



The entrainment of kaolinite particles in copper and gold flotation using fresh water and sea water



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ABSTRACT

In this study, the recovery of kaolinite particles in copper and gold flotation using fresh water and sea water was investigated. Cryo-SEM analyses together with settling tests were employed to examine the formation of kaolinite network structures and its correlation with the entrainment of kaolinite particles. It was found that kaolinite had a negative effect on copper and gold grades of flotation concentrates in fresh water due to the aggregation of clay platelets in the pulp and the transport of clay aggregates into the froth. Sea water modified the association of kaolinite platelets with the formation of cross-linked network structures exacerbating the entrainment, and copper and gold grades. In addition to the compression of the double layer, the adsorption of cations on the clay platelets may also facilitate the formation of network structures in sea water.

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1. Introduction

In froth flotation where valuable minerals are separated from gangue minerals, the mechanical entrainment of gangue minerals occurs along with true flotation, resulting in the low quality of flotation concentrates. It is considered as a two-step process, (1) the rise of suspended solids in the region just below the pulp/froth interface to the froth, and (2) the transfer of entrained particles in the froth to the concentrate launder with water [1]. Unlike true flotation which is chemically selective to mineral surface properties, entrainment is a non-selective process by which both gangue and valuable minerals suspended in water films between air bubbles enter the flotation froth. The finer the particle, the more likely it is recovered by entrainment. Smith and Warren [2] studied the entrainment of particles in flotation and found that for particles smaller than 30 μm , their recovery by entrainment became significant. Clay minerals have colloidal sizes and when present in froth flotation as gangue materials, they may be recovered by entrainment therefore diluting the concentrate grade.

Plate-like clay minerals expose two crystallographically different surfaces, the flat face surface and the edge surface [3]. The face surface has a permanently negative charge arising from isomorphous substitutions, and the charge developed on the surface hydroxyl groups at broken edges is pH-dependent [4]. It is established that clay minerals can form three different modes of associations, edge-to-face (E–F),

edge-to-edge (E–E) and face-to-face (F–F) [5]. These associations result from the state of balance between van der Waals attraction and electrostatic forces that exist between charged double layers at the surfaces of clay platelets with the latter being either attractive or repulsive depending on the charge of the surfaces. The E–F and E–E associations lead to the formation of three-dimensional ‘house-of-cards’ structures. The F–F associations refer to paralleled clay platelets and lead to thicker and larger aggregates [6]. It has been demonstrated that in a flotation cell, stable aggregates of clay particles can be formed as a result of the rapid decline of shear rates away from the impeller tip [7]. However, how these clay particle associations affect the entrainment of clay minerals in flotation has not been studied.

On the other hand, with the depletion of fresh water, the use of sea water or bore water with a high concentration of electrolytes in mineral processing industry has been increased. It is documented that electrolyte solutions can modify the aggregate structures formed by clay minerals [8]. Heller and Keren [9] indicated that the modification of clay associations was possible by altering the solution properties such as pH, electrolyte composition and concentration. A number of studies have established the relationship between pH and the association modes of clay particles at different ionic strengths. At a low ionic strength, the addition of electrolytes at low pH compresses electrical double layers at positive edges and negative faces, reducing the electrostatic attraction and hence the number of E–F associations [10]. However, at low ionic strength and high pH, the number of all three modes of associations is small [11]. When the ionic strength is sufficiently high, the effect of pH is insignificant [12], and electrical double layers are compressed with F–F association promoted [13]. Hence, the

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presence of ions in flotation may further complicate clay particle associations and the subsequent recovery of clay minerals via entrainment.

Kaolinite is a non-swelling clay mineral with a 1:1 structure and a general composition of $Al_2Si_2O_5(OH)_4$. This type of clay minerals has a low chemical reactivity and its anion exchange capacity is typically higher than its cation exchange capacity [14]. Kaolinite consists of plate-like particles that do not have an expanding lattice, therefore no water can penetrate between the layers. The detailed kaolinite structure and properties can be found elsewhere [15,16]. Kaolinite is often associated with other valuable minerals in ore deposits. Understanding its entrainment behaviour in mineral flotation is vitally important for controlling the concentrate grade and providing new insights into mitigation technologies, such as polymeric depression and dispersion. In this study, the effect of water quality (tap water versus sea water) on the association and subsequent entrainment of kaolinite particles in copper and gold flotation was studied.

2. Material and methods

2.1. Raw materials

A copper–gold ore with a low clay content was crushed to a size of -2.36 mm before grinding and flotation. The mineral composition of this ore analysed by quantitative X-ray Diffraction (XRD) is shown in Table 1. The major gangue minerals are quartz, albite and muscovite with a low concentration of kaolinite. The elemental composition of the ore is shown in Table 2 indicating 0.70 wt.% Cu, 0.47 g/t Au, 2.87 wt.% Fe, 0.33 wt.% Zn and 0.86 wt.% S. Diagnostic leaching of the ore shows that about 80 wt.% Cu is associated with primary copper minerals and the rest is associated with secondary copper minerals and oxides. This ore is referred to as “clean ore” in this study. The proportion of free gold in the clean ore is about 30–40 wt.% and most gold is associated with copper minerals.

