTRACT

The performance of heap leaching is dictated by a large number of processes acting at a wide range of length scales. One important scale is that of the individual particles, where the interaction between the rate kinetics at the surfaces of the individual mineral grains and the mass transport through the particle combine to give the overall apparent particle scale kinetics. It has been recognised for a long time that variability in the mineralogy, size and spatial distribution of the mineral grains within the particle are likely to have a large effect on the leach performance and its variability and thus, ultimately, the performance of the heap. In this paper a new method for quantifying this behaviour and its variability at scales from the particle through to the grain and down to the surface kinetics is presented. This method is based on the use of a series of XMT (also called micro-CT) images of a column taken at regular intervals over 168 days of leaching. The key development in the analysis of this data is an algorithm that has allowed every single one of the hundreds of thousands of mineral grains within the column to be individually tracked across all the time points as they undergo dissolution. This has allowed the dependency of the mineral grain leach rate on its size and position in the particle to be decoupled from one another. It also meant that the variability in the surface kinetics of the grains could be assessed, with mineralogical variability being the key source of this variability. We demonstrate that understanding and quantifying this underlying kinetic variability is important as it has a major impact on the time evolution of the average kinetics of the leaching.

1. Introduction

While metal production has kept pace with increased demand this has generally been achieved by exploiting deposits with more problematic mineralogies and ever lower ore grades. As the grades of ores decrease, heap leaching is becoming a more attractive alternative to conventional processing routes, such as flotation followed by smelting, as it does not require milling of the ore and the operating cost per unit of metal is thus less sensitive to grade. Approximately 20% to 30% of the world's copper and more than 12% of gold is produced by this technique (Bouffard and West-Sells, 2009; Jergensen, 1999; Kappes, 2005). The biggest disadvantages of heap leaching, though, are the long processing time and relatively low extraction efficiencies, especially for primary sulphides.

Research into heap leaching can be divided into a range of spatial scales involving different processes and sub-processes, including the macro-scale (heap scale effects), meso-scale (groups of particles, typically investigated through column scale studies), individual ore particle scale and grain scale (Dixon and Petersen, 2003). At each scale, there are several different sub-processes and control parameters which can affect leach behaviour. In general, conditions and concentrations in the fluids around the ore particle, the mass (and heat) transport within the ore particle and surface reaction kinetics are the main factors which can affect the leach performance at the meso-scale and which determine the apparent leach kinetics. Most studies of heap leaching have either concentrated on the first or last of these factors, either using particle sizes representative of real heaps and studying the apparent kinetics as a function of the effluent and/or feed conditions (e.g. van Hille et al. (2010)) at column or larger scale, or have attempted to obtain the surface reaction kinetics by studying the dissolution of finely milled ore or pure mineral particles in stirred tank experiments (Córdoba et al., 2008; Hiroyoshi et al., 2001) at the grain scale. A lack of data on the transport processes within the ore particles makes it very hard to predict heap or even particle scale leach performance based directly on the surface reaction kinetics, while only studying the behaviour based on the overall performance makes it hard to determine the dominant mechanisms at

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work and how these vary spatially, temporally and with operating conditions.

The aim of this paper is not to attempt to mimic all the variability encountered in a real heap or to measure the impact of variability in the fluid conditions around the particles, but to rather examine the leach behaviour and its variability at the scale of the individual particles and the mineral grains within them. An experimental system consisting of multiple small columns was chosen, as this would ensure that all the particles within them would experience similar leach conditions. Small columns have the added advantage of being able to be repeatedly scanned at high resolution.

The technology that allowed us to study the grain scale leach behaviour is X-ray micro-computed tomography (XMT, also termed μCT) coupled to advanced image analysis algorithms. The advantage of XMT is its ability to image the internal structure of materials, including geological samples (Ghorbani et al., 2011b, 2013; Ketcham and Carlson, 2001) in a non-destructive manner. XMT produces images based on differences in X-ray attenuation, which, in turn, depends on the electron density and hence a combination of the density and atomic mass of the materials. This means that within the copper ore used in this study the sulphide species can be readily distinguished from the mainly silicate gangue, though the various sulphide species have similar attenuations and are thus hard to distinguish from one another.

In this work XMT has allowed 3D images of the mineral grain distributions to be obtained within the same leaching particles at a succession of time points. In order to analyse this data we have developed advanced image quantification algorithms (Lin et al., 2015) that have allowed us to track the dissolution of many hundreds of thousands of individual mineral grains over the course of many months of leaching. The analysis of this data set is thus the main focus of this paper. It should be noted that due to the difficulty in distinguishing different sulphide phases this paper examines the dissolution of the sulphide grains rather than specifically the copper extraction. In later sections where the grain scale variability is quantified, much of this will therefore come from mineralogical variability.

