Minerals Engineering xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Minerals Engineering

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

The role of cations in copper flotation in the presence of bentonite

Yanhong Wang [a,*], Yongjun Peng [a,*], Timothy Nicholson [a], Rolf Andreas Lauten [b]

[a] School of Chemical Engineering, The University of Queensland, St. Lucia, QLD 4072, Australia
[b] Pionera, Hjalmar Wesselsvei 10, 1701 Sarpsborg, Norway

ARTICLE INFO

Article history:
Received 22 December 2015
Revised 17 May 2016
Accepted 12 June 2016
Available online xxxx

Keywords:
Cations
Bentonite
Viscosity
Copper flotation
Flotation rate

ABSTRACT

The previous study demonstrated that bentonite had a deleterious effect on copper flotation by increasing pulp viscosity, but this deleterious effect could be mitigated by sea water (Zhang et al., 2015a). In this study, the effect of different cations, Na^+, K^+, Mg^{2+} and Ca^{2+} with the same anion, Cl^-, on the rheology of a copper-gold ore in the presence of bentonite and copper flotation was investigated. It was found that the improvement of copper flotation in the presence of bentonite was generally dependent on the reduction of pulp viscosity by these cations. Divalent cations, Mg^{2+} and Ca^{2+}, had a more significant effect on pulp viscosity and therefore copper flotation than monovalent cation, Na^+, K^+. These cations also interacted with bentonite, with residual cations modifying the froth property. However, this modification was less significant in copper flotation in the presence of bentonite where pulp viscosity played a critical role.

1. Introduction

With the depletion of high quality ores, an increasing amount of low quality ores that contain a high content of clay minerals have to be processed in the mining industry. However, this raises new challenges as clay minerals have deleterious effects on the flotation of valuable minerals. Industry practice in copper-gold flotation plants show that when an ore containing a high amount of clay minerals is floated at a normal solid density of about 30 wt%, effective flotation is not possible and no froth can be formed on the top of the pulp phase. The pulp becomes a continuous gel-like structure with high viscosity. Currently, no reliable and effective methods are available to reduce the deleterious effects of clay minerals, especially in copper and gold flotation.

Clay minerals are phyllosilicate minerals comprising silica tetrahedral (T) sheets and alumina octahedral (O) sheets joining together in certain proportions, with fine sizes less than 2 μm (Theng, 2012). Smectite, as one of the most common clay minerals in mineral processing, is a 2:1 (T—O—T) structure clay mineral. Montmorillonite is the best known member of the smectite group. When Na^+ cations are exclusively in exchange with montmorillonite surface, the clay is known as bentonite (Luckham and Rossi, 1999). If isomorphous substitution happens, which is defined as part of Si^{4+} ions in tetrahedral positions are replaced by Al^{3+} ions, or Al^{3+} ions in octahedral sites are replaced by Mg^{2+} ions, the layer structure of clay minerals acquires a permanent negative charge. For montmorillonite, the negative charge on basal face is neutralized by an interlayer of exchangeable cations, such as Na^+, K^+, Ca^{2+} and Mg^{2+} (Lagaly and Dékány, 2013). In the presence of water these cations tend to hydrate, thereby forcing the clay layers apart in a series of discrete steps. The equilibrium process depends on the surface charge density or surface potential of the clay mineral, the type of exchangeable cations, particle content, the salt concentration, as well as the ratio of the cations in the bulk solution (Boek et al., 1995; Boshoff et al., 2007; Tombacz et al., 1989; Yildiz and Calimli, 2002; Yilmaz and Marschalko, 2014).

The previous study found that different clay minerals caused different issues in flotation. Increasing the proportion of bentonite led to a higher pulp viscosity that decreased the copper recovery with the reduction of froth amount (Wang et al., 2015). Zhang and Peng (2015) also found a strong relationship between pulp rheology manipulated by kaolinite and bentonite, and copper recovery: the higher the pulp viscosity, the lower the copper recovery. Settling tests and Cryo-SEM analysis revealed that it was the gelation and cross-linked network structures formed by bentonite that increased the pulp viscosity (Zhang et al., 2015a). The small pore size in the network structure reduced the frequency of bubble-particle collisions and the mobility of bubble-particle aggregates, leading to a small amount of froth generated in flotation that reduced copper flotation recovery (Zhang and Peng, 2015).

On the other hand, saline water has been widely used in industry operation as a result of the scarcity of fresh water. In nickel flotation plants in Australia, the ionic strength of the saline water

* Corresponding authors.
E-mail addresses: y.wang26@uq.edu.au (Y. Wang), yongjun.peng@uq.edu.au (Y. Peng).

http://dx.doi.org/10.1016/j.mineng.2016.06.012
0892-6875/

is as high as 1.8 mol/kg (Liu and Peng, 2014). Some other processing plants also use seawater with the ionic strength of 0.6 mol/kg in flotation operations (Dickson and Goyet, 1994). Normally, the seawater contains cations including Na^+, K^+, Ca^{2+}, Mg^{2+}, Si^{4+} and anions including Cl^-, SO_4^{2-} and CO_3^{2-} (Liu and Peng, 2014, 2015). In clay science, it is known that increasing the salinity of bentonite suspension reduces the viscosity. In tap water with negligible ions, bentonite suspension can easily gel due to the swelling property and the formation of network structures (Luckham and Rossi, 1999). The addition of cations reduce the yield stress drastically, because the adsorption of metal ions screen the attractive edge (+)-basal(−) face interactions, resulting in a net repulsive basal-basal face association (Lagaly and Ziesmer, 2003). Adding salts may also modify the network structure of bentonite, resulting in a decrease in viscosity. Heller and Keren (2001) found that a free electrolyte clay suspension had a high apparent viscosity due to the edge-to-edge association between Na-rich montmorillonite platelets, whereas face-to-face associations prevailed at high NaCl concentrations with a lower apparent viscosity. Suzuki et al. (2005) also found that the expansion ratio of bentonite aggregates decreased with NaCl concentration.

