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The effect of amorphous silica on pulp rheology and copper flotation

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ABSTRACT

Amorphous silica is an abundant gangue mineral in ore deposits, but its effect on mineral flotation is unknown. In this study, the effect of amorphous silica on pulp rheology and chalcopyrite flotation was investigated. It was found that the presence of amorphous silica increased the pulp viscosity more significantly than quartz especially at a high percentage of solids. This is due to the formation of network structures of amorphous silica particles driven by hydrogen bonds between silanol (Si—OH) groups on adjacent silica units. Flotation tests were conducted using mixtures of chalcopyrite, quartz and amorphous silica. The copper recovery was not affected when the percentage of amorphous silica was less than 30 vol%. However, it started to decrease significantly after the percentage of amorphous silica was further increased, which was caused by the significantly increased pulp viscosity. Although a low percentage of amorphous silica had little influence on copper recovery, it caused a significant increase in mass recovery, leading to the decreased copper grade. This was found to be due to the increased entrainment of gangue minerals resulting from the low particle density of amorphous silica and the network structures formed by amorphous silica particles.

1. Introduction

Silica (SiO_2) is the most abundant mineral in the earth's crust. It occurs in both crystalline and non-crystalline (amorphous) forms. The main type of crystalline silica is quartz, while the common naturally occurring amorphous silica includes flint, opal and diatomaceous earth. Amorphous silica is also present in various base metal and precious metal deposits but is usually neglected due to the difficulty in detection (Nelson, 1988, Ndlovu et al., 2011). Although the basic structural unit of both amorphous and crystalline forms of silica is the SiO_4 tetrahedron, their structures are very different. In the crystalline form, the tetrahedra are organized relative to each other in a definite regular long range order in which both silicon and oxygen atoms have defined positions. However, this long range order is not present in the amorphous form where there is only a short range order between neighbours. While quartz has a simple and regular morphology and surface charge distribution and its roles in mineral processing have been well studied (Shi and Zheng, 2003; Yue and Klein, 2004; Ndlovu et al., 2011; Otsuki et al., 2011; Xu et al., 2012), the roles of amorphous silica which contributes to a significant amount of gangue materials in mineral processing have not been studied.

In other industries, such as paints and coatings, amorphous silica is well known for its ability to enhance the viscosity of organic media (Sacks and Sheu, 1987; Raghavan and Khan, 1997; Raghavan et al., 2000; Zhuravlev, 2000; Amiri et al., 2009). There is a large amount of superficial silanol groups (Si-OH) on amorphous silica surfaces which are the actual reactive centres, forming hydrogen bonds with each other and with other substances. It has been reported that the hydrogen bonds formed between neighbouring amorphous silica particles can result in three dimensional networks as illustrated in Fig. 1. When such linkages are formed extensively and span the sample volume, the suspension becomes a colloidal gel (i.e., a three-dimensional network of particles). The main driving force for silica gelation is expected to be the formation of hydrogen bonds between silanol (Si—OH) groups on adjacent silica units. The formation of networks restricts the mobility of the molecules of the liquid so that the viscosity of the system increases. Similar structures were also reported in some clay mineral suspensions. As studied by Zhang et al. (2015a) using Cryo-SEM analyses, cross-linked network structures formed in bentonite suspensions and significantly increased the pulp viscosity.

A number of studies have indicated a strong relationship between flotation performance and pulp rheological property (Shabalala et al., 2011; Farrokhpay 2012; Patra et al., 2012; Becker et al., 2013; Cruz et al., 2013; Wang et al., 2015; Zhang and Peng, 2015). A higher pulp viscosity usually corresponds to a lower recovery of valuable minerals. In the pulp zone of a flotation cell, a high pulp viscosity can result in increased turbulence damping, poor gas dispersion, a reduced mobility of particles and mineralised bubbles, and a low particle-bubble collision efficiency (Shabalala et al., 2011; Becker et al., 2013). All of these factors can lead to a reduced flotation efficiency.

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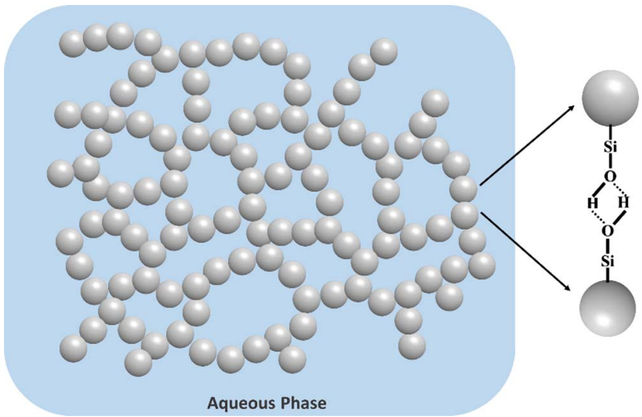

Fig. 1. Schematic representation of the formation of network structures by amorphous silica particles dispersed in an aqueous phase and the possible H-bonding interaction mechanism (adapted from Raghavan et al. (2000)).

