The effect of using pure thiol collectors on the froth flotation of pentlandite containing ore

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Key words: Pentlandite, xanthate, dithiophosphate, dithiocarbamate

Abstract—Sodium ethyl and potassium amyl xanthates are commonly used in bulk and selective froth flotation of pentlandite ores respectively. The xanthate collectors are sensitive to pH and their selectivity in treating complex ores is questionable. With deteriorating nickel sulphide ore reserves more selective collectors have to be used in the extraction of nickel. The dithiocarbamates and dithiophosphates are possible replacement as they are believed to be stable in a wider range of pH and more selective than xanthates respectively. The present study compared the effects of using di-methyl-dithiocarbamate (di-C$_1$-DTC), di-ethyl-dithiophosphate di-C$_2$-DTP, SEX and PAX in froth flotation of pentlandite ore. The collectors were dosed at molar equivalent of 80g/ton PAX. This study showed that the higher cumulative nickel grades and cumulative nickel recovery were obtained by the use of PAX and SEX respectively. Therefore, it was not beneficial to substitute xanthates with either di-C$_1$-DTC or di-C$_2$-DTP in the froth flotation of pentlandite containing ore.

INTRODUCTION

Nickel sulphide mineral ores amounts to more than fifty percent of all commercial nickel (Senior et al., 1995). There is a growing demand for nickel and it is projected that the current nickel sulphide reserves may be depleted by 2030 (Tundermann et al., 1996). Also, nickel sulphide ore reserves are declining and are mostly of low nickel grade. Consequently, more selective collectors should be used in their froth flotation. Furthermore, the nickel sulphide processing industry needs to be more efficient and cost effective to be sustainable as it faces the following challenges: growing demand for nickel, strict environmental constraints on sulphur emissions, nickel oxide ores challenging to be the primary nickel source and inadequately selective xanthate collectors (Pietrobon et al., 1995).

Collectors are heterogeneous organic compounds made of a hydrocarbon chain attached to an in-organic functional group. The non-ionic hydrocarbon chain enhances the hydrophobicity of the mineral-to-collector agglomerates. The in-organic part selectively adsorbs on to the minerals surface by either chemical or physical process (Crozier, 1991; Gupta, 2006). True flotation relies on the difference in hydrophobicity between the valuable and the gangue minerals. Sometimes the difference is minimal and in such instances collectors are used to increase the differences in hydrophobicity (Clark et al., 2006). In the absence of suitable collectors mainly fine particles, both hydrophilic and hydrophobic, will report to the concentrate via the mechanism of entrainment and consequently the flotation cell acts as a classifier or elutriator (Cooper et al., 1982).

The thiol class of collectors is characterized by an ionized group that contains a sulphur atom (Meilczarski et al., 1998). The different classes of thiol collectors form various surface products on different sulphide mineral surfaces. Different metal-thiolates or dithiolates will be formed as a result of the adsorption of collector onto each of the minerals present in the ore. Some of these will be stable and some not. The degree of stability of the metal thiolates or dithiolates will determine the selectivity and mechanism of attachment of the collector (Meilczarski et al., 1998). Also, the stability of the metal-thiolate determines the strength of the collector and the more stable the agglomerate formed, the higher the collector strength. Usually, greater collector strength results in reduced selectivity. This often means that when a strong collector is used more mass is recovered with a consequently low concentrate grade.

