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Experimental study of sulfuric acid effects on hydro-mechanical properties of oxide copper heap soils

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ABSTRACT

Several mechanisms contribute to changes in the performance of oxide copper heaps. These include physical, biological, chemical and thermal interactions between sulfuric acid and the formation of soil particles. A series of experimental studies was conducted by simulating the column leaching process in the laboratory. The leaching of selected gravel and crushed copper oxide ores from two copper mines was carried out to measure their permeability and strength. The influence of effective parameters on gravel clogging was studied and the clogging coefficient was estimated with time. Furthermore, the ratio of particle reduction (R_{PR}) caused by acid seepage was evaluated and an equation for the internal friction angle of ore particles over time was generated. The present study shows significant reductions of gravel permeability (28% after five months leaching) and friction angle of ore particles (25% after eight months leaching). The effects of sulfuric acid flow on the hydro-mechanical properties of oxide copper heap soils could enhance the accuracy of slope stability design and drainage layers design in industrial heap leaching systems.

1. Introduction

Heap leaching is one of the mineral processing techniques whereby a heap of low grade ore is leached with various solvents to extract precious and base metals. Since the 1950s, it has been practised for the extraction of copper, gold, silver, and uranium (Kappes, 2002). The ore is crushed and agglomerated before constructing a heap to achieve a uniform distribution of particles and better percolation of the solvent. Agglomerated ore particles are also used in industrial heaps (Bouffard, 2008; Dhawan et al., 2013). For the extraction of copper from oxide ores, the solvent is sulfuric acid and the leaching rate is in the range of 5–20 L/m^2 h (Petersen, 2016). The leaching process can cause physical and chemical interactions. Consequently, many characteristics of ore particles in the heap such as permeability, particle size distribution, porosity and strength parameters could change over time.

In heap leaching, most of the solvent percolates as vertical flow channels due to gravity. The zones between the networks of channels are occupied by the semi-stagnant solvent due to the interplay between gravity and capillary forces. If the ratio of gravity to capillary forces will be around one, the solvent is stagnant (held up) between the particles. The increase in stagnant liquid holdup could increase the clogging (Ilankoon and Neethling, 2013; de Andrade Lima, 2006). The solvent spreads through the heap with little horizontal spread and the homogenous solvent flow does not typically occur in the heap leaching process (Ilankoon and Neethling, 2016; McBride et al., 2017). It should be noted that after adding a new layer above the surface of heap, the solvent is introduced at the top of that layer. The main flow channels in the previous layer may be changed and/or the solvent may flow through the existing flow paths.

The heap leaching process is simulated at laboratories by column leaching tests. The column dimensions in these tests have considerable ranges depending on the aim of each test. The ratio of the column diameter to the maximum soil particle size should be between 8 and 12 in order to reduce the wall effects (Fraser et al., 1993).

Clogging coefficient is defined as the ratio of permeability before leaching and permeability after leaching. It consists of physical, chemical and biological characteristics and is important for designing heap leaching systems. A good estimation of these coefficients can be obtained by performing tests on leached samples. Clogging takes place on the top of the heap layers due to particle size segregation. Moreover, clogging is formed in the filter layer, drainage layer and the collection pipes due to the movement of fine particles which may be formed after disintegration. The effective parameters in clogging formation are: particle size distribution, constituent elements, solvent flow rate, aeration, liquid holdup and added reagents and their parameters such as pH (Liu and Huang, 2008; Maley et al., 2009; Halinen et al., 2009; Xia et al., 2015; Torkzaban et al., 2015). The elements present in ores responsible for chemical clogging in oxide copper heaps and drainage

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gravel are: calcium, magnesium, manganese and iron (Reddy Nandela, 1992).

The slope stability of heap structures has a considerable economic and environmental importance. Shear strength is the most important ore property that can affect the heap capacity and slope stability (Rahimi and Ghasemzadeh, 2015). It is often approximated by $\tau = \sigma \tan(\varphi) + c$, where σ is the total stress, φ is the internal friction angle and c is the cohesion which can be determined using basic geotechnical laboratory tests such as the direct shear test. For long-term slope stability analyses of heaps, the ore material should be modeled without any cohesion.

The internal friction angle of soil usually decreases when fluid flows through it. For example, leaching of sands by fresh water can cause a reduction in the friction angle. This reduction is between 1° and 3° in different sand types, for friction angles between 28° and 38° (Ismael and Mollah, 1998). In oxide copper heap structures, the flow of sulfuric acid has a greater reducing effect on the friction angle of ore particles due to disintegration of particles and/or less interlocking particles (Thiel and Smith, 2004). For slope stability design of oxide copper heap leaching systems, Sample et al. (2009) and Huang and Jia (2009) assumed that an increase in the friction angle of ore due to greater settlement compared to its reduction caused by disintegration. The influence of disintegration was neglected by Breitenbach (2004). Mortazavi et al. (2015) assumed that the friction angle of a copper ore sample declined from 32° to 22° during the leaching process. However, more experimental studies are required to explain how the internal friction angle of ore changes during the leaching process.

