A Determination of The Effect of Changing Collector Chain Length Under Varying Water Quality

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Abstract

The mineral processing industry needs to recycle process wastewater to decrease the detrimental effects of its discharge into the environment. This is of high importance in regions where water availability is restricted. Recycling process water leads to differences in water quality such as changes in pH, ionic strength (IS), and the concentration of total dissolved solids (TDS). The froth and pulp zones in the flotation cell work interactively to recover minerals and changes to water quality affect both zones. The factors affect the behavior of minerals and chemical reagents, impacting flotation performance.

According to literature, collector behavior can be impacted differently by certain ions. An increase in the IS and TDS of water can result in a decrease in mineral recoveries and grades. This is due to gangue and ions that either coat or create precipitates that passivate mineral surfaces, preventing collector adsorption. However, it is also known ions are capable of activating valuable minerals and gangue.

An increase in collector chain length leads to an increase in the strength of the collector due to an increase in hydrophobicity. However, this order of strength may be affected by pH and IS as these affect the collector adsorption. The selectivity of collectors increases with a decrease in the collector chain length. pH also affects the selectivity of collectors as an increase in pH results in a decrease in grade. However, the stability of collectors is independent of chain length. A high collector dosage may not imply an increase in flotation performance as there is a risk of over-dosage. This may result in other reagents being overpowered in the pulp, leading to decreases in grades and recoveries.

The first objective of this study was to investigate the differences in flotation performance when collectors of different chain lengths are used in synthetic plant water with increasing ionic strength. The second objective was to determine the interactive effects between collector chain length, collector dosage, and ionic strength of synthetic plant water on flotation performance.

To address the objectives, a two-phase factorial design of experiments was created, with Phase one utilising SEX and Phase two, SIBX. The factors selected for investigation were the collector chain length, dosage and the ionic strength of synthetic plant water. Batch flotation on a Merensky ore was utilised to obtain copper and nickel grades and recoveries which illustrated flotation performance. Additionally, batch flotation was used to obtain the entrainment factors of the two collectors at the different ionic strengths of SPW. Zeta potential measurements on chalcopyrite were utilised to determine changes to the mineral surface potential when the factors were varied. Sedimentation tests on the tails samples of the batch flotation tests provided information on the behaviour of the fines, and UV/Vis spectroscopy determined the concentration of residual xanthates present after flotation.

The study found that the longer chained collector, SIBX, behaved atypically to what has been observed in other studies. It obtained lower solids and recoveries than SEX in water with low ionic strengths. Furthermore, under these conditions, SIBX achieved the highest copper and nickel grades. Interestingly, as the ionic strength of the water increased, the trend was reversed. The copper recoveries were independent of the changes made to all the factors, however, the nickel recoveries did show slight variations. Both an increase in the ionic strength and collector chain length resulted in a decrease in the entrainment factor. Additionally, an increase in the ionic strength resulted in a less negative zeta potential. It was determined that there were interactive effects among the factors that were varied and concluded the factor with the largest impact on the flotation response (i.e. solids and water recovery and the recovery and grades of copper and nickel) was the ionic strength of the water.

These conclusions emphasise the importance of investigating the effects of recirculating water within the flotation process. The determination of the effects on flotation performance by different collectors under varying water quality will provide more knowledge into the optimisation of reagent usage in mineral processing in the presence of recycled water. Subsequently, this will provide plant operators with more control over the performance of the process as reagent control may compensate for changes in water quality.

Glossary of Terms

0 SPW	Tap water
3 SPW	Synthetic plant water with 3 times the concentration of inorganic ions
5 SPW	Synthetic plant water with 5 times the concentration of inorganic ions
C1	First concentrate collected at 2 min in a batch flotation experiment
C2	Second concentrate collected at 4 min in a batch flotation experiment
C3	Third concentrate collected at 6 min in a batch flotation experiment
C4	Fourth concentrate collected at 8 min in a batch flotation experiment
CMC	Carboxymethyl cellulose
DOW200	Dowfroth 200
DRIFT	Diffuse reflectance infrared Fourier transform method
Eh	Electrode potential
g/t	grams per ton
IS	Ionic strength
M	Molarity
mg/L	Milligrams per litre
min	Minutes
mL	Millilitres
mm	Millimetres
mol/L	Moles per litre
NFG	Naturally floatable gangue
Ni	Nickel
PGM	Platinum group metal
PAX	Potassium amyl xanthate
ppm	parts per million
rpm	Revolutions per minute
SEX	Sodium ethyl xanthate
SIBX	Sodium isobutyl xanthate
T1	First tails sample taken from the pulp after batch flotation
T2	Second tails sample taken from the pulp after batch flotation
T3	Sample taken from dried filtered tailings after flotation
TDS	Total dissolved solids
UCT	University of Cape Town
UV/Vis spectroscopy	Ultra violet-visible spectroscopy
XRF	X-ray fluorescence
XPS	X-ray photoelectron spectroscopy
μm	Micro-metres

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1. Introduction

1.1 Background

It is estimated that 5% of South Africa's water supply is utilised in the mining industry. Mineral processes such as comminution, leaching and flotation produce process wastewater that contains pollutants. If this water is disposed of into the environment, it can be toxic to biota. Therefore, to decrease the wastage of water and mitigate pollution from mineral processing, this wastewater can be recycled within the processes. Recycling, however, leads to changes in water quality as an accumulation of total dissolved solids (TDS), residual reagents, and changes to the pH and ionic strength (IS).

In froth flotation, the success of the process is highly affected by the pulp chemistry as separation is dependent on the mineral surfaces' affinity to water. 80-85% of the pulp is water, therefore, changing the water quality impacts the chemistry of the pulp. This in turn affects the mineral interactions and behaviour of chemical reagents in the process, altering flotation performance in ways that may be unpredictable. Reagents can be used to improve flotation performance and mitigate the effects of changing water quality. This will ensure the mineral processing industry optimises their processing techniques, whilst improving its environmental sustainability.

1.2 Problem Statement

Recycling process water within flotation can decrease the pollution caused by the mineral processing industry. However, the resultant changes in water quality impact flotation factors such as pulp chemistry, subsequently affecting flotation performance. Water quality also affects the behaviour of reagents such as depressants, modifiers and collectors. Collectors are required to alter the hydrophobicity of the mineral surfaces and increase grades and recoveries. Different dosages and collector chain lengths, however, will have different impacts on the flotation performance. Therefore, to optimise the usage of collectors, their effect on flotation performance under varying water quality needs to be determined.

1.3 Aim

This study aims to investigate the effects of using collectors of different chain lengths in water with varying ionic strengths on flotation performance. The study also aims to determine if there are any interactive effects amongst collector chain length, collector dosage, and increasing ionic strength.

1.4 Scope and Limitations

The factors that affect flotation can be categorised in three ways as shown in Figure 1.1 (Klimpel, 1995). This study kept all the factors under equipment and operation constant. These factors were selected based on previous studies that investigated varying water quality and standard laboratory batch flotation practices utilised by the Centre for Minerals Research Group (CMR) at the University of Cape Town (Manono et al., 2012; Wiese, 2009).

