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# A fundamental study considering specific ion effects on the attachment of sulfide minerals to air bubbles



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#### ABSTRACT

Bubble-particle attachment is one of the most fundamental sub-processes in froth flotation. It is of critical importance in achieving the separation of value from non-value. This sub-process is affected by many factors such as the chemistry of the pulp, action of the reagents, hydrodynamics and operational factors. Understanding the effects of these factors on bubble-particle attachment is thus crucial as they may in turn affect the mineral recoveries attained. With the current drive towards zero effluent discharge on mineral concentrators water quality is an important factor to understand as it can change the pulp chemistry and subsequently affect mineral recoveries. This study thus considers the effect of specific ions found in process water on the bubble-particle attachment of chalcopyrite and galena. Adsorption studies and zeta potential measurements were conducted to interpret the outcomes of the bubble-particle attachment tests. Pulps containing Ca<sup>2+</sup> resulted in lower bubbleparticle attachment probability and recovery of galena and chalcopyrite. Adsorption studies complemented the bubble-particle attachment findings well and showed that in Ca<sup>2+</sup> containing waters, less xanthate was adsorbed on both the chalcopyrite and galena surfaces. The zeta potential measurements showed an increase in mineral potential with Ca<sup>2+</sup> containing salts compared to the very negative mineral potential in NaNO<sub>3</sub>. This work provides evidence of the passivation of the mineral surface with Ca<sup>2+</sup>; which hindered the adsorption of xanthate on the mineral surface in Ca<sup>2+</sup> containing solutions and subsequently resulted in poor bubble-particle attachment

#### 1. Introduction

Froth flotation is used as a method of separation in several industrial applications such as in the treatment of wastewater and domestic sewage by dissolved air flotation, de-inking of paper and in mineral processing. In mineral processing, the surface properties of the valuable particles are selectively altered such that they attach to air bubbles and are subsequently removed. The bubble-particle attachment sub-process is thus critical in achieving the desired separation of valuable particles (Albijanic et al., 2010).

Chalcopyrite (CuFeS<sub>2</sub>) is the most abundant and important cupriferous mineral on earth while galena (PbS) is the most important lead mineral. These respective minerals are often associated with other sulfide minerals and separated by means of froth flotation. Water scarcities challenging parts of the world have led to recycled process water and sea water usage gaining huge interest in the mining industry. These water types are of high ionic strength and thus their water chemistry is very different to that of fresh water and may negatively

affect the efficiency of the separation in froth flotation (Rao and Finch, 1989).

Studies have shown that an increase in the ionic strength of process water results in higher solids and water recoveries (Corin et al., 2011; Manono et al., 2012; Corin and Wiese, 2014). Divalent and polyvalent ions are reported to be capable of adsorption on the mineral surface; while alkali metal cations adsorb on the mineral surface via electrostatic attraction without forming permanent chemical bonds with the mineral surface (Ma, 2005). Consequently, the surface charge is not neutralised by these cations but rather passivated by these ions. The extent of passivation or screening affects the zeta potential of the mineral surface and can lead to the compression of the electrical double layer. It has been proposed that with an increase in the concentration of inorganic electrolytes, the electrical double layer compresses, leading to the accelerated rupturing of the film at the air-water and solid-water interface which leads to bubble-particle attachment and in turn the recovery of mineral particles (Laskowski and Iskra, 1970; Li and Somasundaran, 1993; Harvey et al., 2002; Laskowski and Castro, 2015).

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#### Table 1

Concentrations of ions for the various water qualities.

Water Type	Ca <sup>2+</sup> (mg/L)	Mg <sup>2+</sup> (mg/L)	Na <sup>+</sup> (mg/L)	Cl <sup>-</sup> (mg/L)	SO4 <sup>2-</sup> (mg/L)	NO <sub>3</sub> <sup>-</sup> (mg/L)	CO3 <sup>2-</sup> (mg/L)	TDS (mg/L)	IS (mol/L)
SPW Ca(NO <sub>3</sub> ) <sub>2</sub> CaSO <sub>4</sub> NaNO <sub>3</sub>	400 1610 1207 -	350  	765  2770	1435  -	1200  2894 	880 4981 - 7472	85  	5115 6591 4101 10,242	0.1205 0.1205 0.1205 0.1205

