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Research paper

Influence of clays on the slurry rheology and flotation of a pyritic gold ore

Lahiru Basnayaka, Nimal Subasinghe, Boris Albijanic *

Department of Mining Engineering and Metallurgical Engineering, Western Australian School of Mines, Curtin University, Australia

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ABSTRACT

The presence of clay minerals in ores has been known to adversely affect the flotation performance. This work investigated the influence of kaolin and bentonite clays on the flotation of gold-bearing pyrite in the gold ore. The changes in rheological properties of the flotation pulp under normal operating conditions were also studied with the additions of kaolin and bentonite clays at various solid concentrations. The zeta potential measurements also were carried out to understand the mechanism of adsorption of potential determining ions. It was found that bentonite clay reduced the pyrite recovery, and modified the pulp rheology more than kaolin. The addition of Ca^{2+} ions to the pulp containing bentonite improved the pyrite flotation recovery by its ability to modify the rheological characteristics. It is consistent with the published literature that Ca^{2+} ions suppressed the swelling properties of bentonite, and altered the surface charge properties of bentonite clay particles. Additionally, the rheological characteristics such as the flow index and the consistency index affected the flotation performance as the former indicates the extent of movement of bubbles and particles within flotation pulp. This suggests the possibility of using the rheological measures to monitor the changes in the flotation performance in routine plant operations.

1. Introduction

Clay-bearing ores have been known to cause adverse effects on the process performance of mineral processing plants, due to their ability to affect slurry rheology, consumption of reagents, and adhesion to surfaces of mineral particles. With the depletion of high-grade deposits, processing of lower grade clay-bearing ores would be unavoidable in the near future (Connelly, 2011). While most plant operators are generally aware of the difficulties they may encounter when the feed material contains clay, its effects on the various separation processes such as flotation, gravity concentration, and leaching have not been adequately quantified. The difficulties also arise from the fact that different clays affect these processes in different ways due to their morphological characteristics. Therefore, understanding of the differences in various clay morphologies and underlying mechanisms by which they affect such processes is of paramount interest to the plant operators.

Clay minerals possess distinctive properties due to their very fine particle size, anisotropic surface charges, and platy morphology. Clay particles are <2 μm and thus they have poor settling rates. As a result, clay particles entrain into flotation concentrates, and have higher residence time in flotation circuits (Arnold and Aplan, 1986). Anisotropic shape of clay mineral particles and their large aspect ratio (largest diameter of basal plane/thickness of the particle) might contribute to non-Newtonian behaviour of clay-containing slurries (Mueller et al., 2010).

Clay minerals also adversely affect crusher and milling performance, which are essential stages for valuable mineral liberation. Bridging the openings of crushers and blinding of screens are major difficulties encountered in early processing stages (Connelly, 2011). Grinding efficiency is also adversely affected by the existence of clay due to their higher viscosity, particularly during wet grinding. Due to prevailing high viscosities, mills are subjected to operate at lower densities which reduce the grinding efficiency. The movement of grinding medium (i.e. grinding balls) is also affected by the high viscosity of slurries as it hinders the movement of grinding media (Tangsathitkulchai, 2003). Shi and Napier-Munn (2002) also illustrated that grindability is significantly reduced at higher yield stresses and viscosities.

Yield stress and viscosity are important determinant rheological properties of suspensions. For example, yield stress and apparent viscosities tend to increase with the addition of some clay minerals which result in altering the hydrodynamics in flotation cells. With the increase in yield stress and apparent viscosities, the probability of collision between bubbles and particles is reduced due to poor dispersion of bubbles and mobility of particles in flotation cells which result in poor flotation performance (Bakker et al., 2009; Shabalala et al., 2011). Furthermore, clay minerals coat the surfaces of valuable minerals, restricting the collector adsorption on the valuable minerals and thus reducing the probability of bubble–particle attachment (Forbes et al., 2014; Oats et al., 2010). As a result of very fine particle size of clay minerals, they report to the concentrate stream by entrainment, and the presence of electrolytes enhance the entrainment further which result in the reduction in mineral grade (Wang and Peng, 2014).

Zhang and Peng (2015) found that the presence of bentonite in flotation pulp increased the pulp viscosity which reduced flotation recoveries of both copper and gold. By contrast, kaolin did not affect the flotation recovery of copper and gold appreciably, and also pulp

* Corresponding author.
E-mail address: boris.albijanic@curtin.edu.au (B. Albijanic).

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rheology. They attributed this behaviour to the swelling properties of the clays arising from their degree of crystallization. However, they observed reductions in the recoveries and increase in slurry viscosity with the increasing clay concentration. As such, in the present study, it was investigated the relationships between the flotation performance and the rheological properties of clay-containing pulps to quantify the influence of two clays with distinctly different swelling characteristics (i.e. kaolin and bentonite) present in a pyritic gold ore.

2. Structural differences of clay minerals

Clay minerals are commonly identified as fine-grained phyllosilicate minerals which comprise of silicate tetrahedral "T" layers and alumina octahedral "O" layers as basic building blocks. "T" layers comprises of units in which four oxygen atoms are arranged symmetrically around silicon atom, and those units are interconnected by a shared epical oxygen atom. In octahedral units, a central cation is bonded to six hydroxyl groups in octahedral symmetry. The central cation in the octahedral unit can be either Al^{3+} or Mg^{2+}. If the cation is Al^{3+}, layers have dioctahedral units while layers consist of trioctahedral units if the cation is Mg^{2+}. Various compilations of "T" and "O" layers result in the formation of different types of clay minerals with similar structure, and different physical and chemical properties. However, most of the clay minerals have either 1:1 "T" to "O" (eg. kaolinite) or 2:1 "T" to "O" layer arrangement (eg. smectite). More specifically, a clay mineral consists of a unit cell combining "O" and "T" layers, interconnected by primary bonds; the unit cells are interconnected by secondary bonds between them, forming a clay particle (Ndlovu et al., 2014).