The thiol collectors e.g., xanthates, dithiocarbamates and dithiophosphates are the most commonly used class of collectors in the flotation of sulphide mineral ores (Adkins & Pearse, 1992). These collectors have a high
The xanthates are the mostly used class of thiol collectors (Adkins & Pearse, 1992). This is primarily due to their availability and a lower cost than the other classes of collectors. Furthermore, xanthates have both intermediate selectivity and collecting power. Thus, they are able to float a reasonably higher valuable mineral at an acceptable grade (Adkins & Pearse, 1992). Xanthates are preferred collectors in the bulk flotation of a variety of sulphide mineral ores (Makanza et al., 2008). The flotation of different minerals with xanthates collectors depends on the surface products the collector forms with the mineral surfaces. Some minerals are floated by the formation of dixanthogens on the mineral surfaces while others by the formation of metal-thiolates. The examples of minerals that are floated by the formation of dixanthogens are chalcopyrite, covellite, pyrrhotite and pyrite. Bornite and pentlandite minerals are floated by the formation of metal-xanthate (Lotter & Bradshaw, 2010). Furthermore, xanthates are able to form two surface products depending on the redox condition of the pulp. This makes pH an important variable when using xanthate collectors. Thus, pH should be controlled based on the mineral to be floated. Generally, in normal and acidic pulps xanthates form dixanthogens and metal-xanthate in alkaline pulps.

Dithiocarbamates were discovered in 1850 and they have strong bonding properties with metal. Furthermore, they are known to form insoluble metal-thiolate agglomerates. Their maiden use as a collector however only came nine and half decades after their discovery (Lotter & Bradshaw, 2010). The dithiocarbamates adsorb faster on the mineral surface due to low solubility of dithiocarbamate-mineral product formed on the mineral surface and consequently their use yield fast flotation rates. Also, they are stable in a wide range of pH (Adkins & Pearse, 1992). The dithiocarbamates are also available with alkyl group ranging from two to six carbons. In addition, they have the lone pair of electrons on both nitrogen and sulphur and consequently higher covalent bond strength. Furthermore, dithiocarbamates have a lone pair of electrons on both nitrogen and sulphur hence are more reactive than both dithiophosphates. However, dithiocarbamates have a lone pair of electrons on both nitrogen and sulphur hence dithiocarbamates are generally more reactive than xanthates even though oxygen has higher electronegativity than nitrogen. Generally collector strength (measures by mass recoveries) decrease in the following order: dithiocarbamates < xanthates < dithiophosphates. Consequently xanthates are expected to be more reactive than both dithiocarbamates and dithiophosphates. However, dithiocarbamates have a lone pair of electrons on both nitrogen and sulphur hence dithiocarbamates are generally more reactive than xanthates even though oxygen has higher electronegativity than nitrogen. Generally collector strength (measures by mass recoveries) decrease in the following order: dithiocarbamates < xanthates < dithiophosphates. Sodium ethyl and potassium amyl xanthates are commonly used in bulk and selective froth flotation of pentlandite ores respectively. The xanthate collectors are sensitive to pH and their selectivity in treating complex ores is questionable. With deteriorating nickel sulphide ore reserves more selective collectors have to be used in the extraction of nickel. The dithiocarbamates and dithiophosphates are possible replacement as they are believed to be stable in a wider range of pH and more selective than xanthates respectively. The present
study compared the effects of using di-C$_1$-DTC, di-C$_2$-DTP, SEX and PAX in froth flotation of pentlandite ore. The collectors were dosed at molar equivalent of 80g/ton PAX.

**EXPERIMENTAL DETAILS**

**Mineralogy of the ore**

Pentlandite (1.3%) was identified as the major form of nickel sulphide present in the ore. The other species present in this ore were: Sulphide gangue: Pyrrhotite (10.7%), Chalcopyrite (1%), Pyrite (3%) Non-sulphide gangue: Clinopyroxene (18.8%), Tremolite (10.7%), Serpentine (8.8%), Chromite (9.4%), Chlorite (6.0%)

**Grinding of Ore Samples**

The ore samples were wet milled in a rod mill for 35 minutes to give P80-75 F. The wet milling was conducted at 60% water by mass. The rod mill was charged with 30 stainless steel rods of which 20 were 25mm x 300mm and 10 were 20mm x 300mm. The total charge weight was 25 kg.

