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Investigating the Influence of the Electrochemical Environment on the Flotation of Bornite and Chalcocite

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Abstract: Beneficiation of sulphide ores by flotation is ascribed to the natural electrochemical activity associated with sulphide minerals. Flotation is an electrochemical process comprising many interdependent conditions that are difficult to decouple in terms of controlling flotation performance. The extent of electrochemical activity is mineral dependent and can be measured against a reference cell to differentiate between minerals. This difference in activity is known as the rest potential. The rest potential can be exploited to preferentially float one mineral over another as these properties result in different regions of flotation stability for different minerals. Bornite and chalcocite present an interesting study because when measured against the standard hydrogen electrode (SHE), there is a small difference in rest potential; bornite has a potential of 0.44 V and chalcocite a potential of 0.40 V. The key differentiating factor between the two minerals is the presence of iron in bornite (Cu_5FeS_4) and the lack thereof in chalcocite (Cu_2S). This study considers bornite and chalcocite microflotation, adsorption studies and zeta potential measurements, and three key factors were explored: pH, galvanic interactions and collector adsorption. The overall objective of the study is to understand the response of bornite and chalcocite to changes in pulp chemistry.

Keywords: copper sulphides; bornite; chalcocite; collector adsorption; galvanic interactions

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1. Introduction

Bornite (Cu_5FeS_4) and chalcocite (Cu_2S) are important copper bearing minerals due to their high copper content. Bornite is typically found as a secondary mineral in chalcopyrite and chalcocite deposits in copper-molybdenum and copper-gold ores. Chalcocite, although scarce, is still found as a primary mineral and has proved to be one of the most profitable copper ores to mine as it produces copper concentrates ranging from 37% to 40% compared, for example, to chalcopyrite which ranges from 20% to 30% [1]. As the two minerals are associated in deposits as primary and secondary minerals, understanding their relative floatability may lead to increased productivity and output in industrial operations. The separation of bornite from chalcocite has enjoyed considerable attention over the years since the discovery of the Olympic Dam deposit. Researchers at the former Ian Wark Research Institute had a major programme of research on this topic which is often undertaken as proprietary research. The present study is aimed to continue investigating the relative floatability of these two minerals. At Olympic Dam in particular, these minerals are the host minerals (with chalcopyrite) of the uranium in one of world largest uranium deposits [2].

1.1. Effect of pH on Flotation

pH control can be used to selectively float specific ores in a mineral mixture. This may be of particular importance in complex separations such as in the case of bornite and chalcocite. This is due to the ore itself either exhibiting alkaline or acidic properties, which in turn dictates under which pH conditions a particular ore will float [3]. For instance, pyrite hardly floats in alkaline conditions despite the caustic nature of alkaline solutions helping to clean the surface and possibly enhancing collector adsorption [3]. Flotation is

typically done under alkaline conditions as most collectors are stable under such conditions, and corrosion of piping and equipment is minimized [4]. The pH dependence of pulp potential is largely due to the enhancement or depression of the electrochemical reactions controlled by the presence or lack of ions for electron exchange. Hydroxyl ions interfere with and modify the electrical double layer and zeta potential of the mineral surface and hence collector adsorption. This affects the hydrophobicity of the mineral which in turn impacts its floatability [3].

For a given concentration of collector, there is a pH value where a given mineral will either float or be depressed [3]. This critical value is dependent on factors such as the mineral, collector type, collector concentration and temperature. Figure 1 shows how the critical pH changes with xanthate collector concentration for pyrite, galena and chalcopyrite. The lines on the graph indicate the boundary below which minerals become sufficiently hydrophobic to float. From Figure 1, it is evident that increasing pH at constant collector concentration allows for selective flotation of chalcopyrite from galena and pyrite as galena is not hydrophobic enough to float (region B), and for selective flotation of galena from pyrite, but no selectivity between galena and chalcopyrite as both are hydrophobic enough to float (region C). All minerals will float in region D, and all minerals are not hydrophobic enough to float in region A.