The scope of this study was limited to changes to the factors in the chemistry of the flotation process, i.e. the variation of the collector chain length, dosage and ionic strength. The collector type was limited to xanthate collectors. A depressant and frother were used and kept at a constant dosage throughout the batch flotation experiments. To conduct entrainment tests, the depressant was increased to 300 g/t to obtain the entrainment factors (Wiese et al., 2005). The depressant and frother type was kept constant throughout the study. Furthermore, no activators or pH modifiers were used.

The batch flotation tests conducted on a Merensky ore were complemented by zeta potential tests that measured the surface potential of chalcopyrite.

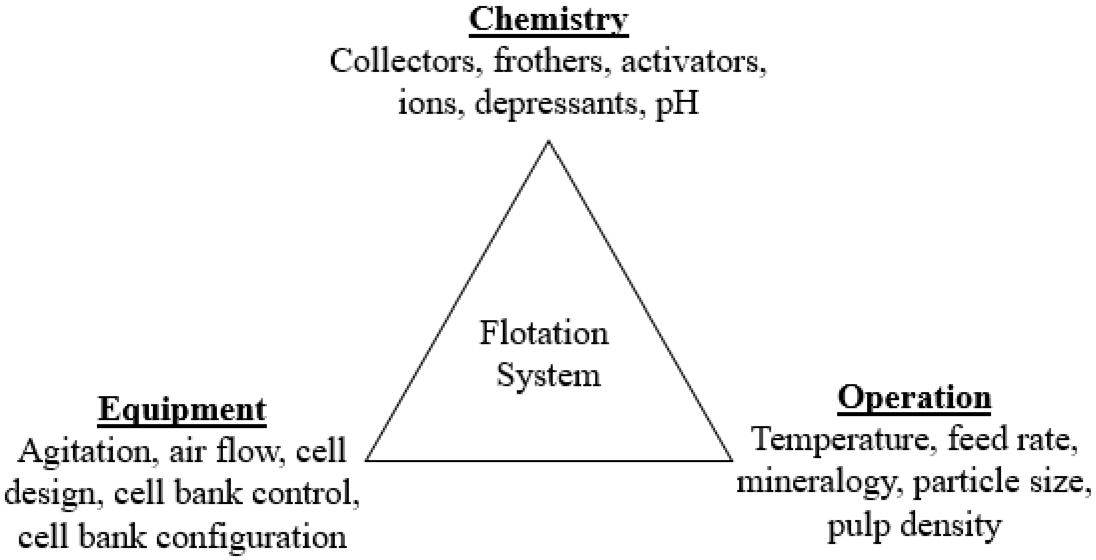


Figure 1.1: Schematic summarising the factors that affect flotation performance (adapted from Klimpel (1995))

2. Literature Review

2.1 Froth Flotation Principles

Flotation is used in the mineral processing industry to recover valuable sulfide minerals from their ores (Kohad, 1998; Bradshaw, 1997). Froth flotation is a separation technique that utilises the differences in the hydrophobicity of particle surfaces to extract the desired particles. Wastewater treatment, recycling, and mineral processing all utilise this process (Rao, 2004).

To prepare the ore and liberate the minerals for the flotation process, the ore undergoes crushing in comminution. To get the correct grinding size, a slurry is formed and the ore is milled, once milling is completed, the slurry is transferred to the flotation cell. Air is bubbled through the slurry and it is agitated with an impeller. After a set conditioning time, reagents are added to the pulp to alter the pulp chemistry (Suli et al., 2017). The pulp chemistry affects the hydrophobicity of the mineral surfaces and therefore, determines their interactions with the air bubbles (Senior et al., 1995; Wills and Napier-Munn, 2006). The flotation pulp is typically comprised of 80-85% water (Muzenda, 2010).

Figure 2.1 shows the distinct zones that are in the flotation cell, i.e. the froth zone and the pulp zone. The process recovers mineral particles via three distinct mechanisms; true flotation, entrapment and entrainment (Kawatra, 2002; Qiu et al., 2022; Wang et al., 2016). The pulp zone is where the collector molecule selectively adsorbs onto the surface of the mineral, rendering it hydrophobic. These hydrophobic minerals attach to air bubbles and travel upwards through the pulp to the froth zone via true flotation (Kawatra, 2002).

Depressants increase the hydrophilicity of the natural floating gangue, keeping them in the pulp zone, and improving the concentrate grade (Wiese et al., 2005). However, when hydrophilic gangue gets trapped within hydrophobic particles, this mechanism that results in their transportation to the concentrate is defined as entrapment (Qiu et al., 2022).

Entrainment is defined as the mechanical transfer process by which particles in the pulp phase enter the froth phase and leave with the minerals that were transported via true flotation (Wang et al., 2016). Gangue minerals are typically recovered in the froth phase via entrainment, therefore, to increase the recovery and grade to industrial standards, multiple flotation stages are required (Wills and Napier-Munn, 2006).

The concentrate is then collected from the froth zone which is an air-water interface. Multiple factors affect the stability of the froth, which is important to support the minerals so that they can be recovered (Wills and Napier-Munn, 2006).

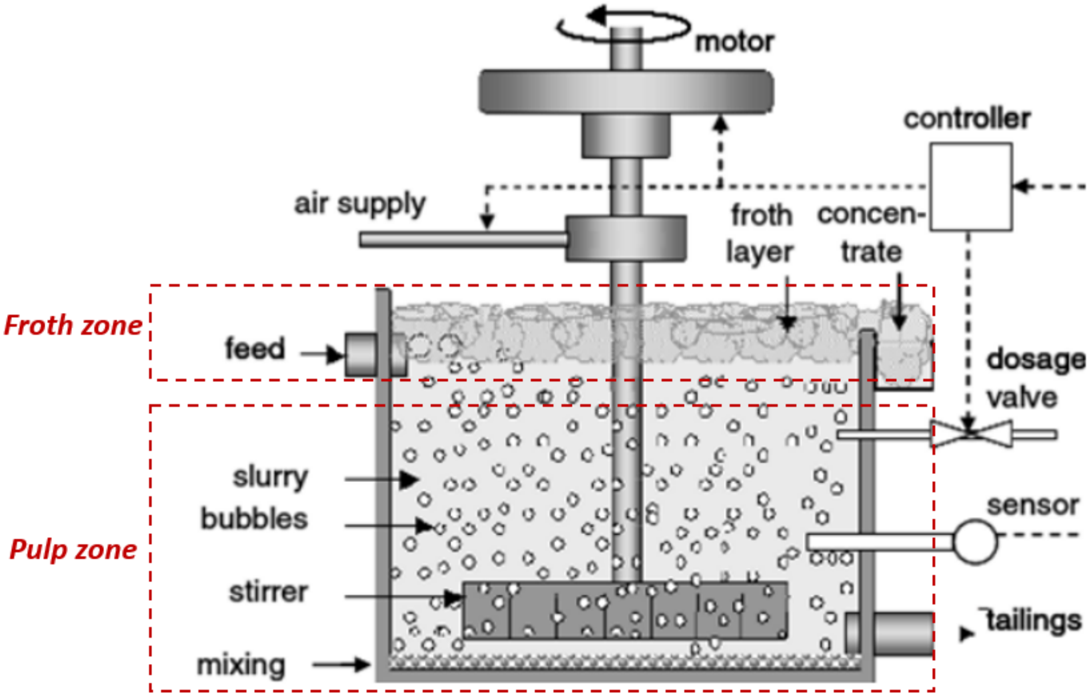


Figure 2.1: Schematic of the flotation process adapted from Suli et al. (2017)

