Rougher flotation of copper sulphide ore using biosolids and humic acids

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ABSTRACT

In the quest of new, less hazardous, and more ambient-friendly froth flotation reagents, the use of biosolids or humic acids as both collector and frother for the concentration of copper sulphide ores was investigated. Rougher flotation tests were conducted in Denver cells on a laboratory scale, and metallurgical indicators such as copper recovery, copper concentrate grade, and concentration and enrichment ratios were compared with those obtained under similar conditions but using conventional collectors and frothers for the industrial flotation of copper sulphide ores. With a dosage of 10% (w/w) biosolids, copper recovery and grade were 26% and 0.81%, respectively. The copper recovery and grade obtained with 1.5% (w/w) salt of humic acids were 29.7% and 3.5%, respectively. A significantly higher copper recovery (65.1%) was obtained with conventional industrial collectors and frothers, but the grade was also low (3.1% Cu). With the same dosage of humic substances, humic acid show that the flotation rate constant was significantly higher ($0.2 \ min^{-1}$) than that obtained with the same dosage of biosolids ($0.09 \ min^{-1}$). These results indicate that humic acids have more affinity than biosolids for copper-containing mineral species, and also show that biosolids and humic acids could be used as both collector and frother in the sulphide mineral concentration process by froth flotation. Because the distribution of iron in the concentrate obtained with biosolids is highest, these materials seem to have more affinity for pyrite.

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1. Introduction

Froth flotation is a physicochemical process that has been used for more than a century in the concentration of copper sulphide minerals (Herrera-Urbina, 2003). This process is based on the wettability of mineral particles to recover the mineral species of interest and depress unwanted gangue. The chemical reagents used in the flotation process to recover copper minerals are collectors, depressants, activators, modifiers and frothers that condition mineral pulp in order to produce copper concentrate and tailings. Each type of reagent plays a different role in the flotation of copper sulphide minerals. Collectors are amphiphilic compounds that allow for the alteration of mineral particles' surface energy, acting at the solid–liquid interface via physical and/or chemical adsorption (Herrera-Urbina, 2003). Frother agents and appropriate modifiers are also necessary for froth flotation, and together allow for an effective and selective recovery of the mineral species of interest.

Physical and/or chemical adsorption of collectors modifies the wettability of the surfaces of mineral particles, thus affecting air-bubble attachment to copper sulphide minerals. The main sulphide mineral collectors currently used are xanthates ($ROCS_2^-$), whose optimum efficiency depends on the length of the hydrocarbon chain, but mineral species selectivity decreases (Bulatovic, 2007). While research has been conducted on the adsorption of xanthates on copper, iron and other metallic sulphides, other collectors have received little attention. Xanthates have been reported to adsorb on copper sulphide through metal xanthate formation (Cases et al., 1993; Buckley, 1994; Nagaraj and Brinen, 2001). In pyrite-type iron sulphide, adsorption occurs via the formation of dixanthogen ($ROCS_2–S_2COR$) and iron xanthate complexes at low pH levels (Leppinen, 1990; Nagaraj and Brinen, 2001).

Research results previously reported have shown that biosolids from wastewater treatment plants decrease the surface tension of solutions and have the ability to physically and chemically adsorb species on sulphide minerals such as chalcopyrite and pyrite, thus changing their hydrophobicity (Reyes-Bozo et al., 2011a,b).

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Biosolids contain a variety of functional groups (most of them phenolic and alcoholic) as well as humic acids, proteins and sugars (Dignac et al., 1998; Murphy et al., 2000; Guellil et al., 2001).

The main objective of this work research was to investigate the use of biosolids and humic acids as collectors and frother for the concentration of copper sulphide ores by froth flotation, and to compare their performance with that of conventional collectors and frothers used in the industrial flotation of these ores. The comparison was made in each case by quantifying copper and iron recovery, copper concentrate grade, and concentration and enrichment ratios obtained by rougher flotation of a copper sulphide ore in Denver cells at laboratory-scale. Because biosolids and humic acids are less hazardous and more ambient-friendly compounds, they may have potential to substitute conventional chemical collectors and frothers used in the sulphide minerals flotation industries.

