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Quantifying rheological and fine particle attachment contributions to coarse particle recovery in flotation

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ABSTRACT

This study focused on the flotation behaviour of very coarse quartz particles in the presence of fine silica and alumina, both of which were used as pulp viscosity modifiers. A decrease in the contact angle of the coarse quartz particles, caused by the attachment of fine particles was believed to be the principal mechanism accounting for the noted depression. Only small surface coverage of attached fine particles may dramatically decrease the quartz particle recovery because the flotation behaviour of the coarse particles was very sensitive to particle hydrophobicity, e.g. less than 5% surface coverage is able to decrease the contact of particles from 83° to 81° and causes a decrease in recovery from 60% to 20%. The effect of removing the fine particles from the pulp, by the process known as desliming, on the flotation behaviour of coarse quartz particles was also investigated. The results showed that desliming is beneficial for the recovery of coarse quartz particles. Furthermore, the recovery of coarse quartz particles attached with fine particles can be restored by conducting flotation in high viscosity medium where glycerol was used as the viscosity modifier.

1. Introduction

Detachment of particles from bubbles is one of the key issues responsible for the low recovery of coarse particles. For coarse particles attached to bubbles, the particle–bubble aggregates must withstand the various forces which are operational in the flotation cell to be successfully transported to the pulp/froth interface. A property-based flotation model, developed at the Ian Wark Research Institute (The Wark flotation model) (Duan et al., 2003; Pyke et al., 2003) suggests that a key parameter which directly controls the stability of a particle–bubble aggregate and which quantifies the mean shear forces acting on the bubble–particle aggregate is the mean turbulent energy dissipation. A decrease in the mean turbulent energy dissipation throughout a flotation cell may benefit the recovery of coarse particles due to the reduction of shear forces acting on the particles attached to the bubbles, increasing the stability of the bubble–particles aggregates. Other studies have shown that increasing the viscosity of the pulp results in a decrease in turbulent energy dissipation in a flotation cell (Kitano et al., 1981; O'Connor et al., 1990).

It has also been suggested that slurry rheology is an important factor for flotation due to its marked effect on cell hydrodynamics, including gas dispersion throughout the cell (O'Connor et al., 1990; Deglon et al., 2007). O'Connor et al. (1990) found that a decrease in pulp viscosity in a viscous slurry resulted in a decrease in the bubble size due to increased turbulence in the cell. However, Deglon et al. (2007) found the opposite trend for the change in bubble size, in a study of Bindura nickel ore slurries. According to Deglon et al. (2007), the bubble size decreases with an increase in the solids concentration. Deglon et al. (2007) proposed that the decrease in bubble size was due to the high yield stress in the slurry, which caused a more concentrated energy dissipation near the impeller and leads to the production of small bubbles. A decrease in the gas hold up was also attributed to the high yield stress of the slurry, which prevents the dispersion of bubbles through the cell (Deglon et al., 2007).

An increase in slurry viscosity may be achieved by increasing the percent solids, particularly using fine particles as the viscosity modifier. An example of the effect of particle concentration on the rheology of titanium dioxide suspensions was reported by Yang et al. (2001). At relatively low volume fraction of the titanium dioxide ($\Phi = 0.109$), the suspension shows Newtonian behaviour, i.e. the viscosity is independent of the shear rate. An increase in the solids volume fraction to $\Phi = 0.174$ results in shear-thinning behaviour, with the viscosity decreasing with an increase in shear rate. With a further increase in the solids volume fraction the rheological behaviour of the suspension remained shear-thinning, but the apparent viscosity values increase considerably by almost three orders of magnitude at $\Phi = 0.431$ (Yang et al., 2001). Similar trends in rheological behaviour was observed for slurries of dolomite (Deglon et al., 2007), galena (Gao and Forssberg, 1993;

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Wang and Forssberg, 1995), quartz (Prestidge, 1997a,b) and coal (Tangsathitkulchai, 2003), though changes in flow behaviour occur at different volume concentrations of the particles.

One of the drawbacks of using fine particles to modify the viscosity is the possible interaction between coarse and fine particles, which may cause a decrease in the flotation recovery of the coarse particles by reducing the hydrophobicity of the coarse particles. Thus, fine particles may modify the flotation behaviour of coarse particles through both viscosity modification and fine particle attachment to coarse particles. This paper investigates the effect of fine particles on the flotation of coarse particles through rheological modification and/or fine particle attachment mechanisms.

2. Experimental

2.1. Material

Samples of quartz (GEO Discoveries, Australia) were ground and screened to two coarse size fractions of interest, namely 150–300 μm and 600–850 μm. Each size fraction of ground quartz were cleaned using the procedure outlined by Pashley and Kitchener (1979). Namely, the particles were washed in concentrated hydrochloric acid three times (2 h each time) and then rinsed with copious amounts of Milli-Q water several times until the pH value of the Milli-Q water (5.6) was restored. The particles were then immersed in a 30% NaOH solution at 60 °C for 1 min, followed by the same rinsing procedure. The particles were then dried in a clean oven at 110 °C overnight and stored in capped bottles in a desiccator under vacuum.

