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The interaction of clay minerals with gypsum and its effects on copper–gold flotation

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ABSTRACT

The interaction of two clay minerals, kaolinite and bentonite with gypsum and its effects on the flotation of a copper–gold ore was investigated in this study. It was found that bentonite increased the viscosity more than kaolinite when mixed with the copper–gold ore at low shear rates. The detrimental effect of these clay minerals on flotation was attributed to the entrainment of clay particles when kaolinite was added to the ore and to a decrease in true flotation by bentonite. Bentonite formed a sponge-like structure with predominant edge–edge (E–E) interactions which might affect hydrodynamics in the flotation cell and have a detrimental effect on flotation recovery. Kaolinite did not form a particular network structure and its aggregates mostly consisted of face–face (F–F) type associations which did not affect flotation hydrodynamics. The addition of gypsum to the ore–bentonite mixture inhibited the formation of interconnected network structures. This led to lower viscosity values with flotation behaviour similar to that of mixtures with kaolinite. In this case, there was an improvement in recovery, but the grade decreased due to entrainment. The addition of gypsum to the ore–kaolinite mixture created aggregates with long strings further enhancing particle entrainment with more mass transported to the froth.

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1. Introduction

Clay minerals can be detrimental to mineral flotation and high viscosity and high particle entrainment promoted by clay minerals are among the main contributing factors (Forbes et al., 2014; Jorjani et al., 2011; Wang and Peng, 2014; Wei et al., 2013; Zhang and Peng, 2015). Incremental reagent consumption has also been suggested as a factor affecting flotation of ores with a high clay content (Connelly, 2011). Bentonite has a 2:1 layer structure and is a swelling clay mineral while kaolinite does not swell and has a 1:1 structure. Both have a small particle size. Zhang and Peng (2015) found that bentonite increased the viscosity of a copper–gold ore slurry and decreased copper and gold flotation recovery, while kaolinite affected the viscosity slightly with simultaneous high gangue entrainment. The decrease in mineral flotation recovery by bentonite may be via the modification of hydrodynamic conditions inside flotation cells, and this is related to fluid flow which is mostly driven by the action of the impeller.

The factors influencing hydrodynamics are flotation cell characteristics, impeller properties, and slurry properties such as density and rheology (Shabalala et al., 2011). In this paper the only factor that is changed is the slurry rheology by adding clay minerals. This increases pulp viscosity and may cause a high yield stress and apparent viscosities in the flotation cell, which decreases the bubble-particle collision efficiency (Schubert, 2008; Xu et al., 2011) and changes gas dispersion parameters such as bubble size, gas hold-up, superficial gas velocity and bubble surface area flux (Shabalala et al., 2011). It is reported that a high yield stress can form a "cavern" around the impeller (Bakker et al., 2010) and this decreases bubble size and gas hold-up. When a "cavern" exists small bubbles are formed in the impeller zone, but the dispersion of these bubbles is poor in the cell (Shabalala et al., 2011). Patra et al. (2012a, 2012b) found that network structures formed by fibrous materials in flotation also interfered with the hydrodynamic conditions and then decreased mineral flotation recovery. Their studies suggest that network structures formed by bentonite may have a similar effect on mineral flotation.

Wang and Peng (2014) studied the negative effect of clay minerals in flotation through the transport of these particles to the concentrate. They found that the degree of entrainment of clay particles was high and also affected by the presence of electrolytes in the process water. The high particle entrainment in flotation in

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the presence of kaolinite was attributed to the formation of aggregates which entered flotation concentrates and then enhanced froth stability (Wang and Peng, 2014). Electrolytes in saline water contributed to the formation of aggregates that were entrained, but when the clay content was too high, entrainment and true flotation were affected due to high pulp viscosity which limited bubble and particle mobility. In that case, edge–edge (E–E) network structures were enhanced (Wang and Peng, 2014).

Calcium bearing minerals can be present in ores and associate with clay minerals. In the previous work, it was found that among the calcium bearing minerals gypsum had the strongest rheological interaction with bentonite and kaolinite (Cruz et al., 2013). Gypsum acted as a potential source for Ca^{2+} and SO_4^{2-} ions released into the process water. It is known that multivalent cations are more strongly attracted to clay particles than monovalent cations (i.e. Na^+ ions) (Lagaly and Dékány, 2013a). Ca^{2+} cations can increase the viscosity of kaolinite slurries by attaching to the clay surfaces modifying the double layers and contributing to the formation of network structures (Abdi and Wild, 1993; Wild et al., 1993). In bentonite slurries a high concentration of Ca^{2+} cations can replace Na^+ cations in the interlayer space deactivating sodium bentonite such that it is no longer possible for hydration and swelling to occur (Alther, 1986; Bradshaw et al., 2013; Meer and Benson, 2007). It is also reported that the presence of gypsum and lime can increase water absorption and swelling pressure of bentonite (Abdi and Wild, 1993; Wild et al., 1993). The Ca^{2+} from lime and gypsum and SO_4^{2-} anions play a role on this effect.

In this study, the interaction of clay minerals with gypsum in the formation of network structures and its effects on copper–gold flotation were investigated.

