Minerals Engineering 39 (2012) 156–164

Contents lists available at SciVerse ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

Microbial colonisation in heaps for mineral bioleaching and the influence of irrigation rate

R. Chiume, S.H. Minnaar, I.E. Ngoma, C.G. Bryan [1], S.T.L. Harrison *

Centre for Bioprocess Engineering Research (CeBER), Department of Chemical Engineering, University of Cape Town, Rondebosch 7701, South Africa

ARTICLE INFO

Article history:
Received 12 February 2012
Accepted 11 July 2012
Available online 5 October 2012

Keywords:
Mineral bioleaching
Heap bioleaching
Sulphide ores
Shear forces
Colonisation
Acidophilic chemolithotrophic micro-organisms

ABSTRACT

Microbial colonisation is important for mineral dissolution in heap bioleaching of low grade ore. Colonisation studies to date have focused on the microbial attachment of single species to mineral concentrates in batch and flow systems. Hydrology and soil engineering studies suggest interaction between microbial colonisation and fluid flow in porous systems that result from solution-ore and microbe-mineral contacting (Wan et al., 1994; Yarwood et al., 2006).

The effect of the irrigation rate on microbial colonisation was assessed using columns packed with acid agglomerated low grade copper-containing ore. Continuous flow, unsaturated, aerated bed reactors were inoculated by pulse irrigation with iron and sulphur oxidising mesophilic microorganisms (10^{12} cells/ton ore), followed by operation at irrigation rates of 2, 6 and 18 l/m^2/h. A novel in-bed sampling technique allowed the extraction of ore samples from the bed during the leaching process. Novel insights regarding microbial growth, interstitial and weakly and strongly attached microbial populations were obtained.

Bacterial adherence and cell number retained in the ore bed increased over the 32 day leaching period. Average specific growth rates of ore-associated micro-organisms of 0.161 ± 0.0045, 0.155 ± 0.026 and 0.120 (± 0.00) 1/h were obtained at 2, 6 and 18 L/m^2/h respectively. Faster colonisation occurred at lower irrigation rates. At higher irrigation rates, higher detachment and cell removal were apparent, based on PLS cell numbers. The interstitial cells from the stagnant fluid in the ore bed formed the dominant contribution to the microbial population within all the heap systems.

1. Introduction

The need for alternative methods to those conventionally used for the recovery and extraction of valuable metals e.g. concentration by flotation and recovery through smelting, has become increasingly important to extract metals from low grade ores and to reduce the energy footprint and environmental burden during extraction. The development of heap bioleaching as an alternative technology was prompted by the increasing complexity and low grade of the ores (Watling, 2006). In the biohydrometallurgical heap leaching process, crushed ore is inoculated with a consortium of micro-organisms to catalyse iron and sulphur oxidation reactions providing leach reagents in the form of ferric iron and acid to assist the mineral dissolution of sulphide minerals (Brierley, 2001).

To optimise the performance of the heap bioleach system, a comprehensive awareness of the contributing processes and sub-processes is required. Watling (2006) highlighted the lack of an in-depth understanding of bioleaching to the separated and independent focus of investigations on different aspects such as chemistry, microbiology and hydrodynamics. The aim of this study is to add to the bioleaching knowledge base through an integrated study of microbiological and hydrological aspects of heap bioleaching. We investigated the effect of irrigation rates on the microbial colonisation of bioheaps.

Microbial colonisation of the mineral surface occurs through the following steps:

(i) The transport of microbial cells occurs as the liquid phase is transported throughout the heap to the mineral surface (Rossi, 1990; van Loosdrecht et al., 1990). The microorganisms can either be eluted in the leachate, or accumulated within the heap in the stagnant zones, or attached to the ore in response to surface interactions (Fig. 1). Microorganisms present in the free-flowing fluid are referred to as planktonic PLS cells, whilst those planktonic cells accumulating in the stagnant fluid regions of the ore bed are known as the interstitial cells.
(ii) There is selective reversible and irreversible attachment to the mineral surface (Rossi, 1990; van Loosdrecht et al., 1990; Rockhold et al., 2002). Reversible attachment accounts

* Corresponding author. Tel.: +27 21 650 2518.
E-mail address: Sue.Harrison@uct.ac.za (S.T.L. Harrison).
[1] Current address: Environment and Sustainability Institute, University of Exeter, Cornwall Campus, Penryn, Cornwall TR10 9EZ, UK.