Another important property of amorphous silica is its low particle density compared to quartz due to the lack of crystalline structures (Flörke et al., 2000). A recent study by Wang et al. (2016) found that particle density can significantly affect the entrainment of gangue minerals in flotation and therefore the grade of flotation concentrates. Entrainment is a mechanical transfer process by which mineral particles suspended in water enter the base of the flotation froth, move upwards, and finally leave the flotation cell with the hydrophobic particles recovered by true flotation. As studied by Wang et al. (2016), the drainage of solids relative to water in the froth (i.e. the degree of entrainment) is a consequence of the balance between the drag force on the particle and the apparent immersed weight of the particle in the water which potentially changes the particle settling rate. A decrease in particle density can result in a decrease in particle settling rate and therefore leads to an increase in the degree of entrainment in flotation.

The presence of amorphous silica in ore deposits may have a significant influence on mineral flotation through the modification of slurry rheology and gangue entrainment. However, up to date, there is no report on the effect of amorphous silica on flotation. In this study, a synthetic ore with the mixture of quartz, amorphous silica and chalcopyrite was used to study its rheological behaviour and corresponding flotation performance.

2. Experimental details

2.1. Minerals and mineral preparation

Natural quartz was obtained from Geo Discoveries Australia in a crystalline form with 97% purity. It was pulverized and wet sieved to collect only size fractions between 38 μm and 75 μm. Laboratory grade amorphous silica particles were obtained from Scharlau and were sieved to collect the same size fractions between 38 μm and 75 μm. The density of quartz and amorphous silica particles was manually measured. A known mass of particles and a known mass of water were thoroughly mixed and then the total volume of mixed slurry was measured using a measuring cylinder. The particle density was calculated by dividing the mass of particles by the volume of particles which was obtained by deducting the volume of water from the total slurry volume. Using this method, the measured density of quartz and amorphous silica particles is 2.65 g/cm^3 and 1.57 g/cm^3, respectively.

Pure chalcopyrite was obtained from Geo Discoveries, Australia, in a rock form. It was crushed through a jaw crusher and then a roll crusher, and then screened to collect −2.35 mm +0.71 mm particle size fractions. Prior to each flotation test, 15 g crushed chalcopyrite was further ground in a stainless rod mill to achieve a particle size of P80 38 μm.

2.2. Rheology measurements

Rheology measurements were conducted using a Discovery HR-1 rheometer (TA Instruments Ltd., U.S.). All tests were conducted with a vane geometry with a 30.36 mm diameter cup and 28.00 mm diameter vane. For each test, 35 mL prepared suspension was taken with a syringe while the suspension was mixed with a magnetic stirrer and poured into the cup and the vane lowered until the gap between the cup and the vane was 6 mm. The rheometer was operated in a strain-controlled mode where the shear rate was fixed and the required torque (shear stress) was the value being measured. The shear rate range chosen was 0.1–100 s^{-1} with a pre-shear at 100 s^{-1} before each measurement to prevent particle settling. All rheology measurements were performed at room temperature of 25 °C. The rheology of pure quartz and amorphous silica suspensions was measured at 2 vol%, 4 vol%, 8 vol%, 10 vol%, 15 vol%, 20 vol% and 30 vol% solids concentration adjusted by using de-ionised water. The rheology of quartz-amorphous silica mixtures was measured at different mixing ratios with the overall solids concentration fixed at 20 vol%, the solids concentration used in flotation tests.

2.3. Flotation tests

In order to examine the effect of amorphous silica on flotation, synthetic ore containing chalcopyrite and different ratios of amorphous silica and quartz were prepared. The solids concentration was fixed at 20 vol% for all the tests and the percentage of amorphous silica varied from 0 vol% to 100 vol%. Chalcopyrite was freshly ground prior to each test in a stainless steel mill with stainless steel rods and then mixed with quartz and amorphous silica in a 1.5 L Agitar mechanical flotation cell.

Industrial grade potassium amyl xanthate (PAX) was used as collector. Huntsman's POLYFROTH W22 which is polyoxyalkylene alkyl ether was used as frother in this study. During flotation, four concentrates were collected after the cumulative time of 1, 3, 6 and 10 min. Before the first and the third concentrate, 20 g/t collector and 15 g/t frother were added, followed by 2 min of conditioning. The air flowrate and the speed of impeller were kept constant at 3.0 L/min and 1000 rpm, respectively, for all flotation tests. The pH of the slurry was adjusted to 9.0 at the start of the test using lime which is normally used in copper flotation plants as the pH modifier.

3. Results and discussion

3.1. Effects of amorphous silica on pulp rheology

In a real ore, amorphous silica usually co-occurs with quartz and the ratio between them varies significantly within different deposits. To achieve a comprehensive understanding of the effect of amorphous silica on pulp rheology, the rheology measurements in this study were conducted in three systems: amorphous silica, quartz, and the mixture of amorphous silica and quartz.

The rheological behaviour of amorphous silica and quartz in water at different solids concentrations was measured firstly. Fig. 2 shows the apparent viscosity of the suspensions at 100 s^{-1}, the average shear rate value in a mechanical flotation cell (Ralston et al., 2007). It can be found that the viscosity of both amorphous silica and quartz suspensions was close to zero when the solids concentration was below 8 vol %, indicating that a low concentration of amorphous silica or quartz did not cause any significant change in rheology. With the solids concentration further increasing, the viscosity of amorphous silica suspensions started to increase exponentially, which indicates a change of flow characteristics. Although the viscosity of quartz suspensions also increased with the solids concentration, it was always significantly lower compared to that of amorphous silica suspensions at the same solids concentration. For example, the apparent viscosity of 20 vol% amorphous silica suspension was 0.286 Pa s, but the apparent viscosity