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Depression of pyrite in the flotation of high pyrite low-grade lead–zinc ore using *Acidithiobacillus ferrooxidans*

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ABSTRACT

In this research work, selective depression of pyrite in the flotation of a low-grade lead–zinc ore containing 31% pyrite was investigated in the absence and presence of *Acidithiobacillus ferrooxidans*. Pyrite was significantly depressed with these bacteria using the optimum dosage of reagents. Sphalerite recovery and Zn grade in the obtained sphalerite concentrate were both enhanced by bacteria. The results of bioflotation experiments showed that bacterial depression of pyrite is very sensitive to the concentration of other flotation reagents. Least significance difference (LSD) bars were used to study the significance of the factors under study with a confidence interval of 90%. Under similar conditions, *A. ferrooxidans* was seen to increase the Zn grade and separation efficiency more effectively than sodium cyanide. Flotation kinetic studies confirmed a considerable decrease in the pyrite kinetic rate constant in the presence of *A. ferrooxidans*.

1. Introduction

The beneficiation of complex base-metal sulfide ores is generally based on the selective production of zinc, lead, and copper concentrates from which the respective metals are extracted using metallurgical processes (Carta et al., 1980). Separation of sphalerite through copper activation becomes complicated when other minerals within the pulp are inadvertently activated along with the sphalerite. Pyrite (FeS_2) is one mineral that responds to copper activation and can be floated together with sphalerite (Wills and Napier-Munn, 2006).

Complete elimination of iron sulfides (e.g., pyrite, pyrrhotite) from zinc concentrates is economically attractive from the angle of subsequent smelting (Gaudin, 1957). This goal can be achieved by floatation in alkaline solutions (lime) using highly selective inorganic modifiers such as cyanides, sulfites, and ferrocyanides in combination with zinc sulfate (Fuerstenau et al., 1985; Shen et al., 1998). Cyanides have been one of the most commonly used depressants; however, their use has raised much concern in regards to environmental issues. Additionally, depletion of available easy-to-process mineral resources will most likely lead to a search for more advanced solutions to the problem of beneficiation of some refractory ores in cases where conventional flotation or flocculation approaches yield poor results (Carta et al., 1980).

The utility of microorganisms in mineral beneficiation has been recently elucidated. Recent developments in biotechnology hold promise for processing of such difficult-to-treat ores as well as for safeguarding the environment. Bioflotation is a relatively new method for processing ores; it is defined as "the selective separation of commercial gangue ores through interactions with microorganisms" (Deo and Natarajan, 1997). Compared to conventional inorganic reagents such as cyanides, hydrosulfides, dichromate, etc., bacteria are non-toxic and environmentally benign. Many investigations have suggested that certain types of bacteria, such as *Acidithiobacillus ferrooxidans*, may prevent flotation of certain minerals, such as pyrite (Sharma and Hanumantha, 2001). *A. ferrooxidans*, a commonly implicated autotrophic, acidophilic, and mesophilic microorganism utilizes sulfur, thiosulfate, and iron as energy sources. These bacteria are Gram-negative and shaped as small rods with dimensions 0.5 by 1–3 μm, occur singly or occasionally in pairs, and have been extensively utilized in mineral bioprocessing (Donati and Sand, 2007).

The selective separation of chalcopyrite, sphalerite, or arsenopyrite from pyrite has been studied in the presence of *A. ferrooxidans* (Chandraprabha et al., 2004a,b; Deshpande et al., 2001, 2004). These papers discuss the utility of *A. ferrooxidans* for selective flotation of minerals from pyrite. With extraction using

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bacterial cells, pyrite is depressed even in the presence of a potassium isopropyl xanthate collector.

The effect of *L. ferrooxidans* on the floatability of chalcopyrite, sphalerite, and pyrohotite was also investigated using xanthate as a collector (Pecina et al., 2009). In this research, the chalcopyrite flotation rate was significantly increased in the presence of *L. ferrooxidans* due to the formation of hydrophobic species. It was concluded that *L. ferrooxidans* causes superficial changes mainly due to oxidation of minerals.

The floatabilities of five sulfide minerals (pyrite, chalcocite, molybdenite, millerite, and galena) were examined in the presence of *A. ferrooxidans* by Nagaoka and co-workers (1999). It was observed that pyrite was significantly depressed by the bacterium, while the floatability of other sulfide minerals was not affected. It was postulated that the suppression of pyrite floatability was caused by profuse bacterial addition to pyrite surfaces (Nagaoka et al., 1999).

The majority of bioflotation studies have been carried out on the micro-scale using pure minerals, but there are few studies on the primary ores (Hosseini et al., 2005; Kolahdoozan et al., 2004; Yüce et al., 2006). In the present research, the efficiencies of *A. ferrooxidans* and the chemical depressant NaCN were compared for selective depression of pyrite in the flotation of a primary Pb–Zn ore. Moreover, selective separation of sphalerite and pyrite was investigated in the absence and presence of *A. ferrooxidans* and NaCN.