**Reagents**

All the collectors that were used in the work were of analytical grade and they were supplied by Axis House. These collectors were SEX; di-C$_1$-DTC and di-C$_2$-DTP. SEX was received as powder while both sodium dimethyldithiocarbamate and sodium di-ethyl dithiophosphate were liquids. All collectors were prepared at a molar equivalent of 80 g/ton PAX (Ngobeni et al., 2012b). Calcium hydroxide was used to increase the pulp pH. It was of analytical grade and was supplied by MERCK. Furthermore it was received as white powder. The pH was maintained at 10. Calcium chloride was used to as pentlandite activator and it was supplied by MERCK. It was received as white soluble salt and was dosed at a molar equivalent to 80 g/ton PAX (Ngobeni et al., 2012b). SAS froth 94 was as the frother used in the study. It was also supplied by Axis House. The frother was dosed at 30 g/ton. The SAS froth 94 was received as liquid and it was prepared just before the flotation to avoided composition.

**EXPERIMENTAL PROCEDURE**

1. The ore samples were wet milled in a rod mill for 35 minutes to give P80-75F
2. The milled ore and the rods were washed with water to ensure all milled particles are recovered and was poured into the flotation cell (flotation was carried out at 30% solids by mass). The impeller of the flotation cell was turned on and maintained at 850 rpm.
3. Calcium hydroxide was added to raise pH to 10 and the slurry was aerated for five minute before further conditioning. After which 20 ml of feed sample was drawn using micro syringe.
4. The pulp was conditioned for two minutes with calcium chloride in order to activate pentlandite mineral surface. The slurry was then conditioned for further 2 minutes by addition of 0.4878 mmol of collector per kg of ore (based on 80 kg/ton of PAX).
5. After that it was conditioned for another minute by addition of 30 g/ton frother. The total conditioning time was 10 minutes i.e. 5, 2, 2 and 1 minute for pH modifier, activator, collector and frother respectively. Air was introduced into the cell by opening the air valve and the air flow rate was kept constant at 7 ml/min.
6. The concentrates was collected into 5 different dishes by scraping the froth at 10 seconds interval for 15 minutes (1; 2; 3; 4 and 5 for dish 1 to 5 respectively). This was equivalent to rougher, cleaner and scavenger flotation sequences in the industrial operation.
7. After 15 minutes the air was switched off and concentrates were weighed, filtered and dried and sent for the analysis. The same procedure was followed for all the experiments.
RESULTS AND DISCUSSION

The results showing the effects of pure collectors PAX, SEX, di-C₁-DTC and di-C₂-DTP are discussed in this section. Klimpel rate constants, cumulative nickel grades vs. cumulative nickel recoveries and cumulative mass recoveries vs. cumulative water recoveries were used to quantify these results.

Table 1 The summary of all the experiment performed

<table>
<thead>
<tr>
<th>Test Run</th>
<th>Collector</th>
<th>Cumulative Concentrate Mass (%)</th>
<th>Cumulative Water (%)</th>
<th>Cumulative Nickel Recovery (%)</th>
<th>Cumulative Nickel Grade (%)</th>
<th>Klimpel Constants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1 min 15 min 1 min 15 min 1 min 15 min 1 min 15 min 1 min 15 min k (min⁻¹) R (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>No Collector</td>
<td>10 28</td>
<td>11 49</td>
<td>8 21</td>
<td>1.1 1.0</td>
<td>0.78 20</td>
</tr>
<tr>
<td>2</td>
<td>PAX</td>
<td>9 32</td>
<td>7 40</td>
<td>17 64</td>
<td>2.8 3.0</td>
<td>0.42 68</td>
</tr>
<tr>
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<td>SEX</td>
<td>9 29</td>
<td>12 61</td>
<td>29 73</td>
<td>3.0 2.5</td>
<td>0.92 78</td>
</tr>
<tr>
<td>4</td>
<td>di-C₁-DTC</td>
<td>11 29</td>
<td>10 48</td>
<td>30 65</td>
<td>3.5 2.8</td>
<td>1.06 70</td>
</tr>
<tr>
<td>5</td>
<td>di-C₂-DTP</td>
<td>10 30</td>
<td>10 51</td>
<td>11 36</td>
<td>1.5 1.6</td>
<td>0.54 39</td>
</tr>
</tbody>
</table>