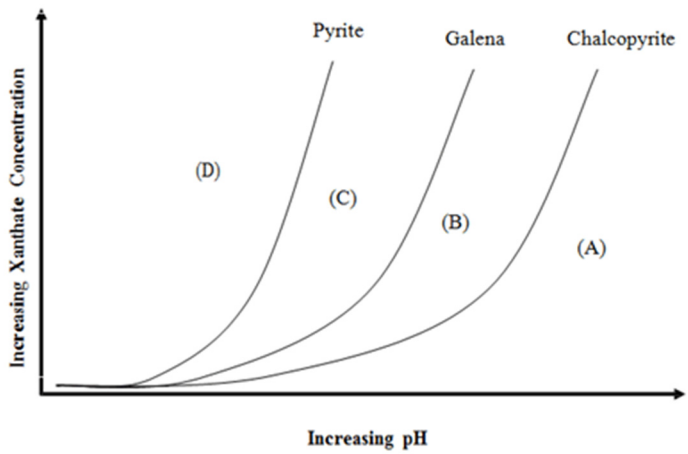

Figure 1. Critical pH change with increasing collector concentration for pyrite, galena and chalcopyrite (adapted from [5,6]).

pH regulation makes use of lime (used to achieve alkalinity) in six different processes on a mine: post crushing, pre rougher flotation, pre concentrate regrind, pre cleaner flotation, in tailings disposal and post concentrate thickening [7]. For sulphide mineral flotation, on average, the cost of lime may be double the cost of collector per ton of ore processed [8].

1.2. Galvanic Interaction in Mineral Mixtures

Apart from factors relating to pH, galvanic interactions may also significantly influence the separation of the two minerals referred to above. When two sulphide minerals are in contact with one another in an electrolyte solution, the mineral with the lower rest potential undergoes oxidation and acts as an anode, while the mineral with the higher rest potential acts as a cathode as seen in Figure 2 [9,10].

The galvanic interactions between two sulphide minerals favours flotation of the anodic mineral as an oxidized mineral surface improves collector adsorption [11]. The potential of the mixture is neither a simple sum nor the difference of the two rest potentials, but rather a value between the two potentials depending on the minerals [12]. This potential is known as the mixed potential and arises due to the occurrence of multiple electrochemical reactions happening simultaneously as shown in Equations (1)–(3) for the example of a pyrite/sphalerite mixed mineral system [13]. The minerals will polarize each other in

solution until they reach an equilibrium potential value. The lower rest potential mineral will thus now have an increased current density in the presence of the higher rest potential mineral compared to the density it experiences when it is by itself [12].

$$ZnS \leftrightarrow Zn^{2+} + S^0 + 2\,e^- \quad (1)$$

$$0.5\,O_2 + H_2O + 2\,e^- \leftrightarrow 2\,OH^- \quad (2)$$

$$Fe \leftrightarrow Fe^{2+} + 2\,e^- \quad (3)$$

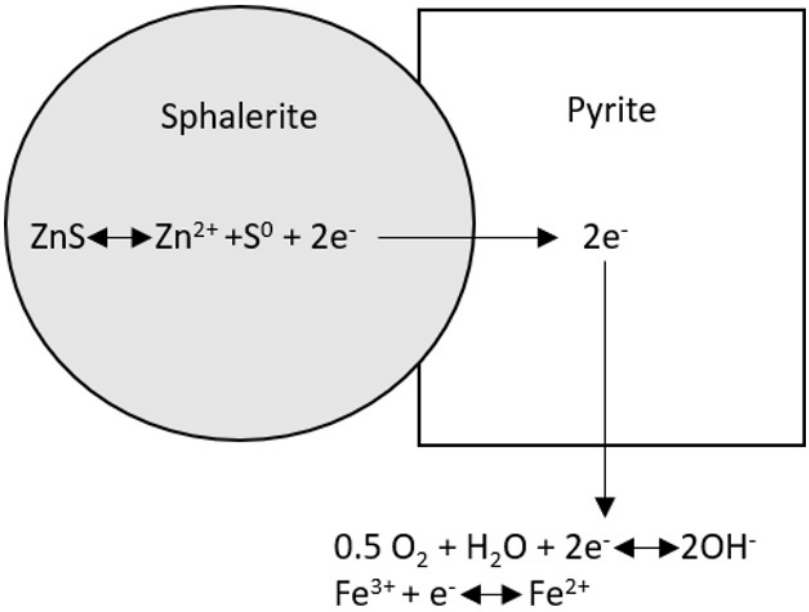

Figure 2. An example of mineral–mineral galvanic interactions between sphalerite and pyrite [9].