2. Experimental methodology

The leached sample consisted of copper sulphide ore particles from Kennecott with a size ranging between 8 and 11.2 mm. The ore composition was obtained using the Mineral Liberation Analyser (MLA) (see Table 1).

As this method is destructive, the composition is not that of the actual particles in the column, but rather that of similar particles.

The small scale column leaching experiments were carried out using an incubator with temperature control, which allows multiple columns to be run at the same time. The reason for using an incubator is because, despite the exothermic reactions, small columns lose too much heat to be able to maintain the temperatures typically encountered within a heap. In these experiments the incubator was maintained at a temperature of 60 °C. Fig. 1 shows a schematic diagram of the experiment setup, a photograph showing a few of the columns loaded with ore particles and undergoing leaching, as well as the scanning regions for each column (blue). Glass columns with a 28 mm internal diameter and 190 mm height were used in the experiments. The resolution of the XMT images depends on the diameter of the sample being scanned. The diameter of the column used is thus the result of a compromise between the amount of sample being leached and the resolution of the 3D images produced.

Table 1
Main mineral species within ore sample used in experiments. Prevalence is reported as volume percentages as these are most relevant to micro-CT analysis, which also measures volume.

Mineral type	vol.%
Copper containing species	**1.05**
Chalcopyrite	0.58
Covellite	0.15
Cu oxides	0.03
Other Cu minerals	0.29
Pyrite	**4.43**
Gangue minerals	**94.5**
Quartz	51.4
Muscovite	39.9
Clays	1.0
Other gangue minerals	2.2

The leach solution used in these experiments contained 5 g/L Fe^{3+} as iron sulphate, as well as 0.1 M H_2SO_4 to achieve a feed pH of approximately 1. The flow rate of this solution into the column was 160 μL/min, which is equivalent to approximately 16 L/m^2/h. The flow rate was controlled by a multi-channel peristaltic pump. The solution was not recycled. The ferric ions were added to the solution to act as the main leaching agent. This was done to mimic the effect of bacterial action, which in an actual heap would generate ferric ions mainly through a combination of the leaching of the pyrite and the oxidation of the ferrous ions in solution. While there is still some controversy as to the exact mechanisms involved, especially for chalcopyrite, the overall ferric leaching reactions for the chalcopyrite and pyrite are typically described as being as follows, with a subsequent reaction in which a portion of the elemental sulphur is converted to a sulphate (Habashi, 1999):

$$CuFeS_2 + 4Fe^{3+} \rightarrow Cu^{2+} + 5Fe^{2+} + 2S^0$$

$$FeS_2 + 2Fe^{3+} \rightarrow 3Fe^{2+} + 2S^0$$

$$2S^0 + 3O_2 + 2H_2O \rightarrow 4H^+ + 2SO_4^{2-}$$

3. Image acquisition and processing methodology

The columns used in this study were scanned using a Nikon Metris Custom Bay with a 1 mm aluminium filter (to reduce beam hardening effects), 89 kV energy, 0.708 s exposure time and 2001 projections. The detector size was 2000 × 2000 pixels, which gave a linear resolution of approximately 17 μm. Three volumes (top, middle and bottom for each column) were scanned at each time point over the leaching period. Scanning was done by removing the entire column from the incubator and placing it within the scanner before replacing it within the incubator. This was done as rapidly as possible in order to minimise the disturbance to the column. As the leaching rate in the columns decreased with time, the interval between scans was increased. The scanning intervals are given in Table 2.

While the entire column was initially imaged, in subsequent scans the same three sub-volumes of the column were imaged (see Fig. 1). The reason for doing this was a combination of the most efficient use of the available equipment time, as well as the desire to minimise disruption of the feed and heating of the column. The total number of tracked whole ore particles[1] within these three sub-volumes was 26 for this column.

After scanning, the images needed to be reconstructed and relevant data quantified. The main image processing steps were as follows:

1. The reconstructed image had a 3 × 3 × 3 median filter applied to reduce the noise level.
2. The rock phase was thresholded using the Otsu algorithm (Otsu, 1979). This algorithm was used as there are distinct peaks in the intensity histogram between the rock and the air phases.

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[1] A whole ore particle means one where the entire ore particle appears in all the images. Ore particles were ignored when only part of the particles appeared in the scan.