In this study, the effects of sulfuric acid flow were investigated on permeability and strength parameters of particles in the heap (drainage gravel and ore particles). Column leaching systems were filled with crushed copper oxide ore and drainage gravel samples. The samples were leached in the cells by sulfuric acid. Direct shear, slake durability, constant head permeability and particle grading tests were performed on the leached samples. The effects of leaching on friction angle, slake durability index, and permeability were studied. The effective parameters of clogging such as leaching duration and the concentration of calcium in the leached particles were investigated and the clogging coefficient was determined.

2. Experimental setup, materials, and methods

2.1. Experimental setup

The designed column leaching system consisted of two parts, leaching cell and permeability cell (Fig. 1). The height, internal diameter and shell thickness of the leaching column were 200 cm, 19 cm and 1 cm, respectively. The ratio of the column diameter to the maximum ore particles size was around 8. To prevent clogging at the bottom of the leaching columns, a 5 cm-thick drainage layer consisting of coarse particles (20–25 mm) was placed. The remaining volume was filled with agglomerated copper ores. A layer of glass-wool was placed at the top to obtain uniform liquid distribution. The height, internal diameter, and shell thickness of the permeability column were 65 cm, 19 cm and 1 cm, respectively. This column was filled with the drainage gravel sample to study the clogging formation in the heap drainage layer.

The leaching cell was irrigated with acid from top and the pilot flow rate was 2×10^{-6} m/s (7.2 L/m^2 h). The solvent that flowed out of the leaching cell was pumped to the top of the permeability cell (Fig. 1). The pH of the out-flow solvent was measured continuously and kept constant by adding fresh acid during the experiment. Then, the solution was pumped back to the top of the leaching cell (Fig. 1). This flow cycle was similar to the solvent circulation in the heap leaching operation. The out-flowed solvent from the leaching cell was pumped to the top of that cell instead of the permeability cell only when constant head permeability tests are performed. Three columns were employed in this work (Fig. 1).

Crushed copper oxide ore leaching with pilot acid flow rate is a time-consuming process in a laboratory. The acid flow rates were increased to speed up the leaching tests. Therefore, four types of column tests were conducted with acid flow rates equal to the pilot acid flow rate, and 10, 15, and 20 times the pilot rate for equivalent one month leaching duration. The equivalent leaching duration of each experiment was obtained by multiplying the real duration of test to speed ratio (Table 1). Speed ratio is the ratio of the acid flow rate in the test to the pilot test. The increase in flow rate has an effect on some parameters such as internal friction angle, liquid holdup, suspension, movement and clogging formation of fine particles. In this study, the results of experiments with different flow rates in equivalent duration were compared with each other to investigate the effect of acid flow rates on ore friction angle. Then, the results were utilized to modify those of direct shear tests performed on leached samples at different flow rates.

Table 1 presents the sulfuric acid flow ratios and equivalent leaching durations of different column leaching tests, A to I. To investigate the scale dependency of the results, the height of leaching cell in the Test E was chosen as about one-third of the others (60 cm).

2.2. Materials and methods

In all the column leaching tests, the solvent was sulfuric acid with a concentration of 3 g/L and a pH of 2. The acid flow rate was constant during leaching tests. In the following column leaching tests, two types of particles were used, namely, the crushed copper oxide ore particles and the drainage gravel. The crushed copper ore samples were extracted from Meydouk copper ores (0.39% oxide copper). These samples were crushed (−25 mm) and then agglomerated with acid using an acid to ore weight ratio of 5%. The specific weights of these samples before and after agglomeration were 1.34 g/cm^3 and 1.45 g/cm^3, respectively. The drainage gravel sample was selected from the drainage materials of the Meydouk copper heap leaching facility. Fig. 2 shows the respective particle size distributions. The results of XRF, XRD and ICP tests of the considered samples are shown in Tables 2–4, respectively. It seems that the percentages of effective elements on clogging formation are not significant in both types of soil samples (for example the percentage of CaO was 0.25% in ore).

Additional tests were carried out using the leached crushed copper oxide ore samples collected from Sarcheshmeh heap. The samples were leached in the heap for two or four months at the same flow rate. The specific weight of these samples after agglomeration was 1.75 g/cm^3. The results of grain size distribution and XRD of these samples are shown in Fig. 3 and Table 5, respectively. In the following, the name of the mine is not referred if test is performed only on Meydouk mine samples. But, the name of related mine is mentioned if test is carried out on the samples of both mines.

2.3. The tests on the leached samples

To study the effects of sulfuric acid leaching on crushed copper oxide ores or drainage gravel, the following tests were performed during or after the leaching tests.

To investigate the effects of clogging on permeability of the gravel sample, the constant head permeability tests (ASTM D2434-68) were conducted using one of the permeability cells for one month leaching duration (Test A). This test was not carried out for the Test B (i.e. during leaching period) to avoid any disturbances of clogging formation between the gravel particles and only a permeability test was performed at the end of leaching test.

Due to the low percentage of calcium ions present in the gravel and the crushed copper oxide ore samples (Tables 2–4), the percentage of calcium should be increased in the gravel sample to investigate the effect of calcium percentage on clogging. 10 g of lime ($CaCO_3$) was added daily at the upper surface of the gravel sample of the