1.3. Collector Adsorption

The collector adsorption rate is dependent on the availability of dissolved oxygen (DO) within the system as it is necessary to complete the collector complexation process [14]. Collector complexation is a process where metal xanthates or dixanthogens are formed as they are responsible for inducing hydrophobicity, and oxygen becomes the final electron acceptor in the process [3,15,16]. Depending on the specific mineral type and extent of sulphide oxidation, the surface can become naturally hydrophobic resulting in its natural flotation without the need to add collector for enhancement.

There are three main mechanisms in which collectors and minerals interact; adsorption of the collector, oxidation of the thiol collector to form its dithiolate and chemisorption as seen in the mineral–collector interaction mechanisms shown in Reactions (4) to (6) [17]. Chemisorption is generally the thermodynamically favourable process and offers the most optimal use of collector through the formation of a monolayer on the mineral surface [16].

$$\begin{gathered}\text{thiol collector adsorption}\\ X^- \rightarrow X_{ads} + e^-\end{gathered} \quad (4)$$

$$\begin{gathered}\text{oxidation to dithiolate}\\ 2X^- \rightarrow X_2 + 2e^-\end{gathered} \quad (5)$$

$$\begin{gathered}\text{chemisorption}\\ MeS + 2X^- \rightarrow MeX_2 + S^0 + 2e^-\\ MeS + 2X^- + 4H_2O \rightarrow MX_2 + 8H^+ + 8e^- + SO_4^{2-}\\ 2MeS + 4X^- + 3H_2O \rightarrow 2MX_2 + 6H^+ + 8e^- + S_2O_3^{2-}\end{gathered} \quad (6)$$

A potential dependence of chemisorption exists which obeys the Frumkin adsorption isotherm (Equation (7)) which takes into account the interaction of species and shows that the presence of a species on an adsorption site reduces the probability of adsorption on neighbouring sites and is a phenomenological equation derived from macroscopic observations [16]. That is to say, from a macroscopic point of view, the presence of any species on an adsorption site results in lower chances of adsorption taking place on neighbouring sites despite them being unoccupied.

$$\begin{gathered} K_{eq} = K_{eq_0} e^{\beta \theta_{eq}} \\ K_{eq} = \text{adsorption equilibrium constant} \\ \theta_{eq} = \text{site coverage at equilibrium} \\ \beta = \text{coverage parameters} \end{gathered} \tag{7}$$

Xanthates are known to readily decompose, whether in atmospheric conditions with oxygen, or in water [18]. However, the decomposition follows various routes depending on the conditions. The xanthate that will be present in the pulp is dependent on the pH of the solution, the DO concentration, the nature and concentration of metal ions in solution and the presence of any catalytic species that promote any of the decomposition processes. Hydrolysis and decomposition of xanthic acid are the primary reactions that take place under acidic conditions, with the extent of decomposition increasing as the pH decreases from pH 7. Hydrolytic decomposition happens under alkaline conditions where the reaction products are stable, and the presence of DO is critical for the oxidation reactions to take place [18].

Flotation chemistry is complex, with multiple intertwined facets that result in the final observed flotation response. As shown above, specific minerals have pH regions in which they float; when coupled with the electrochemical and decomposition reactions that can take place at different pH values, there are then multiple permutations and combinations of the effect of pH on various minerals. In the present instance, this is further complicated by the similarity of bornite and chalcocite, both in terms of their chemical composition and their similar rest potentials which may be the defining parameter in terms of their individual floatability. This study aims to understand the interaction of the different parameters in an investigation into the floatability of bornite and chalcocite and the effect on the final flotation response.

2. Materials and Methods

To investigate the surface chemistry of bornite and chalcocite individually, experiments were conducted at pH 3, 5, 7, 9 and 11 in the presence of water at two different ionic strengths, viz. deionised water (DIW) and a synthetic plant water (SPW1) which was made up of ions typical of that found in many flotation plants and which ensures a constant background ionic strength, which in this case is 0.0241 mol/L [19].