2. Materials and methods

2.1. Origin and physicochemical characteristics of biosolids and humic acids

The biosolids used in this study were obtained from the wastewater treatment plant El Trebal, which is owned by Aguas Andinas S.A. and located in the Metropolitan Region of Santiago, Chile. In this plant, the biological removal of the organic load is performed using activated sludge technology. Biosolids samples obtained from the monofill (23% w/w moisture) were previously ground, homogenised and sieved to a fraction of less than 2 mm. The main physical and chemical characteristics of these biosolids are presented in Table 1. They are mainly composed of organic matter (55% w/w, dry basis; 31.7% C) and proteins (19%), and contain a significant concentration of P (21,210 mg/kg), Ca (20,313 mg/kg), Fe (17,382 mg/kg), Mg (5532 mg/kg), K (3358 mg/kg), Zn (1222 mg/kg), and SO_4^{2-} (1000 mg/kg), as well as minor concentrations of other metals and metalloids. Biosolids also contain humic substances, mainly fulvic acids (3.0%) and humic acids (13.8%).

A commercial salt of humic acids (Sigma–Aldrich™) was used as a representative type of the humic substances present in the biosolids. According to Pandey et al. (1999), this reagent has a characteristic composition of 44.67% organic carbon, 5.87% hydrogen, 4.88% total nitrogen, 43.9% oxygen and 0.58% ash with a total acidity of 12.3 mol/kg. The concentration of functional groups such as –COOH and phenolic –OH is 4.1 and 8.2 mol/kg, respectively. In addition, these substances show the presence of metals at the trace

level (for example, copper content of 50 ppm and 6000 ppm Fe were listed for the batch of reagent used) as well as 280 ppm of total sulphate.

2.2. Physical, chemical and mineralogical characteristics of the copper sulphide ore

A copper sulphide ore sample, already crushed and ground, was obtained from the El Soldado, Division of Anglo American Chile S.A. The size of this material was smaller than 1 mm and free of contamination by industrial chemical flotation reagents. The copper sulphide ore was homogenised and sieved in a ROTAP to produce samples with a size fraction in the range of 38–300 μm for rougher flotation tests. The distribution of this size fraction, which follows a Gaudin–Schuhmann-type size distribution, is shown in Fig. 1. D_{50} particle size is about 90 μm. The physical characteristics of the copper sulphide ore are presented in Table 2, and they coincide with those reported for copper sulphide ores (Wills, 1992).

Chemical analyses indicate that the original copper sulphide ore sample has total copper and iron contents of 7415 mg/kg and 38,140 mg/kg, respectively. Mineralogical results show the presence of copper sulphide in the form of chalcopyrite (0.7%), chalcocite (0.3%) and bornite (0.2%). This ore also contain pyrite (0.1%) and molybdenite (0.1%), while the gangue accounts for 98.4%. The main non-metallic minerals identified in the original copper sulphide ore sample are quartz (28.0%), plagioclase (24.0%), clay (11.5%) and calcite (9.5%). The presence of iron oxide ore in the form of magnetite (0.1%), limonite (0.1%), hematite (0.1%), as well as coal at trace levels also was detected.

