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An investigation into the relationship between particle shape and entrainment

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ABSTRACT

The effect of particle shape on true flotation has been widely reported. The present paper presents results obtained in investigating the effect of particle shape on the entrainment of particles during the flotation process. Different hydrophilic minerals with particles of varying aspect ratios were used and their shape determined using rheological tests and auto-SEM-EDS (QEMSCAN). Their entrainment properties showed a close relationship to their shape with the recovery due to entrainment increasing as the aspect ratio of the particles increased. The effect of surface charge, by changing pH, and size of particles showed that the effect of shape was sustained at different pHs and particle sizes. Proposals are made to explain these observations in terms of the known relationships between drag coefficients and terminal velocities and shape. Since it has been previously reported that different milling procedures can affect particle shape, these results indicate that it is possible that such different procedures may result in increased entrainment of hydrophilic minerals.

1. Introduction

As is well known and has been extensively reviewed, the recovery of particles during the flotation process is achieved either by true flotation or by entrainment. Entrainment in particular refers to particles being recovered by being mechanically transported to the froth phase and then carried by the froth to the launder without attachment to the air bubbles. There is a close linear correlation between the mass of water recovered and the mass of particles entrained (Warren, 1985; Kirjavainen, 1996). Particles of low mass, i.e. very small particles or particles of low density are particularly prone to entrainment. Moreover, even those very fine particles which are hydrophobic may not have sufficient momentum to attach to bubbles in the pulp phase and thus will report to the concentrate by being carried over by the water in the froth phase (Trahar, 1981). It follows, that using milling procedures which increase over-grinding may enhance entrainment by producing excessive amounts of fine particles.

Apart from the fact that milling procedures are aimed at increasing the liberation of valuable minerals while at the same time increasing the amount of fines in the product, it has also been observed that different milling procedures may also produce particles with different shapes or morphologies (e.g. Khonthu et al., 2012; Yekeler et al., 2004; Forssberg et al., 1988). The fact that the recovery of particles by true flotation is influenced by particle shape has been widely reported (e.g. Koh et al., 2009; Vizcarra et al., 2011; Ulusoy and Yekeler, 2005). All of these investigations have shown that elongated particles had higher recoveries by flotation than rounded particles. The common factor in all of these studies was that collectors were used and the studies focused on the relationship between particle shape and true flotation. George et al. (2004) compared the relative roles of true flotation and entrainment of submicron particles using fine bubbles. Neethling and Cilliers (2009) have studied the effect of particle size on entrainment and modelled this phenomenon. They have shown that the entrainment of particles into the froth, in spite of the dominance of their settling velocity against the upward liquid velocity at the interface, is due to dispersion and they proposed that dispersion is a strong function of settling velocity and thus particle size. The same authors also noted that settling velocities play a key role in entrainment since settling velocities are also influenced by particle shape (Neethling and Cilliers, 2002, 2009). From this it may be deduced that when a mineral is treated by flotation, entrainment will not only be a function of the particle size but may also be affected by the shape of the particle due to the relationship between shape and settling velocity. This suggests that it would be of interest to investigate the influence that the shape of particles has on their entrainment, as opposed to their true flotation behaviour.

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Defining the shape of particles is a non-trivial challenge, especially in ensuring that the measurement is not sensitive to changes in image resolution (Little et al., 2015; Pirard, 1989). Some of the commonly used shape descriptors are: aspect ratio, angularity (inverse of circularity), concavity and roundness. Aspect ratio is the ratio of the maximum to minimum Feret diameters where the Feret diameter is defined as the distance between two parallel tangents of the particle at an arbitrary angle (although sometimes the inverse of this ratio is also used to define aspect ratio). Angularity and its inverse circularity is the ratio of the perimeter squared to the projected area. Roundness is the ratio between the area and the long axis. Concavity is the ratio of the diameter of the smallest circumscribed circle (sphere) to the diameter of the largest inscribed circle (sphere) centred in the centre of mass of the particle. In mineral processing applications, however, a wide variety of shape measurements and descriptors have been used, varying from qualitatively characterising shape using SEM micrographs (Kurson and Ulusoy, 2006), a sphericity index based on BET surface area (Koh et al., 2009), to using a combination of shape descriptors derived from auto-SEM-EDS data (c.f. roundness in conjunction with aspect ratio, Little et al., 2015). Another approach is to use the fact that the thickening effect of particles is related to shape at constant solids density. It has been shown that apparent viscosity decreases in the order of rods > plates > cubes/grains > spheres for the same phase volume of particles, i.e. the apparent viscosity increases as particles become less spherical and as aspect ratio increases (Barnes, 2000). This method has been found to be highly reproducible and by using particles of known aspect ratio it is possible to calibrate the experimental procedure and to correlate these observations with the more widely used microscopic procedures.