2.2 Flotation Reagents

To manipulate the hydrophobicity of the surfaces of the minerals and alter the pulp chemistry, flotation reagents are required (Kawatra, 2002). The main reagent types include regulators, frothers, and collectors (Manono et al., 2018).

2.2.1 Regulators

Barbaro (2000) found the difficulty of floating a specific mineral increased when the mineral is in a mixture of other minerals in the same sulfide class. To improve the specificity of the collector (Section 2.3), the usage of regulators is required (Wiese et al., 2005). Examples of regulators include activators, depressants, and pH modifiers. These alter the pulp chemistry and mineral surface conditions, therefore, enhancing the performance of the collector (Kohad, 1998).

Activators in flotation encourage adsorption of collectors onto mineral surfaces by modifying the surface properties through chemical or physical interactions. They adjust the surface charge, form chemical complexes, or alter surface hydrophobicity to enhance collector attachment. These actions promote effective flotation separation by increasing the affinity between the desired mineral particles and the collectors used (Kawatra, 2002). Examples of activators include copper sulfate and lead ions (Wiese et al., 2005). The role of depressants, however, is to increase the hydrophilicity of gangue material (Bradshaw et al., 1998). Examples of depressants include sodium silicate and carboxymethyl cellulose (CMC) (Dimou, 1982). The pH level of the pulp requires control as it affects the efficiency of the flotation process (Goktepe, 2001). To regulate the pH level of the pulp, pH modifiers such as lime and soda ash are utilised (Dimou, 1982).

2.3 Collectors

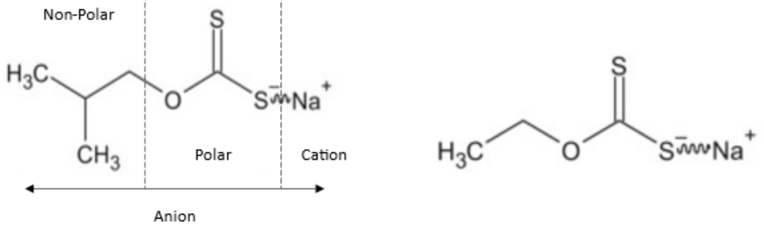
Collector molecules consist of a hydrophilic polar group that attaches to the surface of the mineral and a hydrophobic group that is oriented to the bulk solution. The collector molecules form a monolayer on the mineral of these thin hydrophobic hydrocarbons. These hydrophobic hydrocarbons enhance the hydrophobicity of the mineral (Kawatra, 2002). Therefore, the choice of the collector is important as it affects the contact angle, altering the ability of the mineral to adhere to the bubbles in the froth (Dimou, 1982).

2.3.1 Collector Types and Dosage

Collectors are classified by their charge, i.e. whether they are ionising or non-ionising (Kawatra, 2002). This affects both their molecular structure and their interactions with water. Ionising collectors contain a polar and non-polar end. The charge of the polar end determines whether the collector is anionic or cationic (Wills and Napier-Munn, 2006). Anionic collectors are then further divided into sulfhydryl and oxyhydryl groups. Collectors either adsorb to the mineral surfaces via chemisorption or physisorption (Xie et al., 2016). Physisorption is reversible and occurs when the collector physically adsorbs via hydrogen bonding or Van Der Waal's forces. Chemisorption occurs when the collector covalently bonds with the mineral surfaces. This is irreversible and more selective than physisorption as chemical bonds require specific atoms. The thiol compounds in sulfhydryl collectors enable them to form chemical bonds with sulfide mineral surfaces, making them the most selective in the flotation of sulfide minerals (Kawatra, 2002). Xanthate collectors are the most utilised sulfhydryl collectors in sulfide mineral flotation (Wills and Napier-Munn, 2006).

The management of the dosage of collectors is another important aspect of flotation. Langa et al. (2014) utilised sodium isobutyl xanthate (SIBX) at different dosages to float Palabora copper ore. The results showed that the highest recovery was not obtained with the highest dosage. The study also found the grades recorded were the lowest for the two highest collector dosages. This was due to overdosing of the collector which resulted in a decrease in selectivity. This led to a decrease in the grade due to the amount of collector overpowering depressant action. The collector then adsorbed onto the gangue material, resulting in gangue appearing in the concentrate. Aside from a decrease in flotation performance, overdosing results in the wastage of the collector that negatively impacts the economics of the process.

As shown in Figure 2.2, the xanthate non-polar end consists of a hydrocarbon chain that can contain one to six carbons. An increase in the number of carbons results in a decrease in the solubility of the collector and and an increase in the hydrophobicity of the molecule (Feng et al., 2012; Wills and Napier-Munn, 2006). This affects the characteristics of the collector such as the strength, stability, and selectivity (Mielczarski et al., 1998). These factors affect the recoveries and grades achievable by the collector and the dosages required. These characteristics are discussed further in the following sections.



Sodium iso-butyl xanthate

Sodium ethyl xanthate

Figure 2.2: Sodium iso-butyl xanthate and sodium ethyl-xanthate molecule adapted from Wills and Napier-Munn (2006)

2.3.2 Strength of Collectors

A study utilised micro-flotation to compare collectors, namely, sodium ethyl-xanthate (SEX) to potassium amyl-xanthate (PAX) on the flotation of multiple sulfide minerals (Goktepe, 2001). According to Goktepe (2001), the order of the strength was found to be amyl > isobutyl > isopropyl > ethyl xanthates. This was explained by an increase in hydrophobicity that increases the efficiency of air bubble attachment as there is a larger contact angle (Mielczarski et al., 1998). In the flotation of pyrite, PAX resulted in the highest recoveries due to this increased hydrophobicity at pH levels above 8. At low pH levels, SIBX recovered the most pyrite, opposing the previously observed pattern. SEX, however, consistently performed poorly at recovering the pyrite at all pH levels, remaining the weakest collector.

Eh/pH diagrams from a study by (Janetski et al., 1977) explained that this decrease in the floatability of pyrite was due to the pyrite surface oxidising more readily than the xanthate.