The effects of using pure collectors: PAX, SEX, di-C₁-DTC and di-C₂-DTP on froth flotation of pentlandite

The magnitude of the Klimpel rate constants obtained with the use of pure PAX, SEX, di-C₁-DTC and di-C₂-DTP decreased in the following order: di-C₁-DTC > SEX > di-C₂-DTP > PAX. The numerical values of the Klimpel rate constants were 1.06 min⁻¹, 0.92 min⁻¹, 0.54 min⁻¹, and 0.42 and min⁻¹ respectively (table 1). A plot of percentage cumulative nickel grades versus percentage cumulative nickel recoveries is illustrated below (Figure 1).

Figure 1 Percentage cumulative grade and recovery obtained with pure PAX, SEX, di-C₁-DTC and di-C₂-DTP at a molar dosage 0.488 mmol/ton.
A plot of percentage cumulative nickel grade versus percentage cumulative nickel recovery showed that cumulative nickel recoveries decreased in the following order with the collectors used: SEX > di-C1-DTC > PAX > di-C2-DTP The cumulative nickel recoveries obtained with these use of these collectors were 73%, 65%, 64% and 36% respectively (Figure 1). The cumulative nickel grades decreased in the following order with the collectors used: PAX > di-C1-DTC > SEX > di-C2-DTP

The cumulative nickel grades were 3.0%, 2.8%, 2.5% and 1.6% respectively (Figure 1). A plot of selectivities vs. flotation times showed that average selectivity decreased in the following order:

di-C1-DTC > SEX > PAX > di-C2-DTP

Furthermore, the use of both di-C1-DTC and SEX yielded a higher selectivity than PAX for the first six minutes of flotation. However, their selectivities decreased from the 8th minute of flotation

![Figure 2 Cumulative change in nickel to iron recovery ratio obtained with pure PAX, SEX, di-C1-DTC and di-C2-DTP at molar dosage 0.488 mmol/ton](image)

A relationship between percentage cumulative mass recoveries and percentage cumulative water recoveries obtained with the use of pure PAX, SEX, di-C1-DTC and di-C2-DTP is illustrated below and showed that cumulative water recoveries decreased in the following order with the collectors used:

SEX > di-C2-DTP > di-C1-DTC > PAX

The cumulative water recoveries were 61%, 51%, 48% and 40% respectively and consequently the mass recovery increased in the following order:

SEX < di-C2-DTP < di-C1-DTC < PAX

And their numerical values were 28%, 29%, 30% and 32% respectively (Figure 3).
The effects of alkyl group attached to a pure collectors on Klimpel rate constants

The long chained collectors have slower reaction rates on mineral surfaces than their shorter chained counterparts (Wills, 2006; Lotter & Bradshaw, 2010). Therefore, the reaction between ethyl xanthate and mineral surface may have been faster than the reaction between amyl xanthate on the mineral surface. The rate of flotation in the cell, as measured by the Klimpel rate constant, is a function of the reaction rate on the mineral surface. At higher reaction rates there are higher rates of formation of the mineral-collector agglomerates. This rapid formation of collector mineral agglomerates may result in a higher rate of flotation and higher Klimpel rate constants. Amyl xanthate had a lower flotation rate constant than ethyl xanthate (table 1). The ethyl xanthate’s faster rate of reaction on the mineral surface may have contributed to the higher Klimpel rate constant.

The steric interactions among shorter molecules are fewer than those among longer molecules. Thus, they have higher adsorption densities than their longer-chained counterparts (Meilczarski et al., 1998). Therefore ethyl xanthate has a higher adsorption density than amyl xanthate due to fewer steric interactions associated within the smaller ethyl hydrocarbon chain. The fewer steric interactions on the shorter molecules allows for easy and compact packing on the mineral surface. This may result in the higher reaction rates on the mineral surface and in a higher Klimpel rate constant.