2.3. Rougher flotation tests on a laboratory scale

The effectiveness of using either biosolids or humic acids as both collector and frother for the concentration of a copper sulphide ore was investigated through rougher flotation tests with a Denver cell at laboratory scale. To compare the performance of these materials, rougher flotation tests were also conducted with conventional collectors and frothers currently used in the copper sulphide ore processing industry (Collector: Lib-k, potassium dialkyl-dithiophosphate; P3, mercaptan, and sodium isobutyl xanthate. Frothers: DF-250, DowFroth 250, MIBC, methyl isobutyl carbinol). The general experimental procedure involved adding 1 kg of −300 + 38 μm size fraction of copper sulphide ore to a Denver cell containing 3 L distilled water (solid/liquid ratio of 25%),
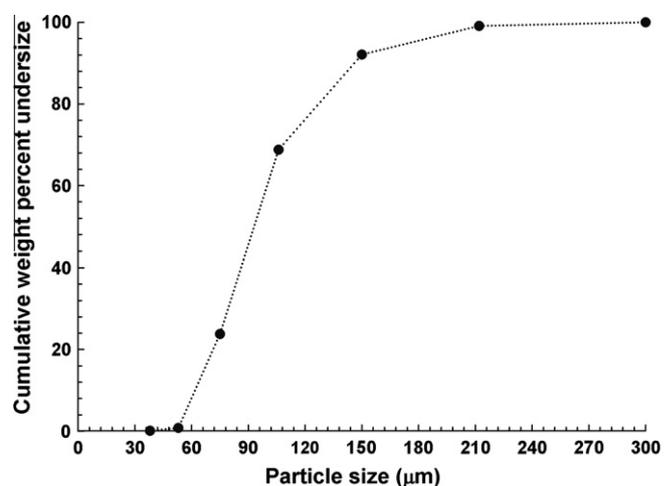
Table 1
Physical and chemical characteristics of biosolids from the El Trebal plant.

Item	Value	Item	Value
Humidity (%)	23.0	P (mg/kg)[a]	21,210
Total solids (%)	76.9	Ni (mg/kg)[a]	60.1
Organic matter (%)[a]	55.0	Se (mg/kg)[a]	7.4
pH (solution 1:2.5 w/v)	7.5	As (mg/kg)[a]	12.8
Electrical conductivity (μS/cm)	7.8	Cd (mg/kg)[a]	0.83
Density (g/mL)	0.71	Cr (mg/kg)[a]	195.4
Ca (mg/kg)[a]	20,313	Hg (mg/kg)[a]	1.5
Cu (mg/kg)[a]	407	Mo (mg/kg)[a]	21
Zn (mg/kg)[a]	1,222	Pb (mg/kg)[a]	55.1
Fe (mg/kg)[a]	17,382	SO_4^{-2} (mg/kg) [a]	1,000
K (mg/kg)[a]	3,358	C (%)	31.7
Mg (mg/kg)[a]	5,532	N (%)	4.4
Mn (mg/kg)[a]	236	Proteins (%)	19.4
Na (mg/kg)[a]	743	Sugars (such as sucrose; %)	0.6

[a] Related to total biosolids concentration in a dry mass basis.

Fig. 1. Size distribution of copper sulphide ore used in this study.

Table 2
Physical characteristics of copper sulphide ore used in experimental trials.

Parameter	El Soldado CSO
Mineral density (g mL⁻¹)	2.5
Bargain density (g mL⁻¹)	2.0
Release diameter (μm)	150
Form factor	0.5
Size factor	0.25
Particle size profile	Function of Gaudin-Schuhmann distribution[a] $F(x) = 100 \cdot \left(\frac{d}{d_{max}}\right)^{0.62}$; $d_{max} = 300$ μm

[a] Where $F(x)$ is the accumulated passing (%) fraction, d it is the particle (μm) size, and d_{max} it is the maximum size of the particle (μm).

stirring the pulp at 1200 rpm, adjusting the pH to 10.5 with NaOH solutions, then adding the collector and frother, and allowing for conditioning of the pulp during 10 min, before the air supply injection valve was opened to introduce 4.5 L/min air. The air-flow rate was controlled with a flow-meter manufactured by Gilmont Instruments, Inc., USA. Collection of the froth phase formed was achieved through paddling during the actual flotation process. Froth samples were collected after 3, 6, 10, 14 and 18 min of flotation.