Goktepe (2001) found that in the flotation of chalcopyrite, at a pH level of 4, sodium isopropyl xanthate (SIPX) had the highest recovery. In the median pH range, SIPX had the lowest recoveries. SEX also achieved higher recoveries than SIBX at pH levels below 5. This implies either the mineral surface or the pH of the system affects the collector behaviour and may have an effect on the pattern of strength previously observed.

However, a study that compared the adsorption of PAX and SEX on the flotation of chalcopyrite obtained results that conflicted with those found by Goktepe (2001) (Xie et al., 2016). According to this study, the order of strength of the collectors is controlled by the collector chain lengths as this affects their bonding energies. This was done by investigating the surface coverage (Γ) of the collectors on the minerals to compare the strength of the collectors. PAX had a greater bonding energy with respect to the cuprous-xanthate bond that formed on the mineral surfaces. The study also investigated the competitive adsorption of the collectors. PAX was added to a solution of SEX that had previously adsorbed on the surface of the mineral. As shown in the insert of Figure 2.3, the SEX begun to reappear as more PAX was added to the solution. It was found that SEX was susceptible to desorption and replacement by the PAX. This was due to the higher bonding energy that the PAX had with the mineral surface. Taguta et al. (2017) calculated the heat of formation of cuprous-xanthate complexes and the binding energy of SEX and PAX. The results confirmed the findings of Xie et al. (2016).

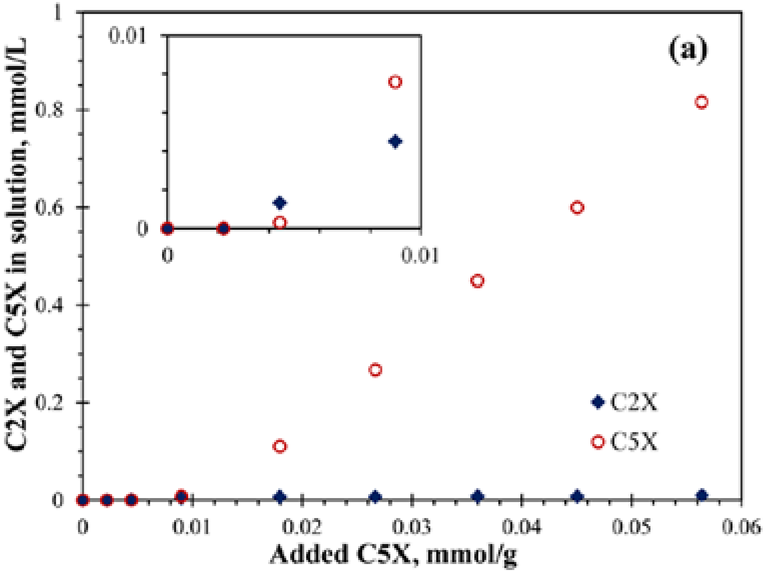


Figure 2.3: Desorption of SEX by PAX from Xie et al. (2016)

Feng et al. (2012) investigated the difference in flotation performance of collectors of different chain lengths on a Jinchuan sulfide ore. In addition to varying the collector chain length, the conditioning time was changed. The results confirmed the findings by Xie et al. (2016), with the potassium octyl-xanthate (POX) achieving a recovery of up to 10% higher than potassium isobutyl-xanthate (PIBX) under the different conditions.

2.3.3 Selectivity of Collectors

A study by Ikotun et al. (2017) compared the collector action of PAX, SIBX, and SEX in the flotation of a low-grade nickel sulfide ore. As shown in Figure 2.4, PAX obtained the lowest nickel grade, whilst SEX achieved the highest nickel grade of above 7%. (Mielczarski et al., 1998) explained this to be due to shorter chains being more able to form insoluble metallic ionic compounds than the longer-chained collectors. This results in higher selectivity of the shorter chained collectors to valuable minerals as they demonstrate a greater affinity for nickel-bearing mineral surfaces compared to other minerals in the flotation system.

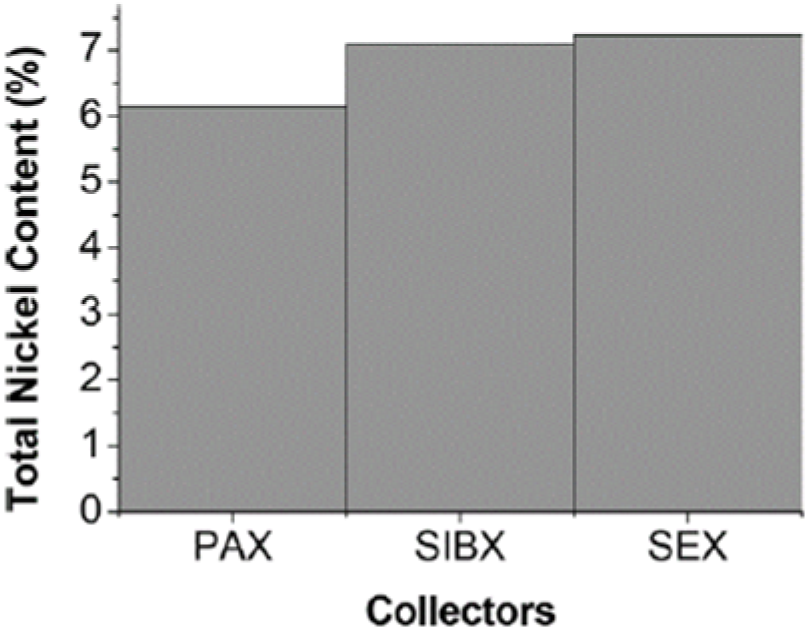


Figure 2.4: Grades obtained for different chained collectors (Ikotun et al., 2017).

This pattern was also observed in another study that found, although the shorter chained collectors were weaker than longer chains, their lower insolubility in water increased their selectivity for the target mineral (Kim et al., 2000).

Studies also showed the selectivity of collectors could be altered by a change in the pH level of the system (Goktepe, 2001). Kim et al. (2000) found that longer chained collectors were more selective in acidic conditions due to a change in their activity. Other studies have observed this change in activity was more pronounced for long-chained collectors (Karlkvist, 2017). This implies that results obtained with longer chained collectors may be more vulnerable to change under differing flotation conditions.

2.3.4 Stability of Collectors

It is important to control the decomposition of xanthates as some of its decomposition products, e.g. carbon disulfide are toxic and are a health hazard. The pH and temperature of the pulp have the largest effect on the stability of the collector. Other factors that have a minor effect on collector stability include the residence time and the amount of UV- light rays going through the pulp. The rate of decomposition of xanthates has been found to increase in acidic conditions (Özün and Ergen, 2019). At low pH levels, the xanthates decompose to form carbon disulfide (Equation 2.1). However, in alkaline conditions, multiple reactions can occur leading to multiple decomposition products. Examples of these decomposition products include dixanthogen (Equation 2.2), perxanthate and mono/ dithio carbonates.

$$RO \cdot CS \cdot SNa + H^{+} \longrightarrow R \cdot OH + Na^{+} + CS_2 \tag{2.1}$$

$$2RO \cdot CS \cdot SNa + H_2O + 0.5O_2 \longrightarrow ((ROCS_2)_2) + 2NaOH \tag{2.2}$$

Xie et al. (2016) conducted a study to compare the rate of decomposition between PAX and SEX. This was done at different pH levels and the results obtained were the same in each case. As seen in Figure 2.5, the rate of degradation did not significantly differ between the two collector types. Although the SEX appears to decompose slightly more than the PAX, it was determined that this difference was negligible and the decomposition of xanthates was independent of chain length.