Previous studies have considered complex synthetic water recipes to replicate conditions on a typical concentrator (October et al., 2019). It is therefore of interest to determine if there are specific ions in plant water that are either beneficial, detrimental or have no effect on the flotation process. Batch flotation studies on a Merensky ore by Manono et al. (2016) showed that the Na<sup>+</sup> resulted in higher recoveries but lower mineral grades whereas the NO3<sup>-</sup> resulted in lower recoveries and higher mineral grades. It is however unclear whether there are specific ions in the plant water that have this type of influence on the fundamental bubble-particle attachment process. Both galena recovery and adsorption of xanthate collector on galena have been reported to decrease in the presence of Ca<sup>2+</sup> (Ikumapayi et al., 2012; Elizondo-Alvarez et al., 2017). Elizondo-Alvarez et al. (2017) attributed the decrease of xanthate adsorption on the galena surface to be as a result of chemisorption of Ca<sup>2+</sup> on active sites, hindering the action of the collector.

The effect that these inorganic electrolytes have on the final mineral recoveries may be due to many factors such as changes in the physicochemical properties of the solution, surface charge, wetting characteristics and collector adsorption (Du et al., 2014). It is widely known that the presence of ionic solutes affects the water structure. When the structure of water is very strongly hydrogen bonded even in the presence of cations and anions, these ions are termed structure making because they tend to retain the strong hydrogen bonds. Small, strongly hydrated inorganic ions such as Na<sup>+</sup>, Li<sup>+</sup>, Mg<sup>2+</sup>, F<sup>-</sup> and Cl<sup>-</sup> are examples of structure makers. However, large inorganic ions, such as Cs<sup>+</sup> and I<sup>-</sup> have the tendency to destroy the strongly hydrogen bonded water structure; these ions are termed structure breakers (Wang and Peng, 2014; Burdukova, 2007; Ma and Pawlik, 2005).

Hancer et al. (2001) in a study of KCl flotation proposed that if the collector adsorbs on the salt interface, the interfacial water will be displaced, and the collector will penetrate through the water structure. Therefore, if the water structure is strongly hydrogen bonded as a result of structure making ions, it will be difficult for the collector to adsorb on the mineral surface and in turn negatively affect the recovery. Conversely if the structure of water is destroyed due to structure breaking ions the collector can easily penetrate and adsorb at the mineral surface.

This study considers the effect of specific ions present in process water on bubble-particle interactions by means of fundamental bubbleparticle attachment and flotation methods. The results of the bubbleparticle interactions from both the fundamental and flotation perspective are then further investigated by studying the impact that these specific ions have on collector adsorption and on the mineral surface potential. The aim of this study is therefore to determine if there are specific ions in plant water that are either beneficial, detrimental or have no effect on the bubble-particle attachment sub-process.

#### 2. Materials and methods

The chalcopyrite and galena, obtained from Ward's Science in 1 kg batches, were crushed using a hammer to 100% passing 1000  $\mu$ m. The crushed minerals were pulverized and sieved through 75 and 38  $\mu$ m sieves respectively. The fraction of particles greater than 75  $\mu$ m was repulverized and re-sieved. The  $-75 + 38 \mu$ m sample was split using a rotary splitter and the split samples were individually purged with

nitrogen and stored at -30 °C. The -75 + 38 µm fraction was used for both the microflotation tests, attachment time tests and adsorption tests. The fraction below 38 µm was sieved through a 25 µm sieve and the particles below 25 µm were used for the zeta potential measurements. This fraction was similarly split, purged with nitrogen and stored at -30 °C.

#### 2.1. Water quality

 $CaSO_4$ ,  $Ca(NO_3)_2$  and  $NaNO_3$  solutions and synthetic plant water of 0.1205 M were used for the attachment timer measurements, microflotation tests, zeta potential measurements and adsorption studies. The ionic strength of 0.1205 M translates to five times the amount of dissolved solids of the standard synthetic plant water (1 SPW) as described by Wiese et al. (2005). Table 1 gives an account of the concentrations of the various ions in the solutions under investigation.

#### 2.2. Attachment time tests

The attachment contact time apparatus (ACTA) used in this investigation was developed at Aalto University and has previously been described by Aspiala et al. (2018) and October et al. (2019). A detailed description of the experimental procedure in terms of particle bed building and running measurements is documented in October et al. (2019). Measurements were taken for each of the water qualities in Table 1 with and without the addition of 50 g/t sodium isobutyl xanthate (SIBX) sourced from Senmin (97% purity). As described in October et al. (2019), a measurement is completed in 66 cycles across the particle bed and thus 66 images are obtained per measurement. Each image shows the six bubbles and where attachment of particles exists, thus the attachment probability is obtained by studying the images for attachment of particles out of the possible 396 bubbles per measurement. All tests were performed in duplicate to minimise error.