The effects of alkyl group attached to a pure collectors on cumulative nickel grades and recoveries

The collectors in the same class e.g. xanthates may display similar characteristics such as reactivity, selectivity and solubility (Wills, 2006). One collector however, may have a higher reactivity compared to others in the same group due to its alkyl group length. Hence, ethyl xanthate was more selective than amyl xanthate (Figure 2), as it had a shorter alkyl group than amyl xanthate (Bloch, 2006).

Since ethyl xanthate was more selective towards nickel than amyl xanthate; it recovered more nickel than amyl xanthate (Figure 1). The ethyl xanthate recovered 10% more nickel than amyl xanthate. Ethyl xanthate selectivity was higher at initial flotation time than in the later flotation time.

Twenty nine percent and five percent of the total nickel was recovered in the first and fifth concentrate respectively i.e. ethyl xanthate cumulative nickel grade decreased with increased cumulative nickel recovery (Figure 1). Amyl xanthate recovered 17 and 14 % nickel in the first and fifth concentrate respectively thus amyl xanthate cumulative nickel grade increased with increased cumulative nickel recovery (Figure 1). These results showed that the selectivity of ethyl xanthate decreased with increase in flotation time while the selectivity of
amyl xanthate increased. The longer molecules have a stronger electron donating ability (Meilczarski et al., 1998). The amyl group is longer than the ethyl group. Therefore, the amyl group on PAX has a stronger electron donating ability than the ethyl group on SEX. This may have resulted in an increased reactivity on the oxygen atom in PAX compared to the one in SEX. The selectivity is a function of reactivity and the more reactive atoms are less selective (Meilczarski et al., 1998). The amyl group on PAX is more reactive than ethyl group on SEX, thus amyl group was expected to be less selective than its ethyl counterpart. In this work pure PAX showed constant selectivity towards nickel with respect to iron throughout flotation time (Figure 2). PAX had recovered a total of 27% nickel in the first concentrate. A total of 26% iron was also recovered in the first concentrate, which in turn reduced nickel grade. Thus, nickel grade in the first concentrate was 2.8% (Figure 3). This may have been due to a higher electron donating ability of amyl group than ethyl group.

Furthermore, pure ethyl xanthate in this work showed a higher selectivity towards nickel with respect to iron than amylyxanthate in the first three concentrates. Hence, SEX recovered 10% less iron than PAX, which in turn increased nickel grade (Figure 1). Consequently, ethyl xanthate yielded a higher nickel grade than PAX at the first concentrate. SEX yielded 3.0% nickel in the first concentrate compared to 2.8% yielded by PAX at the same time (table 1). However, amyl xanthate yielded a higher cumulative nickle grade than ethyl xanthate. This was due to consistent selectivity obtained with the use of amyl xanthate as borne out by the relationship between selectivity versus flotation time (Figure 2).

The effects of alkyl group attached to a pure collector on cumulative mass and water recoveries

The hydrophobicity of the collector is a function of the alkyl group on the collector molecule (Wills, 2006). The longer molecules form more hydrophobic agglomerates in the solution than the shorter molecules (Bloch, 2006). The agglomerates formed with PAX were more hydrophobic than agglomerates formed with SEX. Water recovery is a function of hydrophobicity and the more hydrophobic agglomerates yield less water than their less hydrophobic counterparts (Hangone et al., 2005).

PAX had a longer hydrophobic alkyl group and it formed more hydrophobic insoluble agglomerates in the flotation cell than SEX (Lotter & Bradshaw, 2010). These hydrophobic insoluble agglomerates may have increased the degree of bubble coalescence (Hangone et al., 2005). The increased degree of bubble coalescence reduced water recovery. Hence, the use of PAX yielded a lower water recovery than the use of SEX as borne out by the cumulative water recoveries (Figure 3).