2.1. Mineralogy

The bornite samples were sourced from Mineral World in Cape Town, South Africa, while the chalcocite samples were sourced from stock held at Central South University (CSU), Changsa, China. X-Ray diffraction (XRD) was conducted to determine the bulk mineralogy of the samples. Table 1 shows the mineral composition of the samples. The purity of the samples was not ideal, with the bornite sample containing large portions of gangue minerals, and the chalcocite containing significant portions of marcasite (FeS_2) and pyrite (FeS_2) which are iron containing minerals and thus complicate the use of Fe as a tracer for bornite. It should be noted that sourcing samples of higher purity proved difficult.

Table 1. Bornite and Chalcocite Sample Mineralogy.

Mineral	Chalcocite	Bornite
chalcocite	62	-
bornite	-	42
chalcopyrite	<1	<1
pyrite	8	-
marcasite	24	-
magnetite	-	3
hematite	1	-
goethite	-	3
gibbsite	-	1
calcite	-	28
dolomite	-	3
quartz	4	16
mica	-	4
total	100	100

2.2. Synthetic Plant Water Preparation

Synthetic plant water (SPW1) was used to mimic process water typical of many flotation plants. As stated above, this ensured that all tests were conducted in an environment of constant ionic strength. The water had a TDS value of 1023. Analytical grade salts were used to prepare the SPW1 with ionic concentrations shown in Table 2 in mg/L and the ultimate ionic strength was 0.0241 mol/L.

Table 2. Composition of synthetic plant water (SPW1) [19].

Ion	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	NO_3^-	CO_3^{2-}	TDS	IS (mol/L)
conc. (mg/L)	80	70	153	287	240	176	1023	0.0241

2.3. Microflotation

Microflotation was carried out at a relatively low dosage equivalent to 0.5 pseudo monolayer which is the amount of collector molecules required to cover approximately half the available mineral surface as determined by BET using a molecular footprint value of 2.88×10^{-19} m^2 for the SIBX collector ($C_5H_9NaOS_2$; MW 172.23 g/mol, supplied by AECI Mining Chemicals) and was dosed for active content (90%). To float at different pH conditions, the process water was adjusted to the required pH by adding HCl or NaOH as needed. Microflotation was conducted as per standard UCT procedure [20,21]. Microflotation recovery was determined by mass recovery owing to the use of pure mineral samples.

2.4. Adsorption Studies

Adsorption tests were carried out on the pure mineral samples using UV–vis spectroscopy to determine the xanthate concentration in the solution before and after its contact with the mineral (Biochrom, Holliston, MA, USA). The characteristic absorption wavelength of the xanthate is 301 nm. Details of how these experiments were carried out have been described by October et al. [21]. An amount of 2 g of the mineral of interest was added to 30 mL of the water quality under investigation in a conical flask. The slurry was magnetically stirred, and the pH was adjusted to the desired value using solutions of 0.1 M sodium hydroxide (NaOH), 1.0 M NaOH, 0.1 M hydrochloric acid (HCl), 1.0 M HCl and 0.1 M sodium tetraborate ($Na_2[B_4O_5(OH)].8H_2O$) buffer solution added once the desired pH had been reached to stabilize the solution at that pH value. Collector was dosed into the slurry. The top of the flask was covered in foil and the flask secured in an Ecobath shaking water bath at 25 °C with a shaking speed of 130 rpm. After 3 min of mixing in the water bath, 10 mL of the slurry was extracted using a syringe and filtered through

a 0.45 μm syringe filter. The filtrate was collected and transferred into a cuvette for analysis using the UV–vis spectrophotometer.