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http://dx.doi.org/10.1016/j.mineng.2012.07.002

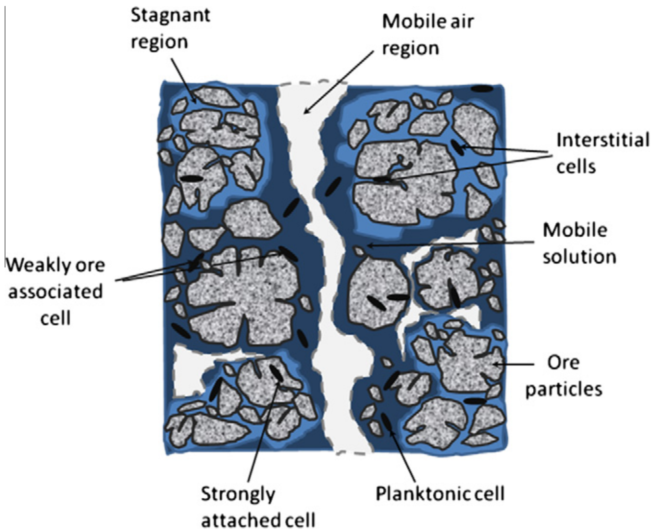

Fig. 1. Diagram of the inside of the heap, showing planktonic cells in the flowing mobile liquid phase, microorganisms weakly and strongly associated with the ore surfaces, and microorganisms accumulating within the stagnant regions of the porous rocks (interstitial cells).

for the microorganisms loosely associated with the ore surface, whilst the irreversible attachment accounts for the microorganisms strongly associated. The loosely attached microorganisms can be detached from the ore surfaces by repulsive electrostatic (Ghauri et al., 2007; Rodriguez et al., 2003) and mild shear forces (Rossi, 1990; van Loosdrecht et al., 1990; Rockhold et al., 2002; Pintelon et al., 2009). The potential for detachment of the cells from the ore also creates an exchange between planktonic and the sessile cells (van Loosdrecht et al., 1990).

(iii) The growth and multiplication of microorganisms results in the formation of microbial cultures which contribute to bio-oxidation (Rossi, 1990; van Loosdrecht et al., 1990; Rockhold et al., 2002, 2007).

Studies of microbial colonisation have focused on the degree of attachment of microorganisms to the mineral concentrates (Gehrke et al., 1998; Sampson et al., 2000; Kinzler et al., 2003; Sand and Gehrke, 2006), the mechanisms behind microbial attachment (Rossi, 1990; van Loosdrecht et al., 1990; Rockhold et al., 2002; Rodriguez et al., 2003; Ghauri et al., 2007), extracellular polymeric substance (EPS) formation, and the location and specificity of microbial attachment to the minerals (Africa et al., 2010, 2012; Bromfield et al., 2011). However, these observations have limited applications because most of the results were obtained from systems which were not analogous to actual heap bioleaching environments.

