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The effect of particle porosity on liquid holdup in heap leaching

I.M.S.K. Ilankoon, S.J. Neethling *

Rio Tinto Centre for Advanced Mineral Recovery, Department of Earth Science and Engineering, Imperial College London, London SW7 2AZ, United Kingdom

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ABSTRACT

The inter- and intra-particle porosities of heaps have two distinct length scales (of order millimetres between the particles versus tens of microns within the particles) and therefore the dominant flow mechanisms within and around the particles are quite different. This paper investigates the effect of particle porosity on heap hydrodynamics by comparing the behaviour of a model system consisting of non-porous glass beads with a system of actual ore particles. The overall liquid holdup behaviour of these two systems initially appears quite different. However, when the effect of the liquid holdup around the particles is separated from that within the particles, the same theoretical flow model can be applied to both the model and ore systems. This demonstrates that correlating the liquid flow to the overall liquid holdup is problematic and that the effect of the inter- and intra-particle liquid holdup should be considered separately. This is important as the amount of liquid held within the ore particles in these experiments was nearly as large as that held around the particles. The model for the external liquid flow proposes a power law relationship between the relative flow rate (flow rate divided by residual holdup) and the excess relative holdup (the steady state liquid holdup divided by the residual holdup minus one) with an exponent of two. It was found that the pre-factor in this relationship was quite a strong function of particle size for the spherical glass beads, but relatively constant for the more angular ore particles.

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1. Introduction

The fluid flow in heap leaching is unsaturated, consisting of both leaching solution and air (Bartlett, 1992). The liquid flow characteristics are a very important aspect of the leaching process, influencing both the overall recovery and apparent kinetics of the system (Murr et al., 1981; Yusuf, 1984). There have been a number of studies of the fluid flow in heap leaching systems, but these studies have either tended to be purely empirical or produced qualitative descriptions of the fluid flow behaviour (e.g. Roman, 1977; Murr et al., 1981; Yusuf, 1984; de Andrade Lima, 2006). More theoretical modelling of the fluid flow in heaps has typically involved using Richard's equation, which is a description for fluid in particle beds often used in ground water and oil reservoir modelling (Decker, 1996; Decker and Tyler, 1999; Cross et al., 2006).

The problem with all these approaches is that they either treat the liquid holdup as an empirical input parameter, which limits the predictive ability of the method, or they propose a direct relationship between the liquid holdup and the flow permeability of the system. In this paper, it will be demonstrated that the use of such a direct relationship is not entirely appropriate for two different reasons. Firstly, these systems exhibit hysteresis, with the steady state liquid holdup depending not only the current flow rate, but also on the flow rate history (Ilankoon and Neethling, 2012). It will also be demonstrated that the presence of porous particles has a marked influence on the liquid holdup and flow behaviour.

The packed bed that constitutes a typical heap has porous particles that are mainly in the size range of millimetres to a few centimetres. Thus, the porosity of the packed particles has two distinct length scales, namely that of the channels between the particles (i.e. interstitial space), which will typically have a length scale of order millimetres, and that within the particles (i.e. intra-particle space), which will typically have a length scale of order tens of microns and smaller. The Bond number, which is the ratio of gravity to capillary forces, will be around 1 for the fluid flow between the particles, indicating that this flow is in the transition region between capillary and gravity dominated flow. However, the existing micro-pores within the particles will have Bond numbers that are many orders of magnitude less than 1, indicating capillary dominated flow (note that a Bond number well below 1 does not mean that gravity does not affect the flow rate, it rather means that the shape of the flow paths is not influenced by gravity). This distinct separation of length scales means that liquid holdup within the particles will not have the same effect on liquid flow as the holdup between the particles and must thus be considered separately.

The main objective of this study is to experimentally investigate and model the effect of the particle porosity on the overall flow through a heap by comparing the behaviour of a model system

* Corresponding author. Tel.: +44 (0)20 7594 934.
E-mail addresses: i.ilankoon08@imperial.ac.uk (I.M.S.K. Ilankoon), s.neethling@imperial.ac.uk (S.J. Neethling).

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consisting of non-porous glass beads with an ore system consisting of similar sized copper ore particles. A theoretical flow model to describe the flow between the particles in a way that it accounts for hysteresis in both systems will be developed.

2. Experimental design and methods

The liquid holdup measurements in a circular Perspex bed of 243 mm diameter and a height of 300 and 500 mm were performed gravimetrically by suspending the column from a high precision load cell. In order to verify that the load cell was able to measure the relatively small changes in liquid content needed in this work, the gravimetric measurements were compared to an independent measurement based on the volume of drained liquid (see Ilankoon and Neethling (2012), for the method and results), with both methods giving virtually identical results and thus providing confidence in the load cell based measurements.

The glass bead system (i.e. model system) consisted of randomly packed mono-dispersed spheres of 2, 10, 14 and 18 mm. This size range covers the particle size typically found in column and industrial heap leaching.

Similar experiments to those performed with the non-porous glass beads were repeated with slightly porous copper ore particles. A sample of copper ore of around 285 kg was collected from Kennecott Utah Bingham Canyon mine.