2.5. Zeta Potential

The surface charge of the minerals at different pH values and in different water types was measured using zeta potential tests. This was done to determine the effects of the presence and absence of ions in the solution on the surface charge of the minerals. The tests were conducted using a Malvern ZetaSizer 4 (Malvern, UK) which uses electrophoretic mobility to calculate the zeta potential and carried out as per October et al. [21]. The tests were conducted at 5 pH values, 3, 5, 7, 9 and 11 with two water types, DIW and SPW1 on both the pure samples of bornite and chalcocite. An amount of 0.15 g of the sample was weighed and transferred into a beaker. Subsequently, 120 mL of the water type was filtered using a 0.22 μm filter paper to ensure purity and remove any suspended solids. The sample and filtered water were then mixed for a period of 5 min using a magnetic stirrer before being transferred for ultrasonication for another 5 min to ensure the sample was well dispersed. The sample was returned to the magnetic stirrer where the pH was adjusted with either HCl or NaOH until the desired pH was attained. A buffer solution of $Na_2[B_4O_5(OH)].8H_2O$ was used to stabilize the pH value and minimize fluctuation. The solution was then allowed to sit for 30 s to allow heavy particles to settle, and the supernatant was transferred into a vial for analysis using the ZetaSizer.

3. Results and Discussion

Figure 3 shows the final recovery obtained for bornite and chalcocite after flotation in both DIW and SPW1 at pHs ranging from 3 to 11. When using DIW, the recoveries of bornite were generally the same between pH 5 and 11 with the final recovery ranging between 59% and 66%. The lowest recovery of 21% occurred at pH 3. When using SPW1, bornite recovery was lower compared to the case of using DIW, with pH from 7 to 11 recording recoveries between 24% and 42%. For bornite, the highest recoveries were 66% at pH 5 in DIW and 42% at pH 3 in SPW1.

In the case of chalcocite in DIW, there were two distinct flotation recovery regions, viz. below 50% recovery for the near neutral pH between 5 and 7 and above 50% in more acidic pH 3 and more alkaline 9 and 11. In the case of using SPW1, there is no distinct trend, with recoveries increasing in the order pH $5 < 9 < 11 < 7 \leq 3$. With the exception of pH 7, chalcocite recovery in SPW1 was lower than DIW, but not as drastic as that observed with bornite in the two water types. For chalcocite, the highest recoveries were 72% at pH 3 and 9 in DIW and 67%/66% at pH 7/pH 3 in SPW1.

While the minerals in this study were not floated as mixtures, the ratio of recovery of bornite over chalcocite may provide some indication of possible conditions which would favour the preferential separation of bornite from chalcocite by flotation. When considering Table 3, it is clear that the majority of conditions used in this study would promote the flotation of chalcocite as shown by the ratios being less than one in most cases. pH 5 in DIW shows a particularly high preference for bornite flotation, while pH 3 in DIW and pH 7 in SPW show a higher preference for chalcocite flotation. It is also clear that bornite flotation is better in DIW, while chalcocite is less impacted by water quality.

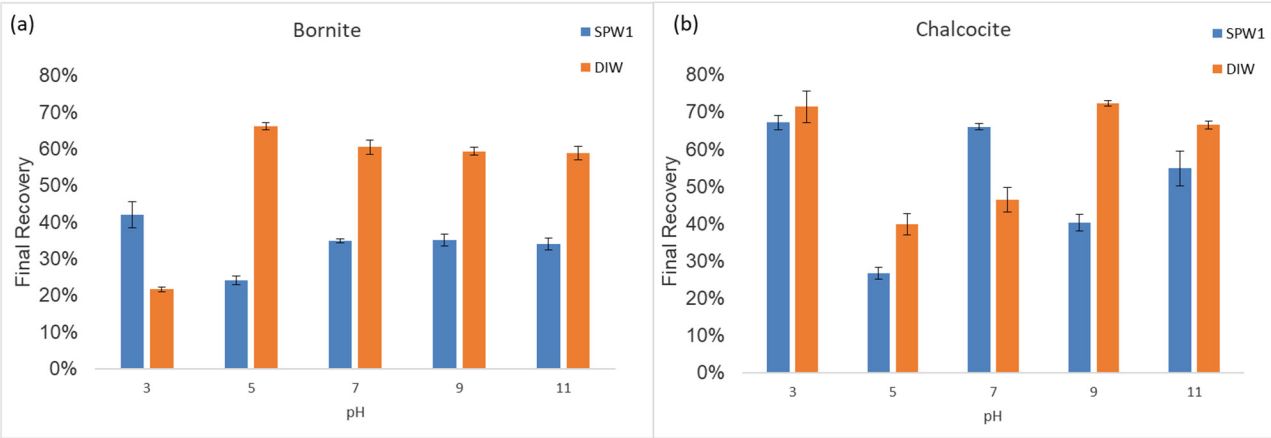

Figure 3. Final mass recovery of bornite and chalcocite at different pH levels.