These studies all provided deeper insight into the patterns observed on flotation performance when collectors of different chain lengths were used. However, aside from pH, all these studies were under standard flotation conditions that did not vary the water quality. Various changes in water quality such as TDS, IS and dissolved oxygen can also affect collector adsorption. These factors are discussed further in the following section.

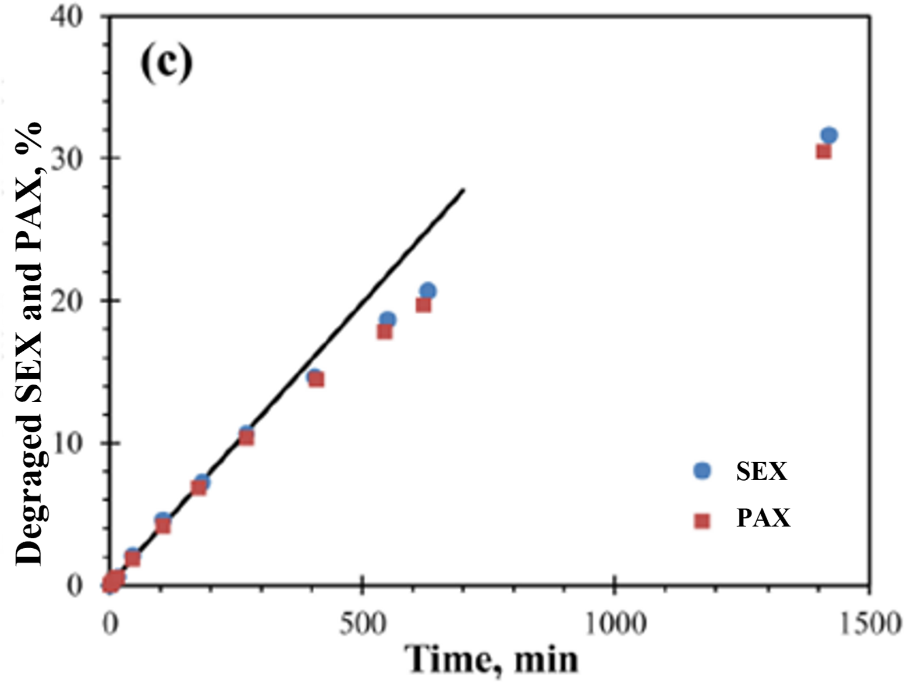


Figure 2.5: Rate of decomposition of xanthate collectors with different chain lengths (Xie et al., 2016)

2.4 Water Quality

The water quality of process water changes with every recycle. There is an increase in the concentration of residual reagents, ionic strength, pH, and total dissolved solids (TDS). The dissolved oxygen levels in the pulp, however, decrease (Sheni et al., 2018). These factors alter the pulp chemistry of the water which affects the interactions with the surfaces of the minerals, affecting flotation performance. In a study by Muzenda (2010) that compared the flotation of PGMs in potable water and recycled water, both the grades and recoveries were affected by changes to the water quality. The recycled water was from multiple sources such as sewerage and tailings dams. The potable water achieved the highest recoveries, but the lowest grades in comparison to the concentrate. This difference in grade was explained to be due to the presence of residual reagents, specifically depressants, that may have increased the grade of the recycled water but negatively impacted the recovery.

The presence of residual reagents can be seen as beneficial as it may lower the consumption of fresh reagents, improving the costs associated with the process (Xie et al., 2016). However, in the case of collectors, there may be negative effects as it could lead to overdosing in the flotation pulp (Langa et al., 2014).

However, other factors such as the IS, concentration of TDS, and pH may also have had an impact on the flotation performance (Muzenda, 2010).

2.4.1 Ionic Strength

The ionic strength is defined as a measure of the concentration of ions in a solution (Muzinda and Schreithofer, 2018). Increasing the ionic strength of water leads to an increase in mass pulls and water recoveries due to an increase in froth stability. Corin et al. (2011) found that the increase in froth stability increased the amount of gangue recovered, leading to a decrease in the grade observed. However, the study also found the recovery of sulfide minerals was unaffected by increasing the ionic strength.

Studies also found certain ions can affect mineral surfaces differently. Muzenda (2010) found that as the ionic strength of the water increased, the presence of metal ions such as Ca^{2+} and Mg^{2+} activated the gangue materials. This increased the amount of gangue that reported to the concentrate decreasing the grade. Therefore, certain ions can act as modifiers and activate or depress certain particle surfaces. This has a potential to affect the ability of the collectors to adsorb onto the minerals.

These observations were confirmed in another study where galena was activated by silver ions. Therefore, during the comminution stage that used recycled water with an increased concentration of silver ions, lead was released. Lead can form complexes with the xanthate molecule, forming precipitates which are typically classified as TDS. These lead precipitates coated the valuable minerals, decreasing collector adsorption, and decreasing the recovery (Özlem Biçak, Ekmekçi, Can and Öztürk, 2012). Studies observed copper, magnesium, and iron ions activate quartz in the gangue. The level of activation was enhanced by an increase in the pH level, decreasing the grade of the concentrate (Coetzer et al., 2003).

It was also observed that the increased presence of zinc ions depressed the sphalerite and the maximum recovery achievable was only 25%. This is due to the colloid precipitates formed by zinc ions that coat the mineral surface decreasing the effectiveness of the collector. Mg^{2+} were observed to have the same effect when the pH level was increased. This is due to the formation of hydroxide precipitates (Coetzer et al., 2003).

However, Coetzer et al. (2003) also found an increase in the IS of copper ions activated the sphalerite surface increasing its recovery to 89%. This was confirmed by (Bulut and Yenial, 2016) that also investigated the flotation of sphalerite and found the grade and recovery increased when copper ions were introduced to the solution. These activated the sphalerite surface decreasing its passivity resulting in an improvement in collector adsorption and flotation performance. In addition to either activating or depressing minerals, certain ions impact the adsorption of collectors to different degrees. Ikumapayi et al. (2012) conducted zeta potential studies on chalcopyrite, galena, and sphalerite minerals. The ionic strengths of calcium and sulfate species were varied in simulated water and compared to the behaviour of tap, deionised, and process water. The results showed that the addition of 300 mg/L of calcium ions to a solution containing sulfate ions led to a sharp increase in the zeta potential observed. However, with the addition of sulfate ions to a solution with calcium ions, there was no change in zeta potential. Therefore, the original ionic composition of the recycled process water may affect the ability of the collectors to adsorb efficiently.