Either 10% biosolids (w/w, dry basis) or 1.5% (w/w) salt of humic acids were used as both collector and frother. These dosages are equivalent when they are expressed in grams of humic substances per ton of ore. The concentrations of conventional collectors and frothers used are as follows. Collectors: Lib-k, 16 g/ton; P3, 11 g/ton and sodium isobutyl xanthate, 5 g/ton. Frothers: DF-250, 2.5 g/ton and MIBC, 25 g/ton. Rougher flotation operating conditions are summarised in Table 3. All rougher flotation tests were done in triplicate. The solids in the froth were separated from the liquid by filtration using Wathmann filters No. 42. They were dried at 80 °C for 24 h, and then weighed. After acid digestion (HF–HNO₃–H₂O₂) of the concentrate samples using a Milestone Ethos D microwave (US, EPA Method 3052), total copper and iron were determined by atomic absorption spectrophotometry with a Perkin Elmer Analyst 300 apparatus. Concentrate weight and assays were used to calculate copper and iron recoveries, copper concentrate grade, and concentration and enrichment ratios for each one of the three different froth flotation procedures. Further, the total organic carbon content (TOC) was quantified using the Walkey-Black wet combustion method (Nelson and Sommers, 1996).

3. Results and discussion

3.1. Metallurgical balance for rougher flotation tests

For assessing the performance of biosolids, a commercial salt of humic acids or a mixture of conventional collectors and frothers to concentrate a copper sulphide ore in a Denver cell at laboratory

scale, we applied the mass balancing method, which involves the use of the two-product formula (Wills, 1992). If the weights of the feed, concentrate and tailings are F, C, and T, respectively, and their corresponding assays f, c, and t, then the global mass balance is obtained using:

$$F = C + T \qquad (1)$$

And, the valuable metal balance is obtained using:

$$F \cdot f = C \cdot c + T \cdot t \qquad (2)$$

Combining these two equations one can derive:

$$F/C = (c - t)/(f - t) \qquad (3)$$

where F/C represents the ratio of concentration.

From assay results alone, one can calculate the percent metal recovery, as follows (Wills, 1992):

$$\text{Recovery} = 100c \cdot (f - t)/f \cdot (c - t) \qquad (4)$$

In addition, the enrichment ratio (c/f) can also be determined form the assay results alone.

Table 4 summarises the rougher flotation results of the concentration of a copper sulphide ore, obtained when either biosolids or a salt of humic acids are used as both collector and frother, or with a mixture of conventional collectors and frothers currently used in the industrial flotation of these ores. This table presents the weight of the feed, and of the concentrate and tailings obtained with the three different froth flotation procedures tested, their corresponding Cu and Fe assays (in %) as well as Cu and Fe weight, and the percent distribution (recovery) of these two metals in the flotation products. For a total flotation time of 18 min, the recovery of copper to the concentrate was 26% with biosolids whereas it was 29.7% with the salt of humic acids. The grade of the copper concentrate obtained with biosolids or the salt of humic acids was 0.81% and 3.47%, respectively. With a mixture of conventional collectors and frothers used for the industrial concentration of coppers sulphide ores, however, copper recovery was 65.6% and the copper grade was 3.15%.

The concentration ratio obtained with biosolids, the salt of humic acids or the conventional collectors and frothers was 4.0, 12.6 and 5.7, respectively. Copper enrichment ratios were: 1.0 with biosolids, 3.7 with the salt of humic acids, and 3.8 with the conventional collectors and frothers. The results presented in Table 4 also give the distribution of iron in the copper concentrate, which was as follows: 35% with biosolids, 10% with the salt of humic acids, and 20% with the conventional collectors and frothers. According to these results, biosolids recovered the smallest quantity of copper and largest quantity of iron, by comparison with the recovery with the salt of humic acids or with the conventional collectors and frothers, thus indicating that these materials have more selectivity towards pyrite.

Film flotation results of pyrite and chalcopyrite conditioned with biosolids also show that these biomaterials have more affinity for the iron sulphides, and allow modification of the natural hydrophobicity of these sulphide minerals (Reyes-Bozo et al., 2011b).

Table 3
Operating conditions for rougher flotation tests in Denver cell on a laboratory scale.