Table 3. Ratio of the recovery of bornite to chalcocite.

pH	DIW			SPW1		
	Bornite	Chalcocite	Ratio	Bornite	Chalcocite	Ratio
3	22%	72%	0.3	42%	67%	0.6
5	66%	40%	1.7	24%	27%	0.9
7	60%	46%	1.3	35%	66%	0.5
9	59%	72%	0.8	35%	40%	0.9
11	59%	67%	0.9	34%	55%	0.6

In the collector adsorption studies, Figure 4 shows that for bornite, the residual collector concentration, viz. the amount of collector that does not absorb onto the mineral surface, varied with pH and with the ionic strength of the water. The minimum residual concentration, or the highest extent of adsorption of collector onto the mineral, was observed at pH 7 for all dosages and water types. For pHs > 7, the residual concentration steadily increased, with pH 11 generally having the highest residual concentration or lowest adsorption for all dosages and water types. At pH < 7, the adsorption was also lower than at pH 7 but not as significantly as at pH > 7. Generally, at pH > 7, the adsorption of collector was lower when using DIW. At a 0.5 monolayer, there was higher residual concentration in SPW1 in acidic to neutral conditions (pH 3, 5 and 7), whereas under alkaline conditions (pH 9 and 11), there was higher residual concentration in DIW. Overall, these results showed that collector adsorption of xanthate onto the surface of bornite varies depending on the pH and on the ionic strength of the water, although the highest extent of adsorption for any ionic strength occurred at pH 7. Eilzondo-Alvarez et al. [22] showed that adsorption of sodium isopropyl xanthate (SIPX) onto galena decreased with increasing pre-conditioning pHs of 5.5, 7.5 and 9.5 and similarly Multani et al. [23] showed the same decrease in adsorption of potassium amyl xanthate (PAX) onto non-magnetic pyrrhotite as pH increased from 7 to 8.5 and 10. Their study showed a different trend for magnetic pyrrhotite where, although there was a decrease in adsorption at pH 10, there was little difference between pH 7 and 8.5; moreover, the adsorption of PAX onto magnetic pyrrhotite was significantly higher overall. These studies indicate the mineral specificity of the system under study and support the difference in adsorption trends seen between bornite and chalcocite.

In the case of chalcocite, there was generally a high extent of adsorption, particularly when using the 0.5 monolayer dosage in which, across all pH values, there was very minimal residual collector concentration. On the other hand, there was distinctly higher residual collector concentration or lower extent of adsorption at one monolayer dosage. This may be owing to the presence of marcasite and p1yrite impurities in the chalcocite sample which contained Fe, with this species possibly oxidising and interacting

with the xanthate to form $Fe(OH)X_2$ and $Fe(OH)_2X$, removing the freely available X^- from solution [24].

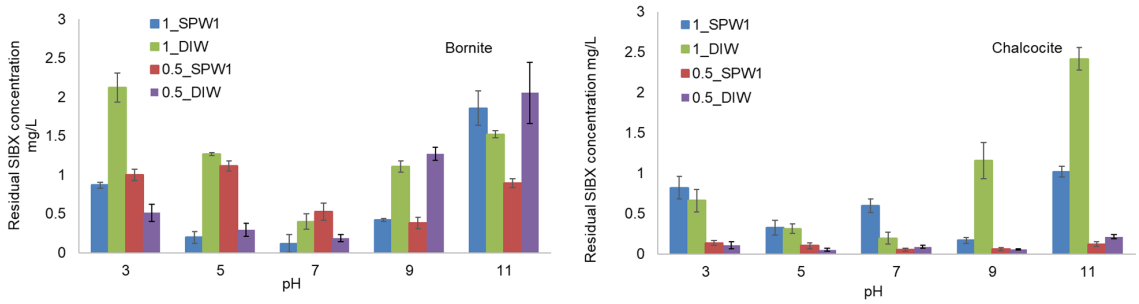

Figure 4. Collector adsorption for bornite and chalcocite in DIW and SPW1 at different pH levels.