Voltammetric studies that investigated the effect of specific ions on pentlandite and pyrrhotite surfaces agreed with these findings (Hodgson and Agar, 1989). Multiple ions were investigated, however, only calcium, sulfate, and thiosulfate ions had an effect on the surfaces of the minerals. Hydrophobicity tests found only calcium ions affected the pyrrhotite surface, to the degree that a higher collector dosage was required to achieve the same hydrophobicity. However, the pentlandite mineral surface was more affected by the ions as both the thiosulfates and calcium ions were competing with the collector for adsorption.

In addition to creating precipitates, the presence of certain ions can encourage the coating of minerals with gangue. The zeta potential of pentlandite reversed once magnesium ions were added to the solution (Alvarez-Silva et al., 2016). This implied the main serpentine gangue had coated the valuable mineral surface.

A study by Corin and Manono (2020) investigated the usage of recycled water in the preparation of reagents. When the ionic strength of the water increased and it was used in the make-up of depressant, the depressant's ability to adsorb was suppressed. Therefore, a decrease in nickel recovery and grades were observed. When used in the make-up of the collector, an increase in the stability of the froth and mass and water recoveries were observed. The usage of varying water quality in the preparation of reagents had similar effects to varying the water quality of the pulp.

2.4.2 Total Dissolved Solids and Total Suspended Solids

TDS and total suspended solids (TSS) include any precipitates, gangue minerals, and metals that are present in the water (Oram, 2019). FTIR and XPS studies showed evidence that calcium carbonate is capable of coating chalcopyrite, decreasing the collector's access to the mineral surface (Ikumapayi et al., 2012). The formation of $CaCO_3$ was due to carbon dioxide in the pulp reacting with the added calcium ions (Ikumapayi et al., 2012). Hodgson and Agar (1989) found the formation of hydrophilic layers on the minerals' surfaces by copper, iron, and iron hydroxyl species that were present in the pulp. Galena was found to be susceptible to coating by lead hydroxide precipitates that were formed during comminution with recycled water (Coetzer et al., 2003). These studies all found that precipitates compete with the collector for adsorption and have a negative impact on flotation.

Muzenda (2010) found potable water had the highest recovery in comparison to the recycled water samples. This potable water contained neither TDS nor TSS, therefore, it was concluded that these may form colloidal particles that attach to the mineral surfaces, decreasing the hydrophobicity of the valuable minerals. This would result in the now hydrophilic minerals being lost in the tailings with the gangue, leading to a decrease in the recovery. Silica, calcium sulfate, magnesium carbonate, and calcium hydroxide also exhibit similar behaviour to this, coating multiple types of valuable minerals, preventing collector adsorption, and decreasing their recovery (Coetzer et al., 2003)

Gangue minerals such as serpentine can coat valuable minerals such as pentlandite in the presence of certain ions, e.g. magnesium ions. Evidence of this was shown in zeta potential studies conducted by Alvarez-Silva et al. (2016).

2.4.3 Changes in pH

The pH of process water increases as it is recycled due to an increase in the concentration of hydroxyl ions (Muzenda, 2010). A study that investigated the effect of pulp chemistry on froth stability found an increase in pH improves the froth stability which leads to higher water recoveries (Sheni et al., 2018). The solids' recovery, however, is negatively affected by the increase in pH as there is passivation on the surfaces due to the increased presence of hydroxyl ions. The passivation hinders the adsorption of the collector onto the mineral surfaces (Ikumapayi et al., 2012).

Figure 2.6 shows Manono et al. (2018) found at low IS, a pH of 11 obtained a higher water recovery than at pH 9. However, as the IS increased, the differences in the water recoveries between the two pH levels decrease. At the highest IS tested, the water recovery was higher for pH 9 than it was for pH 11, conflicting Sheni et al. (2018). This difference may be due to pH having a dominant effect at low IS, and IS having an increase in its effect as IS increases. Therefore, this may imply there is a decrease in the effect of pH on water recovery as water is recycled.

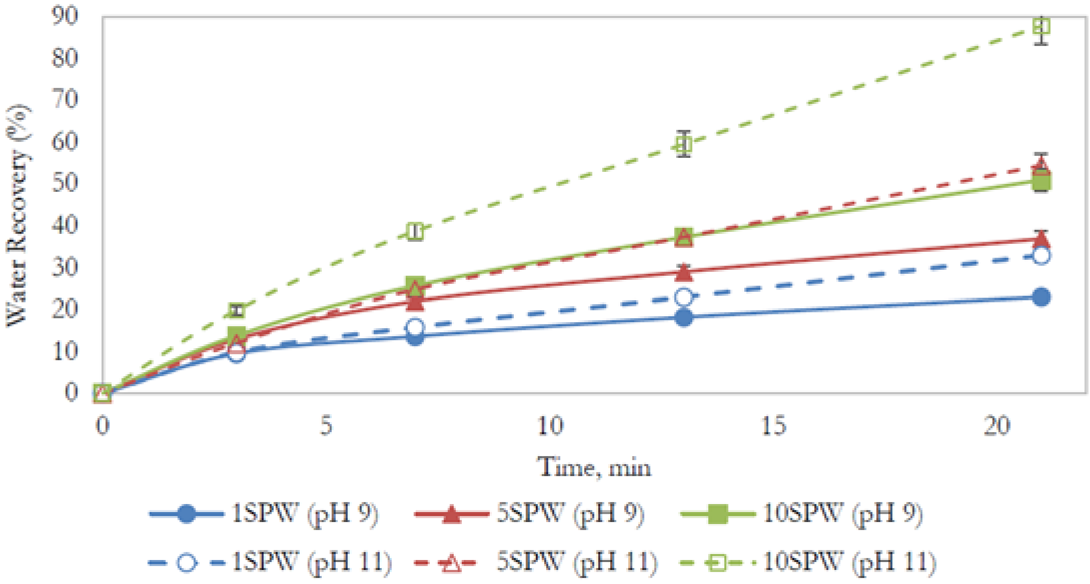


Figure 2.6: The effects of ionic strength and pH on water recovery as a function of time Manono et al. (2018)

Ikumapayi et al. (2012) compared the flotation of different minerals in deionised water and process water whilst varying the pH from 2 to 12. The study found higher recoveries at lower pH levels than those above 9. The zeta potential of the chalcopyrite also became increasingly negative across the pH levels in each water sample. This shows that there are ions that adsorb onto the chalcopyrite surfaces, and the increase in pH enhances this adsorption. These ions prevent collector adsorption, decreasing recovery. This was reinforced by the XPS and DRIFT results that showed sulfoxyl and carbonate species coated on the partially oxidised surfaces. However, Goktepe (2001) contradicted these findings by Ikumapayi et al. (2012) as the study found the chalcopyrite recovery to be independent of pH. The study speculated the reason for these results was due to the mineral surface, however, it concluded that further investigation would be required.