#### 2.3. Microflotation tests

The microflotation cell developed by Bradshaw and O'Connor (1996) was used. 3 g of pure mineral was mixed with 50 mL of the particular water quality under study; the pH of the mixture was adjusted to 6.5, the mixture was then ultra-sonicated for 5 min to allow for good dispersion of the mineral mixture and to remove oxidation products from the mineral surface. The suspension was transferred to the microflotation cell and the pulp was circulated by a peristaltic pump at 90 rpm. For collector runs, 50 g/t of SIBX was added to the slurry for each water type. Air was introduced at the base of the cell at a flow rate of 7 mL/min and concentrates were collected at 2, 6, 12 and 20 min of flotation. The tailings and four concentrates were filtered, dried and weighed. All tests were performed in duplicate to minimise error.

## 2.4. Zeta potential measurements

0.075 g of mineral particles was mixed with 60 mL of the particular water type; the dilute mixtures were equally divided in six containers and the pH was adjusted to 2, 4, 6, 8, 10 and 12 with dilute HCl or dilute NaOH. After 15 min on the magnetic stirrer the pH was measured again and adjusted where needed. 1 mL of the suspension was

transferred to the Malvern Dip Cell and inserted in the Malvern ZetaSizer where measurements were taken. All measurements were performed in triplicate to reduce experimental error.

#### 2.5. Adsorption studies

3 g of pure mineral sample of fraction 75 + 38  $\mu$ m was mixed with 30 mL of the particular water quality under study and the pH of the mixture was adjusted to 6.5. 50 g/t of SIBX (15 µL), was added to the flask containing the mineral slurry, this is equivalent to the collector concentration used in the microflotation and ACTA tests. The maximum amount of xanthate in the slurry was thus 5 g/t which is equivalent to 5 mg/L. The top of the flask was covered with tin foil and placed in an Ecobath shaker at a controlled temperature of 20 °C and speed of 141 rpm for 15 min. After 15 min in the water bath a plastic syringe was used to draw out about 15 mL of the suspension. A 0.45 µm filter was attached at the end of the syringe and the filtrate was collected in a sample container. The xanthate concentration was then measured by placing the filtrate in a quartz cuvette and reading the absorbance at wavelength 301 nm by means of a UV-Vis spectrophotometer. Prior to measuring the absorbance of the filtrate, calibration curves were constructed with solutions of known concentrations, as measured by the peak absorbance observed at 301 nm. The concentration of xanthate in solution for unknown samples could be calculated from the calibration curve. Adsorption tests were done in triplicate to minimise experimental error.

## 3. Results

## 3.1. Effect of specific ions on the recovery of chalcopyrite and galena

The chalcopyrite and galena recovery in microflotation tests in the three single salt solutions and plant water at equivalent ionic strength both in the absence (dashed line) and presence (solid line) of a collector is illustrated in Fig. 1 and Fig. 2 respectively. The NaNO<sub>3</sub> solution yields the highest recovery for the collector and collectorless systems for both the sulfide minerals. CaSO<sub>4</sub> and Ca(NO<sub>3</sub>)<sub>2</sub> showed very similar recoveries with SIBX, however when the collector was absent from the system a cation and anion effect is observed between the three single salt solutions with both sulfide minerals; Na<sup>+</sup> performs better than its  $Ca^{2+}$  counterpart in the NO<sub>3</sub><sup>-</sup> solution and NO<sub>3</sub><sup>-</sup> outperforms SO<sub>4</sub><sup>2-</sup> in the Ca<sup>2+</sup> containing solutions in the chalcopyrite system. With galena, the Ca<sup>2+</sup> again results in poorer recoveries both in the collector and collectorless systems. Interestingly, the synthetic plant water results in the highest chalcopyrite recovery with SIBX and without collector the recovery is only lower than the NaNO3 solution. However, with the synthetic plant water, the lowest galena recovery is obtained both with and without SIBX.



Fig. 1. Chalcopyrite recovery in various ionic solutions with SIBX (solid line) and collectorless (dashed line).



Fig. 2. Galena recovery in various ionic solutions with SIBX (solid line) and collectorless (dashed line).



Fig. 3. Attachment probability and mass recovered of chalcopyrite in the various ionic solutions.



Fig. 4. Attachment probability and mass recovered of galena in the various ionic solutions.