Figure 5 shows the zeta potential results for both bornite and chalcocite in SPW1 and DIW water. For bornite, in both SPW1 and DIW, the zeta potential increased from pH 3 and reached a peak at pH 5 after which the potential decreased until pH = 11. In DIW, the first isoelectric point (IEP) was at approximately pH 4 with the second IEP at pH 8. In SPW1, the IEPs occurred at approximately pH = 4.5 and 6. For chalcocite in DIW, the first IEP occurred roughly at pH 3.5 and the second at approximately pH 6.5. The zeta potential profile in SPW1 was completely negative with no IEPs recorded.

It is noteworthy that bornite and chalcocite have two IEPs and when using DIW these occur between pH 3 and 11. Chalcocite has two IEPs between about 3.5 and 6.5 when using SPW1. The lower IEPs observed, viz at pH = ~3.5, are characteristic of sulphur, which has an IEP between pH 2 and 3, but superficial oxidation on the surface typically shifts it to a higher pH, which may indicate some level of oxidation on the surfaces of bornite and chalcocite [3]. The profiles when using DIW for both minerals are similar in both pattern and magnitude, and these results may indicate similar extents of double layer compression [3]. When using SPW1, chalcocite exhibits greater electrical double layer compression compared to bornite as indicated by the zeta potential trending towards more neutral values over the tested pH range. This suggests that chalcocite has weaker repulsive forces compared to bornite to counteract the effect of added ions [25]. With the key difference between chalcocite and bornite being the lack of and presence of iron respectively, the behaviour of bornite may be due to Fe ions hydrolysing to form iron oxy-hydroxide species which vary in character with pH [18].

In a related study, the oxidation reduction potential (ORP) of a synthetic ore containing 5% pure mineral, 93% quartz and 2% talc, to maintain froth stability, was measured prior to flotation in an SPW1 system. The ORP for the synthetic ore containing bornite was noted to be much lower than the one containing chalcocite, viz. −5 mV and 70 mV, respectively. This possibly explains the lower xanthate adsorption and lower recoveries noted for bornite, owing to the oxidation of xanthate to dixanthogen as well as flotation being favoured under more oxidizing conditions [26].

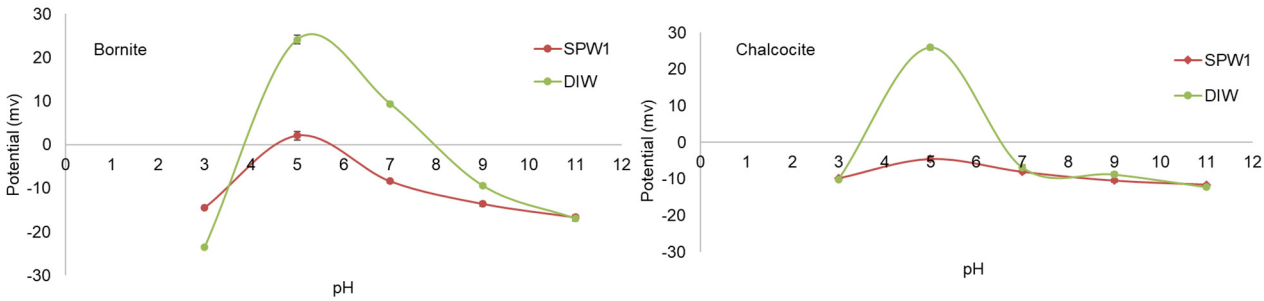

Figure 5. Zeta potential profiles for bornite and chalcocite in SPW1 and DIW at different pH levels.