Trimethylchlorosilane (TMCS) solutions in cyclohexane were used for particle methylation (Pashley and Kitchener, 1979). Since TMCS readily reacts with water, the methylation reaction was performed in a glove box under nitrogen atmosphere. Different concentrations of TMCS were prepared by diluting the required volumes of TMCS in cyclohexane. The cleaned quartz were weighed into a beaker and heated in an oven at 110 °C overnight to remove the physisorbed moisture. Particles with various contact angles were obtained using solutions of different TMCS concentrations and reaction time. All glassware was cleaned and dried before use.

Fine alumina (Hydral 710, Alcoa of Australia Limited) and silica (Sigma–Aldrich Inc., USA) were used to adjust the pulp viscosity. The choice of these particles is based on the fact that at pH < 9, alumina is positively charged (Johnson et al., 2000), and may interact with coarse quartz particles. In contrast, silica has a negative zeta potential in the 3–9 pH range (Ametov and Prestidge, 2004), and is not expected to interact with quartz. The condition of pH 9, i.e., the pH_{IEP} of alumina was used because particle interaction, and consequently viscosity, is most significant at this pH value. The aggregates may facilitate the attachment. Thus, rheological and fine particle attachment contributions to flotation response may be discerned. To contrast the effect of particle interaction in the case of the alumina particles, silica was also examined as a model system that would exhibit lower particle interaction under these conditions. Therefore, using alumina and silica, the effect of colloidal particles on the viscosity of the suspending medium and the flotation behaviour of the coarse quartz may be considered, as a first approximation, as an investigation for the cases of interacting and non-interacting fine particles. Characterisation of fine alumina and silica is presented in the next section.

2.2. Characterisation of fine particles

2.2.1. Zeta potential of alumina and silica particles

Zeta potential of silica and alumina was determined from the particle dynamic mobility using the Nano-ZS Zetasizer instrument (Malvern Instruments Ltd., Worcestershire, UK) in electrophoretic light scattering mode for dilute particle suspensions.

Dilute silica and alumina suspensions were prepared at 0.5 wt.% solids, in 10^{-3} M KCl and dispersed with a magnetic stirrer for 30 min. The suspension was allowed to stand for 5 min, and the colloidal particles (<5 μm in size) in the supernatant were siphoned off for the zeta potential measurement. The suspension pH was altered to a desired value with HCl and KOH solutions, and allowed to equilibrate for 10 min before the samples were directly injected into a disposable capillary cell for zeta potential measurements. The measurements were performed over the pH range 5–9.5 for alumina. The zeta potential of the silica was investigated over pH range 3–9.

2.2.2. Particle size distribution of alumina and silica

The particle size distribution of alumina and silica was determined by laser diffraction using a Mastersizer 2000 (Malvern Instruments Ltd., UK). The basic particle size sensor comprises an optical measurement unit which supplies information to a computer to process data and perform the analysis.

Ultrasonication for 5 min and a polyphosphate dispersant (i.e., Calgon) were used to achieve full dispersion of both alumina and silica particles.

2.2.3. Slime coating of fine particle on quartz surface

Scanning electron microscopy (a PHILIPS XL-20 electron microscope) was used to determine the adsorption of fine silica and alumina particles on the surface of coarse quartz particles. The samples were mounted onto the sample holder using double-sided sticky tape and were coated with a thin carbon layer using a vacuum evaporator.

2.2.4. Slurry rheology

The rheological behaviour of the silica and alumina suspensions was investigated using a Haake RotoVisco RV1 rheometer (Thermo Electron GmbH, Germany) fitted with the concentric cylinder (Couette) sensor.

Each slurry sample (~100 cm^3) was prepared by adding known weights of fine silica or alumina particles to known volumes of the 10^{-3} M KCl solution at pH 9. Prior to the rheology measurement, the suspensions were stirred for 1 h using an overhead stirrer. In the measurement, the shear rate increased from 0 s^{-1} to 1000 s^{-1} (an upward curve) and then decreased down to 0 s^{-1} (a downward curve) in 200 s. The rheological parameters were automatically recorded by a computer. The percentage of fine alumina and silica is shown as volume% in all cases using 2.65 g/cm^3 and 3.95 g/cm^3 density for silica and alumina respectively to convert the mass of fine particles to corresponding volume.

2.3. Methodology

2.3.1. Flotation

Flotation tests on coarse quartz particles were carried out according to the flowsheet shown in Fig. 1. Quartz particles (60 g) of various mean contact angle values and particle sizes were floated in a 1.5 dm^3 bottom driven flotation cell. All flotation tests were carried out at an impeller speed of 600 rpm. Air was introduced into the flotation cell at a flow rate of 3.5 dm^3/min (J_g = 0.4 cm/s). Dowfroth 250 (170 g/t, 8 ppm in solution) was used as frother. Froth depth was 3 ± 1 cm. Quartz particles were hydrophobised to the target value of contact angle before the flotation test. Four concentrates were collected, cumulatively at 0.5 min, 2 min, 4 min and 8 min. Make-up water was used to the cell to keep the interface at the same level during the flotation tests.

The viscosity of the suspending medium was increased by: (i) using glycerol (95% purity)/water mixtures instead of water and