Parameter	Value	Parameter	Value
Ore mass, dry basis (g)	1000	Temperature (°C)	20 ± 1
Percentage of solids (w/w)	25.0	pH	10.5 ± 0.2
Volume of water (L)	3.0	Stirring speed (rpm)	1200
Pulp mass (g)	4000	Air flow (L/min)	4.5
Pulp volume (L)	3.4	Total flotation time (min)	18
Solids by volume	11.8	Nominal capacity of Denver cell (L)	4
Pulp density (g/mL)	1.18	Rotor type	Impeller
		Denver cell material	Transparent plexiglas

Table 4
Distribution of metals, copper and iron for rougher flotation tests on a laboratory scale.

|	Weight (g)	Assay (%)		Weight metal (g)		Distribution (%)	
		Cu	Fe	Cu	Fe	Cu	Fe
Conventional collectors and frothers							
Feed	1000.00	0.84	4.68	8.36	46.84	100.0	100.0
Concentrate	173.70	3.15	5.51	5.47	9.57	65.6	20.4
Tail	826.30	0.35	4.51	2.89	37.26	34.6	79.6
10% (w/w) biosolids							
Feed	1000.00	0.78	4.52	7.78	45.19	100.0	100.0
Concentrate	156.71	0.81	10.05	1.27	15.75	26.0	34.8
Tail	843.29	0.77	3.49	6.51	29.43	83.7	65.2
1.5% (w/w) salt of humic acid							
Feed	1000.00	0.93	5.00	9.32	49.98	100.0	100.0
Concentrate	82.11	3.47	6.21	2.85	5.10	29.7	10.2
Tail	917.89	0.71	4.89	6.47	44.87	69.5	89.8
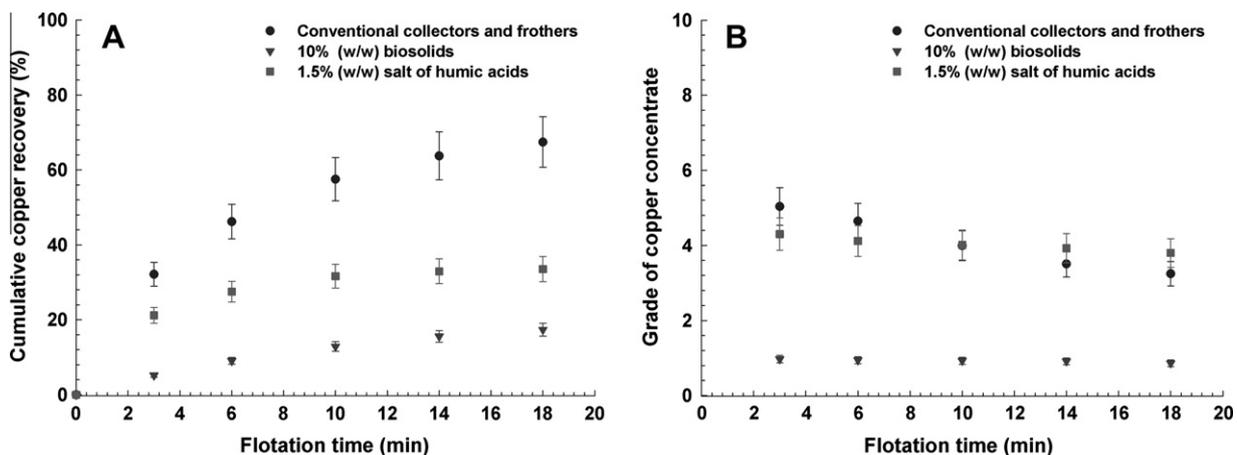
Fig. 2. Metallurgical indicators obtained at different times by rougher flotation of a copper sulphide ore at pH 10.5 with biosolids, a salt of humic acids, and a mixture of conventional collectors and frothers. (A) Cumulative copper recovery. (B) Grade of copper concentrates. Both figures show the average value ($n \geqslant 5$) and standard error.

These results are consistent with those obtained in rougher flotation tests. Because the salt of humic acids, acting as both collector and frother, recovers more copper than iron, it seems to have more affinity for copper-bearing mineral species (mainly chalcopyrite). Cumulative copper recovery at all flotation times tested was always higher with the conventional collectors and frothers, by comparison with copper recoveries obtained with biosolids or the salt of humic acids (see Fig. 2). The mass of the final rougher flotation concentrate obtained was highest with the conventional collectors and frothers (173.7 g) and lowest with the salt of humic acids (82.11 g). As a consequence, the conventional collectors and frothers give the highest recovery.