Hodgson and Agar (1989), found the dosage of collector required to float pyrrhotite and pentlandite increased with an increase in pH. This shows the collector became less effective with the increase in pH. Simultaneously increasing the pH and IS of the water resulted in a significant increase of xanthate collector required. Therefore, both an increase in IS and pH level negatively affect the strength of the collector.

Ikotun et al. (2017) found that at a pH level of 11.65, there was a decrease in grade in comparison to a pH of 9.65. This was attributed to the selectivity of the collector decreasing with an increase in pH. Kim et al. (2000) observed similar results and found acidic conditions resulted in a more selective collector due to a decrease in the collector ions concentration in the pulp as the xanthates dissociated less.

Therefore, the pH of the water may affect both the strength of the collector and its selectivity.

2.5 Sulfide Ores

This study utilises an ore from the Merensky reef, South Africa. Three main ore bodies, the Platreef, UG2 reef, and Merensky reef are in the Bushveld Igneous Complex (BIC) (Barnes and Maier, 2002). The BIC contains the world's largest Platinum Group Mineral (PGM) reserves (Figure 2.7). The PGMs present include sperrylite, braggite, and cooperite. The Base Metal Sulfides (BMS) present in the reef include approximately 30% pentlandite, 40% pyrrhotite, and 15% chalcopyrite with trace amounts of pyrite and cubanite (Cawthorn and Boerst, 2006). The ore contains gangue in the form of silicate minerals such as talc, plagioclase feldspar, pyroxene, and approximately 60% orthopyroxene. Talc is present in trace amounts; however, it is classified as natural floating gangue (NFG) and may be found in the concentrate (Barnes and Maier, 2002).

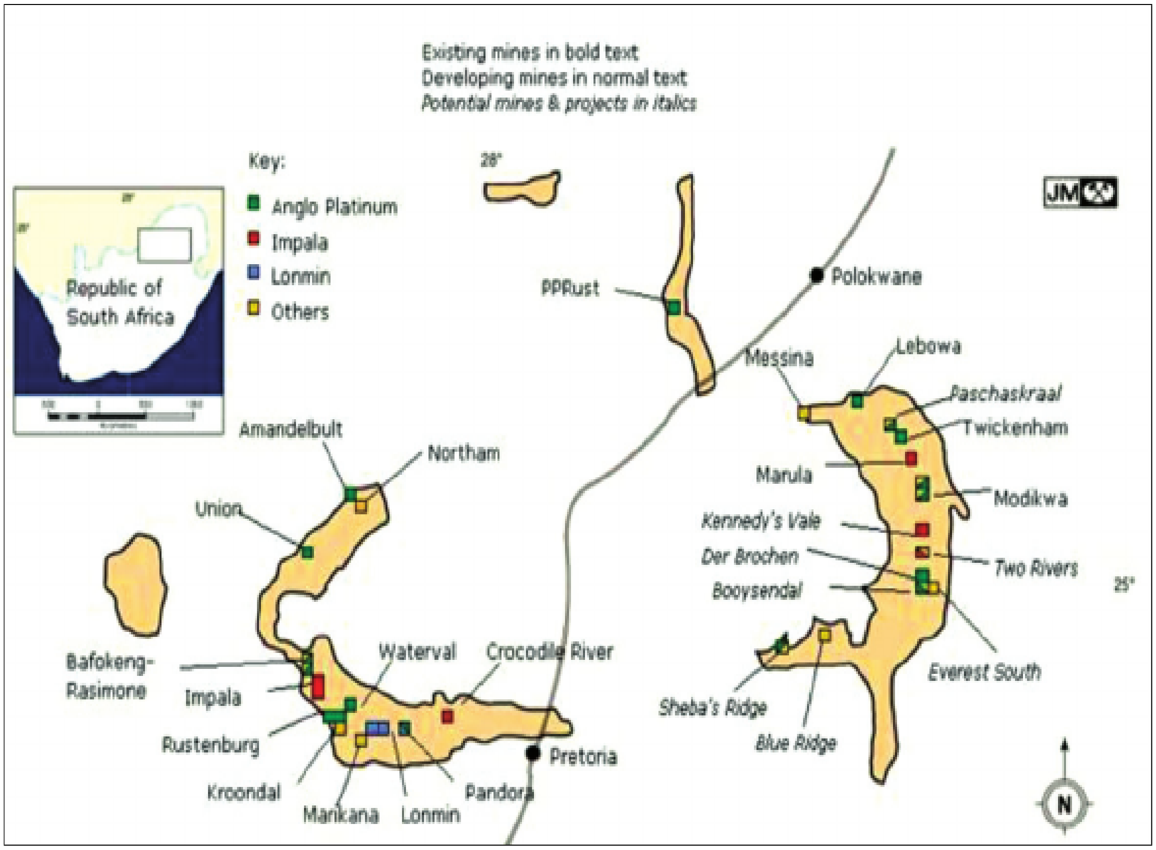


Figure 2.7: Schematic map of the Bushveld Complex Platinum Mines from Nelson (2013)

2.6 Summary of Findings

The summary of the findings obtained from the literature is as follows. The recoveries and grades obtained in flotation are affected by the collector type and dosage selected. The hydrocarbon chain length of collectors affects their strength and selectivity, which impacts the collector choice and dosage. An increase in collector dosage does not imply there will be an increase in recoveries and grades as there is a risk of overdosage in the system. This will result in other reagents being overpowered in the pulp, leading to decreases in grades and recoveries (Langa et al., 2014).

The order of decreasing strength of collectors with different chain lengths observed in literature is amyl > isobutyl > isopropyl > ethyl xanthates. This is due to the increased hydrophobicity that causes a more efficient bubble attachment of the particle (Goktepe, 2001). However, this order of strength may be affected by pH and IS as these affect the collector adsorption (Ikumapayi et al., 2012). The selectivity of collectors increases with a decrease in collector chain length due to the formation of insoluble metal compounds (Ikotun et al., 2017). pH affects the selectivity of collectors, with the grades obtained by longer-chained collectors appearing more vulnerable to change than those from shorter collectors (Ikotun et al., 2017). Collectors decompose to form carbon disulfide in acidic conditions but form other products such as dixanthogen in alkali conditions (Özün and Ergen, 2019). Their stability, however, is independent of chain length (Xie et al., 2016).

Studies showed changes in water quality affect both the pulp and froth zones, thereby impacting flotation performance (Muzenda, 2010). An increase in the IS and TDS of water results in a decrease in recoveries. This is due to ions that either coat or create precipitates that coat mineral surfaces, preventing collector adsorption. Ions can either activate or depress the minerals and gangue. Collector behaviour can be impacted to different degrees in the presence of certain ions. The froth is stabilised by the change in IS and TDS resulting in higher water recoveries (Sheni et al., 2018)

pH increases as water is recycled, thus leading to lower mineral recoveries due to the passivation of mineral surfaces (Ikumapayi et al., 2012). Studies showed the effect of pH on flotation performance is more dominant at low ionic strengths but decreases as the IS increases (Manono et al., 2018). At high IS, pH does not have as large an impact as the IS. There are interactive effects between pH and IS as an increase in both substantially impacted the collector dosage required. Therefore, it is possible for other interactive effects amongst the variables to exist.