In the previous study, Zhang et al. (2015a) found that the deleterious effect of bentonite was mitigated in sea water, because sea water reduced the swelling capacity of bentonite and modified the network structures of bentonite in flotation pulp, which contributed to the improvement of copper and gold recoveries. The composition of seawater in that study included Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^- and SO_4^{2-}. In this paper we aim to further understand how individual salts modify bentonite viscosity and affect copper flotation. NaCl, KCl, $MgCl_2$ and $CaCl_2$ were selected to examine the effect of different cations on pulp viscosity and copper flotation behavior. The results from this study may be used as a guideline to control the types of cations and their concentrations during the bentonite-ore flotation process.

2. Experimental

2.1. Material and reagents

A copper-gold ore with a low clay content was used as a model system and referred to as clean ore in this study. X-ray Diffraction (XRD) analysis in Table 1 shows that the major valuable mineral is chalcopyrite, with pyrite, quartz, albite, muscovite, dolomite and amorphous minerals as gangue minerals. Key element compositions of the ore are shown in Table 2. Sodium bentonite was purchased from Sibelco Group, Australia to represent that occurring in practical copper ores (Zhang and Peng, 2015). It contains 63% montmorillonite, 25% albite and 12% quartz, analysed by XRD. Table 3 shows the key element compositions of the bentonite sample. The particle size distribution of the bentonite sample indicates that 70% of the particles are smaller than 10 μm. The same bentonite sample was used in the previous studies where copper flotation was conducted (Wang et al., 2015; Zhang and Peng, 2015).

Potassium isoamyl xanthate (PAX) obtained from Orica, Australia Pty Ltd, was used as the collector. Plant frother, an aliphatic alcohol based mixture, was used as received. The pH value of slurry in flotation was controlled by the addition of lime. Brisbane tap water was used throughout the flotation process. The ions in tap water have a negligible effect in bentonite viscosity and flotation. Sodium chloride (NaCl), potassium chloride (KCl), magnesium chloride ($MgCl_2$) and calcium chloride ($CaCl_2$) of analytical grade were used to make saline water of different strengths.

2.2. Rheology measurements

Rheology measurements were carried out by an Ares rheometer (TA Instruments Ltd., U.S.), with a 42 mm diameter cup and 28 mm diameter vaned rotor geometry. During measurements, the temperature was maintained at 25 °C with an accuracy of ±1 °C. Each rheology measurement required a sample of 40 ml. Rheograms were collected by measuring the viscosity at shear rates between 1 s^{-1} and 300 s^{-1} over a period of 60 s. The experiments were repeated in triplicate.

2.3. Mineral grinding and flotation

The clean ore was crushed to a size of −2.36 mm using jaw and roll crushers, followed by grinding in a laboratory rod mill with stainless steel rods at 57% solids to obtain 80% passing of 106 μm (P80 = 106 μm). In the flotation of bentonite-ore, 850 g ground clean ore doped with 150 g bentonite as artificial bentonite-ore, was used to simulate the practical copper ore containing bentonite. Then the mixed slurry was transferred to a 3.0 L J.K. flotation cell. Flotation of the bentonite-ore was first conducted in tap water, as a baseline to compare the effects of different salt concentrations. In the flotation of clean ore, 1 kg ground slurry without the addition of bentonite was used.

The flotation procedure was the same as described in the previous study (Wang et al., 2015). Briefly, the artificial bentonite ore was firstly conditioned for 3 min at an agitation rate of 1000 rpm with 30 g/t collector and 15 g/t frother. Then four flotation concentrates were collected after cumulative times of 1, 3, 6 and 10 min with an air flow rate of 3.0 L/min. The flotation froth was scraped every 10 s. After the first 3 min flotation, the second conditioning was followed with 15 g/t collector, and 8 g/t frother for another 2 min. The usage of reagent was maintained the same in the flotation of the ore in the absence and presence of bentonite (Wang et al., 2015). Lime was added to maintain the pulp pH at 9.0 throughout the flotation tests.

3. Results and discussion

3.1. Effect of cations on bentonite viscosity

The previous study indicated that the presence of bentonite decreased copper flotation recovery mainly through the high pulp viscosity, with a less amount of froth generating on the top of pulp phase (Wang et al., 2015). In clay science, it is well-known that bentonite viscosity could be reduced by using salt water (Komine et al., 2009; Lagaly and Ziesmer, 2003; Suzuki et al., 2005). Therefore, in this study rheology measurements were firstly conducted to investigate the effect of different cations on the viscosity of bentonite suspension at pH 9. 15 wt% bentonite was added into different salt water. Fig. 1 shows the apparent viscosity of bentonite as a function of salt concentration at a shear rate of 100 s^{-1}. It can be seen that the apparent viscosity of bentonite suspension decreased gradually from 91 to 8 mPa·s with increasing the concentration of NaCl and KCl from 0 to 0.6 mol/L, whereas the apparent viscosity of

Table 1
Mineral compositions of the clean ore analysed by XRD (wt%).

Quartz	Albite	Muscovite	Dolomite	Pyrite	Chalcopyrite	Amorphous
27.7	35.2	6.8	8.4	2.9	1.4	17.5

Please cite this article in press as: Wang, Y., et al. The role of cations in copper flotation in the presence of bentonite. Miner. Eng. (2016), http://dx.doi.org/10.1016/j.mineng.2016.06.012