3.2. Effect of specific ions on the bubble-particle attachment of chalcopyrite and galena

The fundamental bubble-particle attachment tests are shown in Fig. 3 for chalcopyrite and Fig. 4 for galena. The attachment probability of chalcopyrite particles to air bubbles is observed to be higher in the NaNO<sub>3</sub> solution; the NaNO<sub>3</sub> solution also results in the highest chalcopyrite mass recovered. The attachment probability of chalcopyrite with the single salts solutions corroborates the microflotation tests; in that the Na<sup>+</sup> results in higher bubble-particle attachment compared to Ca<sup>2+</sup> in NO<sub>3</sub><sup>-</sup> solutions and the NO<sub>3</sub><sup>-</sup> performs better than SO<sub>4</sub><sup>2-</sup> in Ca<sup>2+</sup> solutions. In the case of chalcopyrite, the mass recovered with CaSO<sub>4</sub> is slightly more than with Ca(NO<sub>3</sub>)<sub>2</sub>, this does not correspond with the attachment probability as it would be expected that a higher attachment probability will also result in a greater mass recovered. This discrepancy between the two measures can be expected due to the fact that attachment as measured by the attachment timer is deemed

successful whether one or more particles are attached and the inability of the machine to detect the actual number of particles attached on each bubble. Furthermore, with the microflotation tests it was observed that in the presence of SIBX, the difference in chalcopyrite recovery was minimal in the  $CaSO_4$  and  $Ca(NO_3)_2$  solutions. For the synthetic plant water case at the same ionic strength as the single salt solutions with SIBX, an attachment probability of 85.2% is achieved and a total mass of 2.7 mg is recovered. This corresponds to the microflotation tests where the synthetic plant water resulted in the highest recovery of chalcopyrite in the SIBX system.

In Fig. 4 the attachment probability of galena particles to air bubbles and the mass of particles attached to air bubbles is highest in the NaNO<sub>3</sub> solution. This corresponds with what was observed in terms of galena recovery in the microflotation system. Again, suggesting that the  $Ca^{2+}$  has a negative effect on bubble-particle attachment as compared to Na<sup>+</sup>, as with the microflotation tests.

In the case of the anions, it is the  $SO_4^{2-}$  that performs better than the  $NO_3^-$  with  $Ca^{2+}$  as the cation. The synthetic plant water results in the lower attachment probability of galena when compared to the CaSO<sub>4</sub> and NaNO<sub>3</sub> solutions, whereas the microflotation tests show that the complex water solution results in the poorest galena recovery compared to the three single salt solutions.

Both the microflotation and fundamental bubble-particle attachment techniques indicate that  $Ca^{2+}$  containing salts result in poorer performance compared to the Na<sup>+</sup> containing salt. This therefore raises questions with regards to xanthate adsorption on the mineral surface as well as the charge of the mineral surface with  $Ca^{2+}$  containing solutions.

# 3.3. Effect of specific ions on the adsorption of xanthate on chalcopyrite and galena surfaces

Figs. 5 and 6 show the concentration of xanthate adsorbed on the mineral surface as well as the residual xanthate left in the solution for chalcopyrite and galena respectively. CaSO4 and Ca(NO3)2 show a similar amount of xanthate adsorbed on the chalcopyrite surface in Fig. 5, however a clear cation and anion effect can be observed in that Na<sup>+</sup> results in a higher adsorption compared to Ca<sup>2+</sup> for the NO<sub>3</sub> salts. The NO<sub>3</sub><sup>-</sup> results in a slightly better adsorption of xanthate onto chalcopyrite compared to the  $SO_4^{2-}$  for the  $Ca^{2+}$  salts. These adsorption results correspond relatively well with the microflotation and attachment timer results. The bubble-particle attachment techniques, both fundamental and flotation have indicated that Ca<sup>2+</sup> containing salts result in lower attachment probability and recovery in a system with SIBX. The results in Fig. 5 indicate that this is because less SIBX is actually adsorbed on the mineral surface in Ca<sup>2+</sup> containing salts, indicating that the adsorption of xanthate on the chalcopyrite surface is hindered in the presence of  $Ca^{2+}$ .



Fig. 5. Xanthate adsorbed on chalcopyrite surface and residual xanthate in various ionic solutions.



Fig. 6. Xanthate adsorbed on galena surface and residual xanthate in various ionic solutions.