Mass recovery is a function of reactivity of a collector’s functional group and the more reactive functional groups recover more mass (Meilczarski et al., 1998). As pointed out earlier, the amyl group on PAX is more reactive than the ethyl group on SEX. Thus, the amyl group was expected to recover more mass than its ethyl counterpart. This was borne out by higher mass recovery obtained by the amyl xanthate (Figure 3).

The degree of entrainment is directly proportional to water recovery (Bradshaw, 1997). The ethyl xanthate collector had a higher percentage cumulative water recovery compared to amyl xanthate (Figure 3). Also, there was a drop in nickel grade as obtained with the ethyl xanthate towards the end of flotation time. The higher water recovery yielded by ethyl xanthate may have resulted in a higher degree of entrainment. This higher degree of entrainment may have resulted in a decrease in nickel grade obtained with the use of pure SEX.

The effects of functional group attached to pure collectors on Klimpel rate constants

A collector’s attraction towards a mineral surface is a function of the mineral-collector agglomerate’s hydrophobicity in the pulp of a flotation cell. The collector agglomerates with a high hydrophobicity have a higher attraction rate towards the mineral surface. A higher attraction rate results in a higher collector adsorption rate on the mineral surface and the higher collector adsorption rates result in a higher flotation rates (Hangone et al., 2005).

The di-C\textsubscript{2}-DTP molecule has an extra hydrophobic ethyl group compared to SEX, thus it was expected to form extra hydrophobic agglomerates with pentlandite mineral surface compared to SEX. Thus, di-C\textsubscript{2}-DTP hydrophobic agglomerates were expected to have a higher attraction and flotation rates than SEX agglomerates. Consequently di-C\textsubscript{2}-DTP was expected to constitute to a higher Klimpel rate constant than SEX. However, di-C\textsubscript{2}-DTP yielded a lower Klimpel rate constant than SEX (table 1); this may be due to the extra ethyl group on di-C\textsubscript{2}-DTP collector molecule. Also, the reaction rate is a function of hydrophobic chain and electronic
interactions between the mineral surfaces and the collector molecules (Marabini et al., 2007). The hydrophobic chain and the electronic interactions are indirectly proportional. A higher hydrophobic chain interaction impairs electronic interactions. The di-C$_2$-DTP molecule has an extra ethyl group compared to SEX. Therefore, the extra ethyl group on di-C$_2$-DTP made it more hydrophobic and consequently less electronegative. Thus, electronegativity contribution may have nullified the effect of alkyl group hydrophobicity on the reaction rates and Klimpel rate constant.

**The effects of functional group attached to pure collectors on cumulative nickel grades and recoveries**

A collector’s attraction towards a mineral surface is a function of the mineral-collector agglomerate’s hydrophobicity in the pulp of a flotation cell. The collector agglomerates with a high hydrophobicity have a higher attraction rate towards the mineral surface. A higher attraction rate results in a higher collector adsorption rate on the mineral surface and the higher collector adsorption rates result in a higher flotation rates (Hangone et al., 2005).

A collector’s selectivity is a function of the inorganic functional group (Crozier, 1991). Oxygen on SEX has a higher electronegativity than phosphate on di-C$_2$-DTP. Oxygen is more prone to accepting electrons (Bradshaw, 1997), making it more reactive. As discussed earlier the more reactive atoms are less selective than their less reactive counterparts (Meilczarski et al., 1998). As discussed above, di-C$_2$-DTP was less selective than SEX. Thus, a low selectivity of di-C$_2$-DTP resulted in a drop in nickel grade. This was borne out by the relationships among cumulative nickel grades versus cumulative nickel recoveries as they showed that SEX yielded a higher nickel grade and nickel recovery than di-C$_2$-DTP (Figure 1).