Kennecott Utah Bingham Canyon mine is a low grade ore deposit that contains finely disseminated sulphide minerals, primarily copper and iron sulphides within a predominantly quartz monzonite host rock (Lufkin, 2010; Rio Tinto, 2009). This porphyry copper ore body has zones of both primary (containing mainly Chalcopyrite ($CuFeS_2$) and Bornite (Cu_5FeS_4)) and secondary (containing Chalcocite (Cu_2S) and other species) sulphide mineralisation. The current grade of this deposit is less than about 0.75% copper (Lufkin, 2010). After drilling and blasting, the rock is crushed to less than 250 mm (10 in.) in diameter in a gyratory crusher (Rio Tinto, 2012). The ore sample used in this project was obtained from the product of this primary crusher. The original ore sample thus has a size distribution that is wider and coarser than that typically encountered in heap leaching and is more typical of a dump leaching size distribution. The original size distribution is not especially relevant to the results obtained as narrow size intervals were obtained from the sample for use in the experiments presented in this work. Sieve analysis was performed using the sieve sizes of 2, 4, 8, 11.2, 13.2, 16, 20, 26.5, 31.5, 37.5 and 45 mm. The resultant particle size distribution curve is shown in Fig. 1.

All the ore experiments were conducted in the 300 mm column, as there were insufficient particles in each size range to fill a 500 mm column. Typically, about 18 kg of particles were required to fill the 300 mm column. The bottom plate of the column has apertures of 2 mm, thus setting the smallest size of particles that could be tested. The 2–4 mm particle size range did not contain sufficient material to fill the column and thus the smallest size range tested was the 4–8 mm fraction.

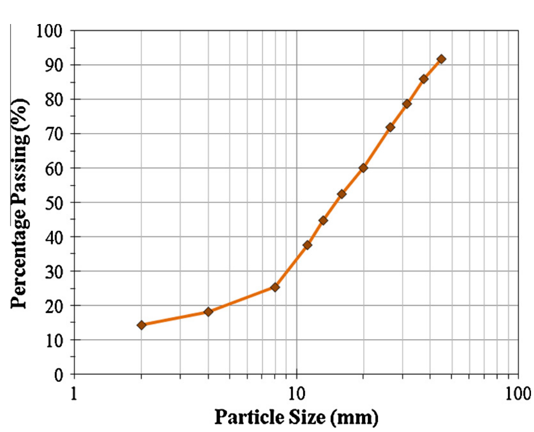

Fig. 1. Particle size distribution of the original copper ore sample.

Nine different narrow size fractions of ore particles were used in these tests, namely 4–8 mm, 8–11.2 mm, 11.2–13.2 mm, 13.2–16 mm, 16–20 mm, 20–26.5 mm, 26.5–31.5 mm, 31.5–37.5 mm and 37.5–45 mm (Fig. 2).

The water accessible porosity of the ore was obtained by subtracting the weight of ore particles which were soaked for 3 days from the dry weight of the particles. The soaked particles were screened and patted down with a cloth to remove any external water. This can cause some inaccuracies and therefore porosity values are only estimates. The water accessible porosity is likely to be lower than the actual porosity as some of the pore volume might not be connected to the particle surface. The porosity values are within the range of 2–7%. Larger water accessible porosities were found in the smaller ore particles (e.g. 7.1% in the 4–8 mm fraction versus 2.2% in the 37.5–45 mm fraction). The most likely reason for this is that the average distance to the surface is smaller in the smaller particles and therefore there are less likely to be unconnected pore spaces in the smaller particles. Another possible contribution is that more porous regions of the ore might fracture more easily and thus be over-represented in the smaller size fractions.

Fig. 3 shows both the model system and the ore system together with the other main components of the 1-D experimental rig.

A novel liquid distributor was designed so that liquid could be evenly distributed over the surface of the packed bed (Fig. 3 and see Ilankoon and Neethling, 2012). The distributor consists of 32 individual drip points with equal flow from each point. The liquid distributor was mounted over the packed bed as a separate unit, thus not affecting the weight measured by the load cell. The superficial flow rates within the range of 0.0075–0.12 mm/s were used, the lower values of which are within the relevant range of solution application rates in industrial leaching and studies of column leaching (Roman et al., 1974; Cariaga et al., 2003; de Andrade Lima, 2006). The full details of the experimental setup can be found in Ilankoon and Neethling (2012).

2.1. Steady state and residual liquid holdup measurements with the model system

Liquid was introduced at the lowest rate (i.e. 0.0075 mm/s) to the non-porous system to measure the steady state liquid holdup, which was achieved after approximately an hour. After recording the steady state liquid content, the bed was allowed to drain until no more liquid comes out of the bottom of the column and a constant residual holdup was achieved. This drainage time is usually between 15 and 20 min. The liquid flow is then turned back on at the next liquid addition rate (i.e. 0.015 mm/s) and the procedure is repeated over the other three flow rates (0.03, 0.06 and 0.12 mm/s). After the highest flow rate, the same procedure was performed while reducing the flow rate following the same sequence, once again measuring the respective steady state and residual liquid holdup values (see Fig. 4). The output of this procedure is a set of steady state liquid holdup values and corresponding residual liquid contents (Ilankoon and Neethling, 2012).

3. Inter-particle flow model

A theoretically based model has been developed by the authors (Ilankoon and Neethling, 2012), which describes low saturation

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