The adsorption of SIBX on the galena surface was predominantly high in the ionic solutions particularly in the single salt solutions, with only 0.01 mg/L of SIBX not adsorbed on the galena with the NaNO<sub>3</sub> solution, it is still however evident that  $Ca^{2+}$  containing salts result in lower adsorption of the collector on the mineral surface. The synthetic plant water however results in the lowest concentration of SIBX adsorbed on the galena; this corresponds well to the microflotation tests and bubble-particle attachment tests where the recovery and attachment probability of galena was lowest with synthetic plant water. This may be due to the combined effect of the various ions in the solution or another ion that has not been investigated in this study hindering of xanthate adsorption on the galena, reducing its floatability.

### 3.4. Effect of specific ions on the zeta potential of chalcopyrite and galena

As illustrated in Fig. 7 the zeta potential of both galena and chalcopyrite in the various ionic solutions display similar trends in that the ultra-purified water results in the most negative potential of the sulfide minerals. The isoelectric point of chalcopyrite is around pH 3-4 which is in agreement with studies by Ikumapayi et al. (2012) and Moignard et al. (1977). Both minerals additionally show an increase in potential between pH 10 and 12 while the Ca<sup>2+</sup> containing solutions result in a sign change from negative to positive mineral potential over this range. This may be due to metal hydroxide precipitation at the mineral surface (Harvey et al., 2002; Ikumapayi et al., 2012; Hirajima et al. (2016)). Work by Davila-Pulido et al. (2015) further attributed the reduction in hydrophobicity of sphalerite in the pH range of 7-11 to Ca(OH)<sub>2</sub> precipitation on the sphalerite surface. The monovalent salt and ultrapurified water however does not show this increase in potential between pH 10 and 12; thus this distinct increase in potential over pH 10 to 12 may be specific to  $Ca^{2+}$  or divalent ion containing solutions. Furthermore, the Ca<sup>2+</sup> containing salt solutions result in a much less this negative or more positive potential of chalcopyrite and galena.

# 4. Discussion

Synthetic plant water yielded the lowest galena recovery with and without SIBX, whilst this water quality resulted in the highest chalcopyrite recovery. The mechanism behind this result is not fully understood however, this may be due to the differences in mineral properties; as shown by Liu and Zhang (2000) the affinity of ions towards the mineral surface varies by mineral type. And given the complex nature of the synthetic plant water, the combination of the various ions such as  $Ca^{2+}$ ,  $Mg^{2+}$ ,  $Na^+$ ,  $CO_3^{2-}$ ,  $SO_4^{2-}$ ,  $NO_3^{-}$  each having a different role and thus able to act simultaneously, some mineral dependent flotation response may be expected.

Microflotation tests of galena and chalcopyrite showed that Ca<sup>2+</sup> containing solutions resulted in lower recovery of these mineral



particles. And that the Na<sup>+</sup> containing solution resulted in higher recoveries of these mineral particles; collectorless tests with the Na<sup>+</sup> containing salts performed similarly to the system with the collector present. Bubble-particle attachment tests showed that even at this fundamental bubble-particle level,  $Ca^{2+}$  containing salts resulted in lower attachment probabilities and less particles recovered. Similarly, Na<sup>+</sup> containing solutions outperformed the other salt solutions in terms of the probability of particle attachment to air bubbles.

Both techniques thus reinforced the negative effect of  $Ca^{2+}$  containing solutions on floatability. Studies have shown that solutions of increasing ionic strength lower the stability of the hydration layer (Wang and Peng, 2014) and that this is particularly evident in monovalent salt solutions (Blake and Kitchener, 1972; Li et al., 2017). Hirajima et al. (2016) further ascribed longer induction times and thus decreased bubble-particle interactions to an increase in the hydration layer stability. Thus, a decrease in the stability of the hydration layer is expected to yield an increase in recovery. The results obtained in Figs. 1 and 2 show that the Na<sup>+</sup> gave higher chalcopyrite and galena recoveries and this may be due to the reduced stability of the hydration layer in this monovalent salt solution (Li et al., 2017).