Clay mineral faces may carry pH independent negative charges due to the isomorphous substitution of cations (i.e. the replacement of higher valence (eg. Si^{4+}) cations with lower valency (eg. Al^{3+})) (Swartzen-Allen and Matijevic, 1974; Johnson et al., 2000). By contrast, given that edges of clay mineral particles have the broken bonds, edges can carry either positive or negative charge. Nevertheless, the overall surface charge of clay mineral particles is negative, particularly at pulp pH values encountered in a flotation cell.

Given that clay mineral particles have anisotropic shape and surface charges, there are three types of aggregation of clay mineral particles: Edge-edge, edge-face and face-face (Rand and Melton, 1977). Edge-edge and edge-face aggregation of clay mineral particles exhibit voluminous structure, resulting in higher viscosities and yield stresses of clay slurries (Swartzen-Allen and Matijevic, 1974; Luckham and Rossi, 1999). Face-face aggregation of clay mineral particles has a thicker flaky structure, preventing the increase in viscosity and yield stress of clay mineral particles.

3. Experimentation

3.1. Materials

The gold ore tested comprised of predominantly gold bearing pyrite from Western Australia. The ore was first crushed to −2.36 mm in size prior to the grinding. After the crushing, the ore was dry ground to the particle size of 80% passing of 150 μm using a laboratory scale rod mill. Kaolin and bentonite clays were purchased from Sibelco Group, Australia. Malvern Mastersizer was used for the measuring of particle size distribution of clay samples. It was found that P_{80} of kaolin and bentonite was around 10 μm.

3.2. XRD methodology

XRD technique was performed using a diffractometer Olympus with radiation Co-Kα in the range between 5 and 55° (2θ). The mineralogical composition of the ore was determined by quantitative XRD analysis which is illustrated in Table 1. The composition of clays also was analysed using the XRD analysis. It should be noted that the glycol saturation method (Inoue et al., 1989) was used for the preparation of clay samples. Kaolin clay contained 87% kaolinite and 13% quartz whereas bentonite had 82.9% montmorillonite and 17.1% quartz. The XRD diffractograms of kaolin and bentonite are given in Fig. 1.

3.3. Flotation experiments

The flotation tests were carried out with the gold ore containing artificially mixed bentonite and kaolin at certain solid ratios. A 3L Leeds cell with vaned impeller was used for the experiments. The flotation experiments were planned to evaluate the flotation performance of the gold ore in the presence of clays in order to investigate the effect of clay type on the flotation recovery considering solid concentrations of clays, and operating variables such as air flow rate, pulp pH, and polyacrylate based dispersant (Cytec Cyquest 3223) using a factorial design. Additionally, the flotation experiments also were conducted substituting the dispersant with Ca^{2+} which is known to affect the swelling properties of clays (Assemi et al., 2015; Cruz et al., 2015). It should be noted that the dispersant or Ca^{2+} ions were mixed in the deionized water before adding the clay-containing ore. Ca^{2+} ions are encountered in flotation pulps as the pulp pH is commonly raised using lime. The ore and clay mixtures were prepared separately, and introduced into the agitating flotation cell, and the slurry level was adjusted by adding deionized water with 18.2 MΩ cm to achieve 30% w/w. The slurry was well stirred for 15 min at 1500 rpm after the addition of dispersant or $CaCl_2$.

Flotation experiments were conducted under the similar reagent conditions to that used in operating gold plants in Western Australia, treating gold bearing pyritic ores. More precisely, the pulp was conditioned with analytical grade reagents: $CuSO_4$ activator (40 g/t), PAX collector (40 g/t), and MIBC (10 g/t). The flotation concentrates were collected after 15, 30, 60, 120, and 240 s. The impeller speed was kept at 800 rpm, and NaOH and HCl were used for adjusting the pulp pH.

3.4. Rheological measurements

The rheological measurements were performed with an LV1 viscometer (Brookfield, USA) using a small sample of slurry (16 mL), which was taken from the conditioned flotation pulp. The slurry was introduced into the viscometer, and rheograms were generated at the shear rates from 0 to 122 s^{-1}. The rheological properties of pure clay slurries were measured in the presence and absence of Ca^{2+} ions i.e. $CaCl_2$. All rheological measurements were conducted at 20 ± 2 °C.

3.5. Zeta potential measurements

The zeta potential measurements were carried out using a Zetasizer (Malvern Nano Z, UK). 0.05 g each of pure pyrite and clay samples were mixed for 5 min with deionized water. The experiments were performed in the absence and presence of Ca^{2+} ions. Coarse particles were allowed to settle down, and the supernatant solution containing fine particles was used for the zeta potential measurements which were repeated 4 times, and the mean value was used for further analysis.

3.6. Settling tests

The settling tests were performed using 5% w/w pure clay slurries in deionized water to identify the settling behaviour of kaolin and bentonite clays in the presence and absence of Ca^{2+} ions. Settling behaviour

Table 1
Mineralogical composition of ore (wt.%).

Dolomite	Albite	Pyrite	Quartz	Non-crystalline material
19.7	43	3	25.1	9.1