2. Materials and methods

2.1. Ore characterization

A low grade Pb–Zn ore sample, containing 31% pyrite and 44% dolomite and assayed at 2.34% Pb, 6.91% Zn and 15.36% Fe, was prepared from the Kooshk mine in Yazd province, Iran, and used as the primary ore in flotation and bioflotation experiments. Mineralogical and elemental compositions of the ore were studied using semi-quantitative X-ray diffraction (SQXRD) and atomic absorption spectroscopy (AAS) techniques, respectively.

2.2. Bacterial culture

Pure strains of *A. ferrooxidans* and *Acidithiobacillus thiooxidans*, isolated from the acidic water drainage of Sarcheshmeh copper mine (Iran), were used in this study. The bacteria were grown in the laboratory using 9 k medium (3 g/l $(NH_4)_2SO_4$, 0.5 g/l $MgSO_4$ $7H_2O$, 0.5 g/l K_2HPO_4, 0.1 g/l KCl and pH = 1.85), and were cultured by inoculating 10 ml of pure strain of the bacterial cells into the medium. Potassium nitrate was used to maintain ionic strength. The cultures were incubated at 32 °C in a rotary shaker maintained at 160 rpm. Microorganisms were adapted with 50 g/l original ore. *A. ferrooxidans* and *A. thiooxidans* were grown separately on ferrous sulfate and elemental sulfur, respectively. The culture solution was filtered through Whatman filter paper to remove the suspended solids. The cells were separated from the medium using the biological filter paper (0.42 μm) and then suspended in distilled water. During the experiments, the cell number in the solution was estimated by direct counting, using a Thoma chamber of 0.1 mm depth and 0.0025 mm^2 area with an optical microscope.

2.3. Flotation and bioflotation experiments

Flotation and bioflotation experiments were performed in a 1.5 l Denver cell running at 850 rpm using 300 g ore sample (25% pulp density) with a size of 95 μm (d_{90}). Industrial grade potassium ethyl xanthate (PEX) and potassium amyl xanthate (PAX) were used as galena and sphalerite collectors, respectively. Copper sulfate and sodium hydroxide, which were used for sphalerite activation and pH adjustment, were of analytical grade. Four control factors and their levels used in the bioflotation experiments are presented in Table 1. Each of these factors was varied in two levels, including collector dosage, activator dosage, NaCN dosage, and volume of bacterial solution (*A. ferrooxidans*). Fig. 1 describes the baseline of the flotation and bioflotation experiments. In all experiments, organic materials in the ore were pre-floated using 120 g/t methyl isobutyl carbonyl (MIBC) and 250 g/t diesel oil. For this purpose, the pulp was conditioned for 2 min at pH = 7–7.5 followed by froth collection for 4 min, and the impeller speed was 850 rpm. Pulp pH was adjusted to 9.5 and 11 in the conditioning stage of galena and sphalerite, respectively. In bioflotation experiments, in which bacteria were used as the pyrite depressant, the minerals were conditioned after pre-floating with 300 ml bacteria solution for 20 min, using an impeller speed of 120 rpm. The bacterial population in the solution was counted at about 3×10^7 cells/ml. In the sphalerite frothing stage, the flotation froth was collected for 7.5 min. According to Table 2, nineteen flotation experiments in a full factorial design (H1–H16) with the center points (H17–19) were carried out. These experiments are as follows:

- Four experiments without pyrite depressant.
- Four experiments using NaCN as pyrite depressant.
- Four experiments using *A. ferrooxidans* as pyrite depressant.
- Four experiments using both NaCN and *A. ferrooxidans* as pyrite depressant.
- Three experiments using the center points of the factors to estimate operator error in the tests.

2.4. Separation efficiency

Separation efficiency was calculated as an indicator of the metallurgical performance of the sphalerite flotation process using the equation:

$$SE = 100C\frac{m(c-f)}{f(m-f)}, \quad (1)$$

where C is the weight percent of the feed to the concentrate, m is theoretical zinc content of the sphalerite mineral, c is Zn grade of sphalerite concentrate, and f is Zn grade in the original feed ore sample.

2.5. Least significant difference (LSD)

LSD is a numerical value that can be used as a benchmark for comparing treatment means. The LSD is calculated as a comparative tool with:

$$\mathrm{LSD} = t \times s \times \sqrt{(2/n)}, \quad (2)$$

where t is a factor that depends on the desired confidence and the degrees of freedom for estimation of error, s is standard deviation, and n is the sample size. The t value obtained from the t-distribution table under the desired conditions was 2.92 (Anderson and

Table 1
Studied factors and levels in flotation and bioflotation experiments.

Level	A: PAX (g/t)	B: $CuSO_4$ (g/t)	C: NaCN (g/t)	D: bacterial solution (ml)
High	140	700	0	0
Low	280	1400	100	300
Center	210	1050	50	150