In contact angle measurements Li et al. (2017) showed that the floatability of chalcopyrite was promoted with NaCl and KCl by increasing the xanthate adsorption on the mineral surface in a shorter time compared to divalent salts. This work confirms that in Ca<sup>2+</sup> containing solutions less xanthate actually adsorbs onto the mineral surface. This is in alignment with the work of Ikumapayi et al. (2012) and Elizondo-Alvarez et al. (2017). Ikumapavi et al. (2012) showed that Ca<sup>2+</sup> resulted in the formation of soluble complexes of calcium carbonate and sulfoxy species which resulted in a reduction of xanthate adsorption on the galena surface. While Elizondo-Alvarez et al. (2017), attributed this to the chemisorption of  $Ca^{2+}$  on active sites, hindering the action of the xanthate collector. Research by Fuerstenau (1982) detailed that above pH 6, Ca<sup>2+</sup> adsorbs onto negatively charged pyrite via an electrostatic attraction; thus, hindering the oxidation of xanthate and ultimately its adsorption on the mineral surface. It should also be noted that the SPW also shows a significant concentration of sulfate (1200 mg/L) while it contains a lower concentration of calcium (400 mg/L), compared to the solutions of calcium nitrate (1610 mg Ca/ L) and calcium sulfate (1207 mg Ca/L). This indicates the role of sulfate ions; probably playing in conjunction with calcium ions, since there is evidence that  $\mathrm{SO_4}^{2-}$  passivates the galena surface and decreases the adsorption of xanthate, resulting in lower galena recoveries (Elizondo-Alvarez et al., 2017).

Across the pH 2–12 range, zeta potential measurements of both minerals showed a less negative potential on the surface in  $Ca^{2+}$  containing solutions. With the potential in NaNO<sub>3</sub> resembling that of ultrapurified water very closely. The potential of the mineral surface becoming less negative in  $Ca^{2+}$  containing solutions makes it clearly evident that  $Ca^{2+}$  passivates the mineral surface to a larger extent and indicates the compression of the electrical double layer (Ma, 2005; Li

## et al., 2017; Ikumapayi et al., 2012).

Collectorless microflotation results show that Na<sup>+</sup> achieves higher mineral recoveries, the potential of the mineral is also seen to be most negative with Na<sup>+</sup> compared to Ca<sup>2+</sup>. Generally, Ca(NO<sub>3</sub>)<sub>2</sub> resulted in the least negative potential of the mineral, followed by CaSO<sub>4</sub> and the synthetic plant water. A less negative zeta potential of the mineral surface is indicative of a decrease in the electrostatic repulsion between solid surfaces (Li et al., 2017; Hirajima et al., 2016).

It is thus expected that the  $Ca(NO_3)_2$  solution would yield the highest mineral recoveries of the three salt solutions, however that was not the observation in the microflotation tests and bubble-particle attachment measurements with both galena and chalcopyrite. Fuerstenau (1982) proposed that the electrical double layer drives the adsorption of physically-adsorbing reagents by the magnitude and sign of the surface charge and that a high surface charge may hinder the adsorption of chemically-adsorbing collectors.

This work proved that less xanthate is adsorbed on chalcopyrite and galena surfaces in  $Ca^{2+}$  containing solutions hence the poorer bubbleparticle attachment shown in the fundamental attachment timer and in a microflotation system observed in this work. Thus, the increased zeta potential and therefore high surface charge on chalcopyrite and galena may either hinder the adsorption of xanthate; or the bubble-particle attachment of chalcopyrite and galena is affected more by the adsorption of collector on the mineral surface regardless of the change in electrostatic repulsion that the ionic composition of the water brings to the system.

### 5. Conclusions

Two techniques assessing the bubble-particle attachment of chalcopyrite and galena were used, one fundamental and one simplifying what happens in the pulp phase in a flotation system. Both bubbleparticle attachment techniques showed that  $Ca^{2+}$  containing solutions resulted in the lowest bubble-particle attachment, while the Na<sup>+</sup> containing single salt solution consistently resulted in the highest bubbleparticle attachment probability and recovery.

Adsorption test results further displayed that  $Ca^{2+}$  containing solutions resulted in less xanthate adsorbing on the mineral surface and hence reducing the attachment probability and subsequently mineral recovery as found in this investigation. Zeta potential measurements showed that the  $Ca^{2+}$  containing solutions result in the least negative mineral surface; which is indicative of the mineral surface being screened or passivated by these divalent cations. This investigation therefore provides evidence that the passivation of the mineral surface with  $Ca^{2+}$  inhibits the adsorption of xanthate and thus negatively affects the bubble-particle attachment.

#### CRediT authorship contribution statement

L.L. October: Writing - original draft. K.C. Corin: Supervision,

Methodology, Resources, Writing - review & editing, Funding acquisition. **M.S. Manono:** Supervision, Methodology, Writing - review & editing. **N. Schreithofer:** Resources, Methodology, Writing - review & editing, Funding acquisition. **J.G. Wiese:** Supervision.

#### **Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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