Fig. 2 shows the cumulative recovery and the grade of the copper concentrate for the rougher flotation of a copper sulphide ore at different flotation times (3, 6, 10, 14 and 18 min) with conventional collectors and frothers, 10% (w/w) biosolids, and 1.5% (w/w) salt of humic acids. As Fig. 2A shows, copper recovery increases as the flotation time increases for the three cases investigated, but it is more pronounced with the conventional collectors and frothers. This figure also indicates that the majority of floatable minerals reports to the concentrate during the first 6 min of flotation. As opposed to the copper recovery trend, the copper concentrate grade decreases as flotation time increases, being almost constant and lowest when biosolids are used as both collector and frother (Fig. 2B). Fig. 2B also indicates that the concentrates obtained with conventional collectors and frothers, and with the salt of humic acids at 3 and 6 min of flotation have the highest grade.

The results of copper recovery versus concentrate grade at the different flotation times investigated, and for the three different collectors and frothers used are plotted in Fig. 3. In all cases, they follow the same trend observed with conventional collectors and frothers used in sulphide ore flotation, such that the recovery decreases if the grade increases (Wills, 1992). The relative position of the series representing the biosolids, the salt of the humic acids, and the conventional collectors and frothers indicate an increased selectivity as contour lines move away from the point of origin of the figure. In addition, the dynamic behaviour of the concentrate grade as a function of flotation time for conventional collectors and frothers, and for the salt of humic acids does not present noticeable differences, confirming their higher affinity for copper-containing mineral species. For its part, the dynamics of the copper grade versus flotation time for biosolids showed a different behaviour, decreasing slightly at about 1% grade, which relates to its lower selectivity (Fig. 2).

An efficient recovery of copper-containing minerals requires the formation of a froth phase with adequate stability. In regards to the frother capacity of biosolids, the salt of humic acids, and the mixture of conventional collectors and frothers, results reported by Reyes-Bozo et al. (2011a), who assessed the foaming capacity of biosolids and the salt of humic acids through surface tension measurements as well as their ability to form and stabilize foams (Bikerman tests), show that these materials have surfactant characteristics similar to those exhibited by industrial frothers such as MIBC for equivalent concentrations. The change of surface tension with biosolids, the salt of humic acids, and the conventional collectors and frothers allows foams to be formed and stabilized in transient state, determining a dynamic generation of foam in the range of 1.5–2.2 s and static stability of foam in 4 s.
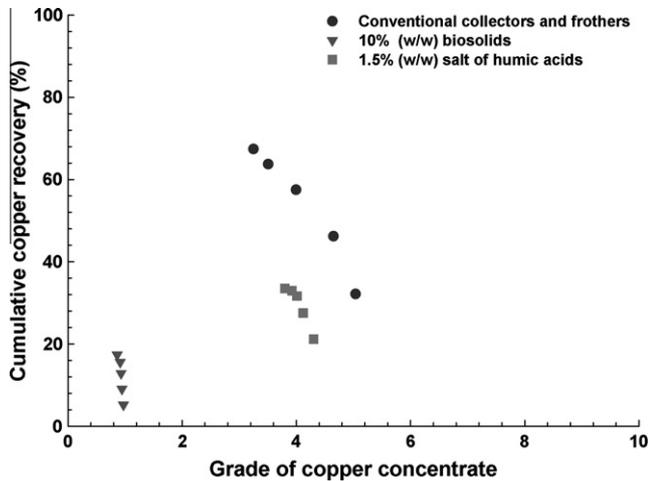
Fig. 3. Cumulative copper recovery as a function of grade of copper concentrates obtained at different times by rougher flotation of a copper sulphide ore at pH 10.5 with biosolids, a salt of humic acids, and a mixture of conventional collectors and frothers. This figure shows the average value ($n \geqslant 5$).