Kaolinite Q38 purchased from Sibelco Group, Australia is a dry milled product with a surface area of 26 m²/g. Quantitative XRD analysis shows that the Q38 sample contains 85 wt.% kaolinite with 4 wt.% quartz and 11 wt.% muscovite. The relatively low-crystallinity Q38 kaolinite with Hinckley crystallinity index (I_H) of 0.5, derived from the XRD pattern [17], was chosen in this study because it is close to the I_H of the kaolinite in the clean ore (0.6). High purity quartz (>95%) was purchased from Geo Discovery Group, Australia and tested in this study for a comparison with kaolinite.

The particle size distribution of the kaolinite sample and pulverized quartz was measured by a Laser Diffraction Malvern Mastersizer (Malvern Instrument Ltd., U.K.). The detailed procedure was described elsewhere [18]. The particle size distribution of mill discharge of the clean ore was measured using both wet/dry screens from 425 μ m to 38 μ m. The size distributions of the kaolinite sample, pulverized quartz and ground clean ore are shown in Fig. 1. The procedure to grind the clean ore was detailed below. The kaolinite sample and pulverized quartz have a similar size distribution with 77% particles smaller than 14 μ m. The P80 of the ground clean ore is 212 μ m which is used in the plant where the ore was supplied.

Sodium isopropyl xanthate (SIPX) and Cytec Aero 3894A (a thionocarbamate) were used in this study as collectors. Huntsman Polyfroth W22 was used as the frother. Brisbane tap water and artificial sea water were used in the study in parallel. The sea water used in this study was the same as used in the flotation plant where the ore was supplied. Its composition is shown in Table 3. The sea

Table 2
Key elements of the clean ore sample.

Copper (wt.%)	Gold (g/t)	Iron (wt.%)	Zinc (wt.%)	Sulphur (wt.%)
0.70	0.47	2.87	0.33	0.86

water was prepared by dissolving 35 g API Aquarium Salt purchased from Age of Aquariums, Australia, in deionized water to make up 1 L.

2.2. Mineral grinding and flotation

1 kg crushed clean ore sample was ground in a laboratory stainless steel rod mill with stainless steel rods at 50% solids to obtain 80% particles passing 212 μ m with the addition of 8 g/t Cytec 3894A. The mill discharge was then transferred to a 3.0 L Agitair flotation cell.

In order to study the entrainment of kaolinite particles in copper and gold flotation using tap water and sea water, the artificial mixtures of the clean ore and kaolinite/quartz were prepared. For each test the calculated amount of clean ore slurry (15% of the total solid by weight) in each case was taken out from the agitating flotation cell and replaced by the same amount of a well-mixed kaolinite or quartz suspension so that the concentration of kaolinite or quartz in the mixture was 15 wt.% while the solid density for all tests was kept constant. The mixed slurry was then conditioned with SIPX collector (6 g/t) and frother (15 g/t) before flotation. During flotation, four concentrates were collected after the cumulative times of 1, 3, 7 and 17 min. After the second concentrate, SIPX collector (4 g/t) and frother (15 g/t) were added again to the pulp. Flotation was operated at an air flow rate of 8.0 L/min. The speed of the impeller was kept constant at 800 rpm. Lime was used to control the pH 9.5 in the end of grinding and during flotation.

2.3. Size-by-size analysis

The recovery of kaolinite particles from different size fractions from flotation in tap water and sea water was analysed. Flotation concentrates and tailings were dried and then sieved using both dry/wet screens from 150, 106, 75 μ m down to 53 μ m. The sub 53 μ m fraction was further separated by a Warman cyclosizer to obtain 6 fine fractions, $-53 + 46$, $-46 + 35$, $-35 + 24$, $-24 + 16$, $-16 + 11$ and -11 μ m. The amount of kaolinite in each size fraction was quantified by XRD, based on which the recovery of kaolinite from each size fraction was calculated.

2.4. Cryo-SEM

The Cryo-SEM technique is widely used in many applications to avoid changes in structure induced by vacuum drying or freeze-drying since the water is vitrified without crystallization as ice [19]. Two 6 mm long copper tubes with outer-diameter 4 mm and inner-diameter 3 mm were joined together by superglue to hold liquid samples. The samples were collected from pulp zone as well as froth overflow during flotation by using a wide-bore pipette. The copper tube with the sample inside was immediately sealed with dental wax, placed in a container and plunged into liquid nitrogen. Each sample was preserved in liquid nitrogen until transferred to the sample preparation chamber of the PHILIPS XL30 field emission gun scanning electron microscope (FESEM) equipped with Oxford Cryo-transfer and fracture stage. The top tube of the two glue-jointed tubes was then knocked off by a metal knife on the fracture stage to expose a fresh sample surface inside the tube. The sample temperature was raised to 175 K to sublime

Table 1
The mineral composition of the clean ore sample analysed by XRD (wt.%).

Quartz	Albite	Kaolinite	Muscovite	Chlorite	Chalcopyrite	Pyrite	Carbonates
27	46	5	11	6	1	2	2

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