2. Experimental

2.1. Materials

For the flotation experiments sodium isopropyl xanthate (SIPX), and the promoter Aero 3894 were used as the collectors. Both reagents were supplied by Cytec. The frother Polyfroth W22 was supplied by Huntsman Performance Products, and it is low molecular weight polyoxyalkylene alkyl ether frother partially soluble in water. The pH in flotation was adjusted using AR grade hydrated lime ($Ca(OH)_2$). These reagents are used in the industrial flotation of the copper–gold ore examined in this study.

The gypsum (calcium sulphate dihydrate) that was added to the ore–clay mineral mixtures had a high purity ($\geqslant 99\%$), and was purchased from Sigma–Aldrich. Kaolinite Q38, sodium bentonite, and quartz were supplied by Sibelco Group, Australia. Q38 is a dry milled kaolinite with a surface area of 26 m^2/g. Quantitative XRD analysis showed that the composition of the kaolinite sample was 85 wt.% kaolinite, 4 wt.% quartz and 11 wt.% muscovite, while the composition of the sodium bentonite sample was 63 wt.% montmorillonite, 25 wt.% albite and 12 wt.% quartz. The relatively low-crystallinity of Q38 kaolinite with Hinckley crystallinity index (I_H) of 0.5, derived from the XRD pattern (Plancon et al., 1988), was chosen in our experiments because it is close to the I_H of the kaolinite in the copper–gold ore (0.6).

The copper–gold ore was obtained from one of the sponsors. This was considered a low-clay ore. Quantitative XRD analysis indicated that the mineral composition of the ore was 3 wt.% kaolinite, 1 wt.% pyrite, 28 wt.% quartz, 10 wt.% muscovite, 50 wt.% albite and 8 wt.% clinochlore. The head assays of gold and copper were 0.46 ppm and 0.55 wt.%, respectively. 1 kg crushed ore was ground to a P80 of 106 μm before preparing the different mixtures with clay minerals and gypsum. By following this procedure the valuable mineral liberation was similar for all the experiments.

Particle size measurements were conducted with a Mastersizer Microplus from Malvern Instruments. This equipment measures particle size distribution in very dilute solutions by using laser diffraction with a standard procedure to avoid particle agglomeration. The P80 of both kaolinite and bentonite was about 14 μm, and the P80 of gypsum was about 77 μm. Further size reduction for gypsum was difficult due to agglomeration that occurred during pulverization. Quartz had an original P80 of about 52 μm, and it was pulverized to achieve a P80 of 14 μm. Its final particle size distribution was very close to the size distribution of the clay minerals.

2.2. Preparation of mineral slurries

The low-clay copper–gold ore was used to prepare five different slurries by mixing it with known amounts of kaolinite (30 wt.%), sodium bentonite (15 wt.%), kaolinite–gypsum (30–5 wt.%), sodium bentonite–gypsum (15–5 wt.%), and quartz (30 wt.%). The low-clay ore with no clay addition was used as a baseline. The mixture with quartz served two purposes: (1) understanding the effect of the dilution of copper and gold in the feed on the flotation, and (2) comparing the effect from quartz and clay minerals. A 30 wt.% quartz content was chosen since it was the highest clay content used. Although the particle size of the quartz is smaller than the particle size of the low-clay ore, it can still provide information about the effect on recovery when feed grade is changed during the mixture preparation. The solid concentration for all the slurries was maintained at 30 wt.% (about 14.6 vol.%) and the total weight of the mixtures was 1 kg for all cases. The slurries were prepared using Brisbane tap water.

The low-clay ore was wet ground to a P80 of 106 μm at a 60 wt.% solid concentration. Hydrated lime (800 g/t) and promoter Aero 3894 (8 g/t) were added to the mill to mimic the plant scale processing. After grinding, the slurry was transferred to a 3 L flotation cell where it was well mixed at 1500 RPM and a known volume of slurry was removed. The same weight of solids that was removed was replaced with quartz, clay mineral or a mixture of clay mineral and gypsum. Water was added to make up the slurry to 30 wt.% for flotation. The removed slurry was filtered, dried and weighted to confirm that a correct amount of solids was taken from the original slurry.

After adding the quartz, clay mineral or the mixture of clay mineral and gypsum to the flotation cell, stirring continued at 900 RPM for 30 min when adding quartz or kaolinite and for 45 min when adding bentonite. When adding bentonite to the ore, agglomerates were formed and more mixing time was required. It was also observed that after 30 or 45 min the rheology measurements became consistent for the mixtures with kaolinite or bentonite. Once the slurry was mixed, the pH was adjusted to 10 by the addition of hydrated lime.

2.3. Rheology measurements

A 20 mL syringe was used to draw a sample from the flotation cell after the addition of flotation reagents. This sample was immediately transferred to the cup of an Anton Paar DSR 301 rheometer. This cup was part of a Couette geometry (bob and cup) that was installed for this equipment. A rheogram was produced in 35 s to reduce the effect of particle settling. The tests were done at ambient temperature (23 °C), and the shear rate for the rheograms was between 0.1 and 350 s^{-1}, but the shear rate of the rheograms shown in this paper was from 0.1 to 222 s^{-1}. For some slurries with low viscosities, turbulence was created inside the Couette geometry at shear rate values more than 222 s^{-1}.