3.2. Flotation kinetics

For any flotation condition, its kinetics rate constant, k (time^{-1}), represents a quantitative measure of the likelihood that a particle of a given species (e.g., chalcopyrite) will be recovered in the concentrate (Gupta and Yan, 2006). This rate constant will be used to compare the performance of biosolids, the salt of humic acids, and the conventional collectors and frothers tested in Denver cell flotation experiments while maintaining unchanged all other flotation conditions (pH, agitation speed, air flow rate, conditioning time, temperature, etc.).

3.2.1. Calculation of kinetic parameters from rougher flotation data

In order to determine the flotation kinetics rate constant from rougher flotation data we considered that flotation of the copper sulphide ore followed a law of first order (Bulatovic, 2007; Gupta and Yan, 2006; King, 2001). The first order rate equation can be expressed by:

$$R(t) = R_\infty \cdot (1 - \exp(-k \cdot t)) \tag{5}$$

where $R(t)$ is the cumulative recovery after time t, R_∞ is the maximum theoretical flotation recovery, and t is the cumulative flotation time. From the first order rate equation we derived the following expression for the rate constant:

$$k = \left(\frac{1}{t}\right) \cdot \ln\left(\frac{R_\infty}{R_\infty - R(t)}\right) \tag{6}$$

Using the experimental results of cumulative copper recovery after time t, the calculated values of k and R_∞ were adjusted by minimising the coefficient of variation of k, (CV_k), which is the ratio of the standard deviation divided by the mean value of k.

Table 5 presents the first order flotation rate constant, the maximum theoretical flotation recovery, and the coefficient of variation of the rate constant, obtained from the data of rougher flotation of a copper sulphide ore with 10% (w/w) biosolids, 1.5% (w/w) salt of humic acids, and a mixture of conventional collectors and frothers used in the industrial flotation of copper sulphides. The kinetic parameters reported minimize the coefficient of variation of k (CV_k). Based on these variation coefficients, the calculated rate constant for copper sulphide ore flotation with 1.5% (w/w) salt of humic acids has a value of 0.25 min^{-1}, 0.19 min^{-1} with the mixture of conventional collectors and frothers, and a low value of 0.09 min^{-1} with 10% (w/w) biosolids. According to these rate constant values,

Table 5
Kinetic parameters for rougher flotation tests of copper sulphide ore with 10% (w/w) biosolids, 1.5% (w/w) salt of humic acid and conventional collectors and frothers.

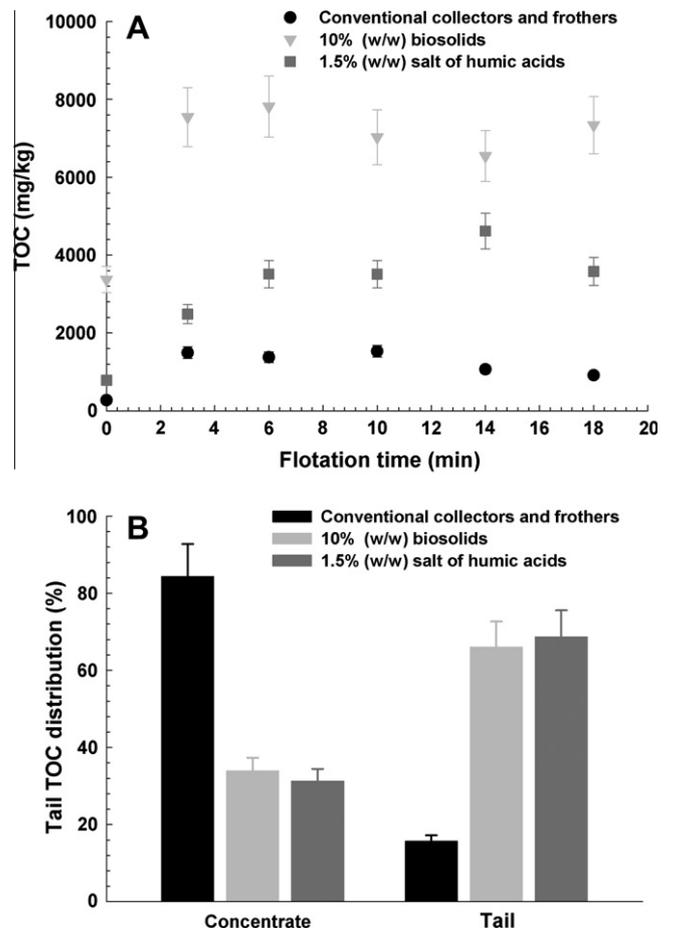| Experimental condition	k (min^{-1})	R_∞ (%)	CV_k (%)
Conventional collectors + frothers	0.19	69.43	7.04
10% (w/w) biosolids	0.09	21.36	0.63
1.5% (w/w) salt of humic acid	0.25	34.52	18.32