In interpreting the above results, it is important to note that there are related factors crucial in the flotation response, viz. the redox reactions occurring at a specific pH and the xanthate and the ionic species present which interact with the mineral as well as participating in the redox reactions [17]. The distinction between bornite and chalcocite is the presence of iron in bornite (Cu_5FeS_4) and its absence in chalcocite (Cu_2S). Fe ions produced from bornite are electrochemically active and can form hydrophilic iron hydroxide species in solution, which can subsequently associate with the surface of the mineral, reducing the adsorption of the collector and thus reducing the floatability of the mineral [27]. However, under acidic conditions, such hydroxide species are oxidised, which would result in a higher flotation recovery at lower pH due to the greater inhibition of the formation of hydroxide species for bornite [17]. Mikhlin et al. [28] showed that the primary Fe species leached from bornite is in the form of Fe^{3+} and that the prevalent species in solution under most pH conditions would most likely be $Fe(OH)_3$, owing to the propensity of Fe^{3+} to be hydrolyzed across pH levels between 4 and 12 [18]. However, Figure 4 shows that the highest recoveries of bornite were generally at alkaline pHs. This then leads to the possibility that it is the second factor that affects the flotation response of bornite, viz. the xanthate species present. The pH affects the xanthate speciation and thus the collector–mineral interactions. In acidic conditions, the xanthate ion hydrolyses to form xanthic acid, with the extent of reaction being controlled by the strength of the acidic conditions. As the conditions become more acidic, the xanthic acid decomposes, and the results thus suggest that at pH 5, it is likely xanthic acid forms, and at pH 3 further decomposition takes place to form carbon disulphide [18,29]. This results in more hydrophobicity being induced at pH 3 by the carbon disulphide species, which may form a film around the mineral surface and result in greater flotation recovery compared to pH 5 where only hydrophilic xanthic acid has been formed. In alkaline conditions, xanthate is oxidised to either form a metal xanthate or dixanthogen. In these forms, xanthate is sufficiently hydrophobic to induce flotation, hence the consistently higher recoveries at high pH values. The flotation response in SPW1 resulted in lower recoveries compared to that in DIW. The cations in SPW1 have been shown to speciate to form sulphate and hydroxide species of Ca^{2+}, Mg^{2+} and Na^{+} [30]. Formation of these sulphate species in solution, which may associate themselves with the mineral surface, reduces the available surface area for collector adsorption, thus reducing the floatability and recovery [30].

There is generally higher residual collector concentration at pH 3 and 11 with lower residual concentrations between pH 5 and 9. The differences in collector adsorption are regulated by the pH, which dictates the specific collector mineral interactions and the xanthate species formed under the given conditions. The collector mineral interactions are dictated by the pulp potential, which is heavily influenced by the pH of the system. For the pure bornite and pure chalcocite adsorption tests, there is distinctly better adsorption onto the surface of chalcocite compared to bornite across all conditions. The key difference likely lies in the presence of iron in bornite and the lack thereof in chalcocite. For chalcocite, copper xanthate formation can take place via dissolution of Cu^{2+} as shown in Reaction (8) and corrosion of copper hydroxide as shown in Reaction (9) resulting in minimal xanthate ion remaining in solution [31]. For bornite, the presence of iron results in the formation of iron hydroxides that are hydrophilic and thus will inhibit the adsorption of collector onto the mineral surface in alkaline conditions [32].

$$\underset{\text{copper xanthate formation from dissolution}}{Cu^{2+} + 2\,X^{-} \leftrightarrow CuX_2} \tag{8}$$

$$\underset{\text{copper xanthate formation from corrosion}}{Cu(OH)_2 + 2\,X^{-} \leftrightarrow CuX_2 + 2\,OH^{-}} \tag{9}$$

4. Conclusions

The separation of bornite from chalcopyrite by flotation is a complex but important challenge. It is evident that pH plays a vital role in controlling electrochemical processes

through the inhibition and promotion of certain redox reactions. This has an additional impact on speciation, surface charge due to the species present and ultimately the flotation response of the minerals. The pH controls collector adsorption, flotation recovery and surface charge by dictating what type of species is present in the electrochemical environment through redox reactions. Under acidic conditions, xanthate collector decomposes to carbon disulphide and the respective alkyl alcohol [17]. The carbon disulphide that can form a film around the mineral surface results in high bornite and chalcocite recoveries at low pH levels. In alkaline conditions, the xanthate ion is stable and can adsorb onto the mineral surface. The pH also changes surface active species in the system, which then inherently dictate the surface charge. Understanding the individual characteristics of bornite and chalcocite provides an important basis towards a better understanding of conditions which may be favourable for the separation of these minerals by flotation.

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