The aim of the present study was to investigate more specifically the relationship between the recovery via entrainment of a range of different hydrophilic mineral particles and their shapes. The only reagent used was a frother. In the case of talc, its natural floatability was first fully suppressed using previously reported methods (Wiese et al., 2007). The effect of particle size and surface charge was also investigated. Proposals are made to explain the results obtained.

2. Material and methods

The minerals used in the present study were mica, vermiculite, wollastonite and talc as well as glass ballotini (synthetic SiO_2). Hand-picked samples of the minerals were crushed, pulverised and screened. Ballotini was used as received. A sub-sample was then mounted in resin and prepared into QEMSCAN polished blocks for analysis using a LEO 1450 QEMSCAN. Between 5000 and 10,000 particles were analysed for each of the minerals of interest using the Particle Mineralogical Analysis method on QEMSCAN and the results interpreted with iExplorer software. Their purities were all greater than 90% with the exception of vermiculite which had a purity of ~43%. The latter sample showed the presence of significant amounts of iron oxides and apatite. All samples were typical of the class of naturally hydrophilic Mg, Ca, Al-silicates with the exception of talc which can be both hydrophobic and hydrophilic (Rotenberg et al., 2011). The shape and aspect ratio of the samples was determined, using several different methods. Firstly, an FEI Nova Nano scanning electron microscope was used to obtain micrographs of the samples. Secondly, the roundness and aspect ratio of the particles was measured using QEMSCAN. Thirdly, the relationship between the aspect ratio and particle size was determined using a laser diffraction instrument (Sympatec©). Finally, the relationship between apparent viscosity of each sample and shape was determined using an AR 1500 rheometer with a standard 4 panel vaned rotor geometry. These tests were carried out using volume percentage solids in the range between 10% and 45% at increments of 5% and were performed on particles which were less than 25 μm in size. The temperature of the instrument was set at 23 °C and the test solutions were prepared using synthetic plant water (Wiese et al., 2005). The particle size distributions of the feed and mill product were determined using a Malvern MasterSizer 2000 particle size analyser.

Batch flotation tests to determine the mass of solids, i.e. mass entrained, and water recovered were carried out in a 3 L flotation cell agitated at 1200 rpm with an air flow rate of 7 L/min using 30 g of the mineral and synthetic plant water. Unless otherwise indicated, the pH was in the range 7–8. The only reagent used was the frother, Dowfroth 200, but, in the case of talc, tests were carried out in the presence and absence of a guar gum depressant. The guar gum served to depress the naturally floatable fraction in the sample after which the particles recovered would be due to their recovery by entrainment (Wiese et al., 2007).

3. Results

The particle size distributions of all samples used had a $d_{80} < 38$ μm although the ballotini was much finer with a $d_{80} < 13$ μm. This smaller particle size will be of significance when interpreting the results. Differences in particle shape measured by QEMSCAN are illustrated in Fig. 1 by comparison of their roundness and aspect ratios. It is evident from Fig. 1 that the ballotini particles were more rounded than any of the other mineral particles. All samples show a distribution of aspect ratios (short/long axis). The ballotini particles exhibit a more narrow distribution with aspect ratios close to one which is indicative that these particles were more equant. In contrast, wollastonite, mica and talc are all considerably more elongate. The SEM images of the minerals as shown in Fig. 2 clearly demonstrate the spherical shape of the ballotini particles and the very elongated shape of the wollastonite particles. The results obtained from QEMSCAN did not show as large a difference in particle shape between wollastonite and mica as was expected. This may be due to the preferential orientation of the wollastonite particles in the resin during the preparation of the polished blocks, as other methods used to determine particle shape suggest a larger difference in shape between these two minerals.

Table 1 shows the results obtained using the Sympatec© instrument. The Table shows the aspect ratios for 40 μm particles but the instrument determined the ratios for a range from 5 μm to 75 μm. The differences, especially between ballotini and wollastonite, are clear.

Fig. 3 shows the results obtained in the rheology tests. Also shown in this figure is a false colour image of a particle of each mineral obtained from the QEMSCAN results. This figure shows clearly that in the case of ballotini and wollastonite there was a significant increase in the apparent viscosity as the aspect ratio increased which is consistent with previous findings (Barnes, 2000). The observations made in the case of the phyllosilicate minerals (viz. mica, vermiculite and talc) are not consistent with the previously referenced relationship between apparent viscosity and aspect ratio due to fact that it is well-known that they have anisotropic surface charges causing more complex rheology (Ndlovu et al., 2014).

Fig. 4 shows the relationship between the mass of solids and mass of water recovered when flotation was carried out as described in the experimental section. In every case these results reflect the typical linear relationship expected when entrainment is the dominant mode of recovery (Warren, 1985). The plot of the talc recovery is for the sample pre-treated with guar. In the absence of guar the combined recovery of talc due to entrainment