Fig. 4. Content of total organic carbon obtained at different times by rougher flotation of a copper sulphide ore at pH 10.5 with biosolids, a salt of humic acids, and a mixture of conventional collectors and frothers. (A) Total organic carbon in the copper concentrate as a function of flotation time. (B) Distribution of total organic carbon in the concentrate and tailings. Both figures show the average value ($n \geqslant 5$) and standard error.

the fastest floating conditions are achieved with the salt of humic acids, whereas with biosolids the recovered minerals are the slowest floating. The maximum theoretical flotation recovery was 69.4% for the conventional collectors and frothers system, 34.5% for flotation with 1.5% salt of humic acids, and 21.4% for flotation with 10% biosolids. These results are consistent with those presented in Figs. 2 and 3. In spite of the big difference between the maximum theoretical flotation recovery with conventional collectors and frothers, and with the salt of humic acids, the grade of the corresponding concentrates is almost the same.

3.3. Quantification of total organic carbon (TOC) in concentrate

Fig. 4A shows the total organic carbon content of the copper concentrates obtained at different flotation times using biosolids, the salt of humic acids, and the conventional collectors and frothers. Compared with the results of using conventional collectors

and frothers, total organic carbon in the concentrates was an average of 6 and 3 times greater with biosolids and the salt of humic acids, respectively. As Fig. 4B shows, however, the distribution of total organic carbon is significantly higher (85%) in the concentrates produced with the conventional collectors and frothers. The distribution of organic carbon was similar for the concentrates produced with biosolids or the salt of humic acids (30%). Only 0.45% of the initial mass of the salt of humic acids contributed to the concentrate mass, whereas 3% of the initial mass of biosolids contributed to the concentrate mass.

4. Conclusions

Rougher flotation results for the concentration of a copper sulphide ore in a Denver cell with biosolids or a salt of humic acids as both collector and frother indicate that these materials have potential to substitute conventional chemical collectors and frothers used in the industrial flotation of sulphide minerals in Chile. Under the flotation conditions investigated, the concentrate produced with biosolids, which contain a significant amount of humic acids, assayed 0.81% Cu with a recovery of 26%. With a salt of humic acids, the recovery was a bit greater (29.7%), but the copper assay was significantly higher (3.47% Cu). When a mixture of conventional collectors and frothers were used, the recovery increased to 65%, but the grade was still low (3.15% Cu). Flotation kinetics data show conventional collectors and frothers, as well as the salt of humic acids, to give the fastest flotation conditions for the recovery of copper sulphides. Because the lowest flotation rate constant ($0.09 \ min^{-1}$) was obtained when biosolids are used as both collector and frothers, these materials give the slowest flotation conditions. Humic acids show more affinity for copper sulphides than biosolids, which seem to be more selective towards pyrite.

The total initial organic carbon of biosolids and the salt of humic acids mainly reports to the tailings: only 0.45% C of the humic acids and 3% C of the biosolids contributes to the concentrate mass. Biosolids seem to offer an alternative to partially substitute conventional chemical collectors and frothers used for the industrial flotation of copper sulphides, which are more hazardous and less ambient-friendly.

Acknowledgments

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