Bioheaps are typically irrigated at a rate which does not cause saturation (Brierley, 2001), to ensure oxygen and carbon dioxide transfer to microbes. Researchers have investigated the effect of irrigation rate on the temperature in the heap, sulphide oxidation rate and metal recovery (Cooper and Dixon, 2006; Bouffard and Dixon, 2009), using heap leaching simulations rather than actual experiments. Few researchers have assessed the fate of the bioleaching microorganisms under the different irrigation rates employed during heap leaching operations. Typically irrigation rates used in heap bioleaching are approximately 5–20 l/m^2/h (Petersen and Dixon, 2007). Lizama et al. (2005) investigated the heap leaching of pyrite and sphalerite at irrigation rates ranging from 1.8 to 21.6 l/m^2/h in columns at heights between 1 and 8 m. They concluded that increased irrigation rates had no effect on the initial colonisation period. However, the detachment of microbes from the heap system by fluid shear forces (Rossi, 1990; van Loosdrecht et al., 1990; Rockhold et al., 2002, 2007; Pintelon et al., 2009) and the preferential sorption of microbes onto the gas–water interface over the solid–water interface (Wan et al., 1994) suggested otherwise. From their studies, it can be postulated that low irrigation rates facilitated good microbe-mineral contact, enhancing colonisation rates while preventing detachment of microbes due to fluid shear. The objective of this study was to examine the effect of irrigation rates on microbial attachment, growth rates and removal of microbes in systems that mimic heap conditions.

2. Methodology

2.1. Ore, microbial cultures and growth media

Low grade copper-bearing ore, containing 0.69% copper, 2.95% iron and 2.02% sulphur was utilised. The crushed ore (d_{20} = 0.6 mm, d_{50} = 4.0 mm, d_{80} = 8.0 mm) was acid agglomerated, using 4.0 kg 98% H_2SO_4 per ton ore, resulting in a moisture content of approximately 5.5%.

A mixed mesophilic stock culture containing *Acidithiobacillus ferrooxidans*, *Acidithiobacillus caldus*, and predominantly *Leptospirillum ferriphilum*, grown on pyrite concentrate in a batch stirred tank reactor at 30 °C and sub-cultured weekly, was used. A preliminary study was conducted to determine the inoculum concentration at which the concentration of the cells eluting without attachment was within the detection limit of the total microscopic cell count (3×10^5 cells/ml). The range of 10^8–10^{13} cells/ton of ore was investigated and 10^{12} cells/ton of ore was utilised in this investigation (Tupikina et al., 2011).

The irrigation feed composition was: 0.5 g/l $FeSO_4 \cdot 7H_2O$, 183.3 mg/l $(NH_4)_2SO_4$, 60.5 mg/l $NH_4H_2PO_4$, and 111.2 mg/l K_2SO_4 in deionised water. The pH was adjusted to pH 1.15 using 96–98% concentrated sulphuric acid (H_2SO_4). All reagents used were of analytical grade.

2.2. Column operation

The experiments were carried out in small scale heap leach columns of 100 mm diameter and 360 mm height (Fig. 2). The columns were packed with approximately 4 kg acid agglomerated ore as described by van Hille et al. (2010). Liquid irrigation rates of 2 (Run A), 6 (Run B) and 18 (Run C) l/m^2/h were used. Runs A and C were conducted in duplicate (Run A1, A2, C1 and C2) and run B at 6 l/m^2/h was conducted in triplicate (Run B1, B2 and B3). Prior to inoculation, the systems were acid washed at the same rate (6 l/m^2/h) for 1 day to remove readily leachable materials and create an environment conducive to microbial attachment to the ore surface. The inoculum was added once-off to the columns via

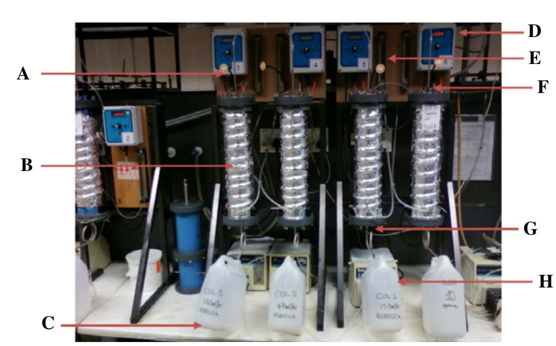

Fig. 2. Heap leach columns (A – Air outlet, B – Column, C- PLS collection vessel, D – Temperature sensor, E – Rotameter, F- Inlet feed point, G – Air inlet, H – Pump).