The di-C$_2$-DTP was expected to yield a higher nickel grade than all the pure collectors based on a lower electronegativity value of its functional group (Lotter & Bradshaw, 2010). However, most dithiophosphates have inherent frothing properties (Adkins & Pearse, 1992). Thus, there might have been synergistic effects between the frother and di-C$_2$-DTP in the flotation cell. These synergistic effects may have changed the froth stability from meta-stable condition to over-stable condition. As pointed out in the literature review, over stable froths produce small bubbles. These bubbles are difficult to rupture; this poor bubble rupture leads to poor drainage (Wills, 2006) which impairs the selectivity as there would be minimal drop back of the entrained particles (Bradshaw, 1997). The relationships among selectivities of nickel to iron versus time showed that SEX had a higher selectivity than di-C$_2$-DTP (Figure 2). The pure di-C$_2$-DTP was expected to be more selective than SEX since phosphate on di-C$_2$-DTP is less electronegative than oxygen on SEX (Lotter & Bradshaw, 2010). However, SEX had one ethyl group attached to it compared to two on di-C$_2$-DTP. The two ethyl groups have a higher electron density than one ethyl group. Thus, the two ethyl groups may have nullified the effect of electronegativity of phosphate on reactivity and selectivity. A decrease in selectivity caused a decline in cumulative nickel concentrate grade. Hence, the final nickel recoveries obtained with use of SEX and di-C$_2$-DTP collectors were respectively 73% and 36% with the average nickel grades of 2.9 and 2.4% (Figure 1).

**The effects of the functional group attached to a pure collector on the cumulative mass and water recoveries**

The relationships among mass recoveries versus water recoveries showed that the use of SEX yielded a higher water recovery than the use of di-C$_2$-DTP (Figure 3). Two factors could have contributed to the low water recovery obtained with the use of di-C$_2$-DTP i.e. the presence of di-ethyl group and the presence phosphate on di-C$_2$-DTP molecule. The degree of hydrophobicity is a function of the alkyl group (Wills, 2006). Thus, diethyl on the di-C$_2$-DTP molecules made di-C$_2$-DTP agglomerates more hydrophobic than SEX agglomerates. Due to the higher hydrophobicity di-C$_2$-DTP formed more insoluble agglomerates in the flotation cell. Thus, less water was recovered with di-C$_2$-DTP than with SEX. Also, the DTC functional group has lower polarity than xanthate functional group due to lower polarity of phosphate on di-C$_2$-DTP than oxygen on SEX. Thus, di-C$_2$-DTP molecule would recover less water as its inorganic end would be more water repellent than SEX’s inorganic end. Mass recovery is the function of water recovery and selective flotation (Figure 3). The final cumulative water recoveries were 48% and 61% for di-C$_2$-DTP and SEX respectively. Consequently, the use of pure di-C$_2$-DTP yielded a lower mass recovery than the use of pure SEX as there was a decreased degree of entrainments in di-C$_2$-DTP flotation system due to a lower water recovery.
CONCLUSIONS

This study showed that concentrate grades and recoveries depended on the water recoveries and selectivity. The high water recoveries nullified the effects of selectivity. The high water recoveries nullified the positive effect of selectivity as the degree of entrainment is proportional to water recovery. The xanthates were more efficient than both di-C\textsubscript{1}-DTC and di-C\textsubscript{2}-DTP since higher cumulative nickel grades and cumulative nickel recovery were obtained by the use of PAX and SEX respectively. Therefore, it was not beneficial to use either di-C\textsubscript{1}-DTC or di-C\textsubscript{2}-DTP in the froth flotation of pentlandite ore. Thus, these collectors may not be able to replace xanthates as collectors in froth flotation of pentlandite ores.

ACKNOWLEDGEMENTS

First and foremost we would like to thank God for keeping us alive and for granting us the intellectual abilities which enabled the completion of this work. We are grateful for the role that Axis House and the staff, Mr. Jules Kitenge and Mr. Gonzalo Bernal, played in the success of this work. They provided the ore and the collectors, allowed us to use their X-Ray Florescent Spectrometer for assays.

REFERENCE