The majority of studies illustrating the behaviour of collectors with different chain lengths were conducted under baseline flotation conditions i.e. non-recycled process water. Goktepe

(2001); Ikotun et al. (2017) investigated a few pH levels but some of the results were not explained and recommended for future investigation. However, these studies did show the vulnerability long-chained collectors had to changes in flotation conditions. Therefore, there is a need to further understand the effect of these different chained collectors in different water qualities.

3. Objectives, Hypothesis and Key Questions

3.1 Objectives of the Study

The objectives of this study are to:

- Investigate the differences in the recoveries and grades of copper and nickel from a Merensky ore when collectors of different chain lengths are used in synthetic plant water with increasing ionic strength.
- Determine the interactive effects between collector chain length, collector dosage, and ionic strength of synthetic plant water on the recoveries and grades of the target minerals from a merensky ore.

3.2 Key Questions

The following are the key questions in this study:

- How do collectors of different chain lengths impact flotation performance when used in process water with increasing ionic strength?
- How does increasing the collector dosage impact flotation performance when used in process water with an increase in ionic strength?
- Are there interactive effects amongst collector chain length, collector dosage, and the ionic strength of process water?
- Amongst the variables, i.e. collector chain length, collector dosage, and the ionic strength of process water, which factor has the largest impact on the flotation performance?

Flotation performance in this study is defined as the recoveries and grades of the copper and nickel from the flotation of a Merensky ore.

3.3 Hypothesis

The simultaneous usage of a longer chain collector, higher collector dosage, and recycled water results in a higher recovery of solids and a lower grade of concentrate. This is due to:

- the increased strength of longer chains, which are less selective for valuable minerals i.e. chalcopyrite and pentlandite. Merensky ore is a PGM ore, however, chalcopyrite and pentlandite are associated with the PGMs and can be used as a proxy for PGM recovery (Moimane, 2015).

- the increased ionic strength of the water owing to the increase in dissolved ions with increased process water recycling, which may coat the mineral surface in preference to the collector, decreasing its adsorption. Recycled water in this study was simulated by Synthetic Plant Water (Section 4.2.3)
- the higher collector dosage which may overcome the coating effect of the increase in ionic strength

3.4 The Sustainability Aspects of the Study

The Sustainable Development Goals (SDGs) are a set of global goals created to achieve a more sustainable future for all (UNDP, 2020). This study contributes to several Sustainable Development Goals (SDGs). Firstly, it aligns with SDG 6 (Clean Water and Sanitation) by examining the effects of water recycling on the flotation process, which has implications for efficient water management and reduces water consumption in mining operations. Secondly, it relates to SDG 12 (Responsible Consumption and Production) by investigating the impact of changing pulp chemistry on the recovery and grade of valuable minerals, aiming to optimize resource utilization and minimize waste generation. Furthermore, it addresses SDG 13 (Climate Action) by exploring the potential environmental benefits of water recycling in terms of reducing freshwater extraction and associated energy consumption. Finally, it is relevant to SDG 14 (Life Below Water) as it contributes to understanding the potential effects of altered water chemistry on the recovery of copper and nickel, which are economically valuable and have implications for marine ecosystems when mining activities impact coastal areas (Figure 3.1).

Figure 3.1: SDGs relating to the study from UNDP (2020)

4. Experimental Programme

4.1 Factorial Design of Experiments

The factorial design of experiments method allows for the simultaneous investigation of the effects of multiple independent variables in a study Anderson and Whitcomb (2007). This is suitable for a complex system such as the flotation process. In flotation, changes to one variable may have interactive effects with other variables resulting in a combined effect. Therefore, investigating each variable singularly may result in the exclusion of information that would lead to the incorrect interpretation of the results obtained.

A factorial design of experiments consists of a minimum of two independent variables or factors. Each variable has a discrete number of levels, e.g., high, medium, or low.

The experiments for the study were conducted in two phases to investigate two collectors of different chain lengths. Phase 1 utilised a two hydrocarbon-chained collector, sodium ethyl-xanthate (SEX). For Phase 2, a branched four hydrocarbon-chained collector, sodium isobutyl-xanthate (SIBX) was selected. Steric hindrances caused by branched alkanes is less prominent at carbon chain lengths of less than 5 (Wills and Napier-Munn, 2006). Both collectors were sourced from Senmin and had a purity of 98 wt%. The variables selected for manipulation were the ionic strength of the water and the dosage of the collectors. All other variables such as the grinding conditions, dosage of the depressant and frother, the air flowrate and the impeller speed of the flotation cell were kept constant.

Three levels for each factor, i.e., high, low, and medium were selected as shown in Table 4.1. Therefore, with a 3^2 factorial design, there were a total of 18 experimental conditions, without duplicates, for the two phases.

Due to systemic and random errors that occur from the usage of laboratory equipment, there is a degree of uncertainty associated with each experiment. Therefore, all experiments were conducted in duplicates to ensure the reproducibility of the results.

Table 4.1: Phases, factors, and levels selected for the study

Phase 1: SIBX			
Variable	Low level	Medium level	High level
SPW (Synthetic plant water)	0	3	5
Collector dosage (g/t)	50	100	150
Phase 2: SEX			
Variable	Low level	Medium level	High level
SPW (Synthetic plant water)	0	3	5
Collector dosage (g/t)	50	100	150

4.2 Experimental Techniques

The ore type selected for flotation in this study was a PGM-bearing ore from the Merensky reef. This selection was based on the similarity of this ore to previous studies on the impact of water quality on flotation (Manono et al., 2012; Moimane, 2015). Therefore, using this ore provided further insight into the behaviour of the minerals once floated with different collectors under varying water quality. Table 4.2 shows the quantitative mineralogical data of the Merensky ore. The bulk ore sample was crushed, blended, riffled, and split into 1 kg samples.

Table 4.2: Mineralogical data of the Merensky ore in weight % (Wiese, 2009)

Mineral	**Feed ore (wt%)**
Pentlandite	0.31
Chalcopyrite	0.25
Pyrrhotite	0.44
Pyrite	0.08
Other Sulphides	0.02
Total Sulphides	**1.10**
Plagioclase	43.38
Orthopyroxene	32.60
Olivine	0.59
Clinopyroxene	7.48
Talc	3.51
Serpentine	0.80
Chlorite	0.83
Phlogopite	0.46
Quartz	0.67
Calcite	0.18
Oxides	8.10
Other	0.32
Total	**100**

4.2.1 Reagent Suite

As seen in Section 4.1, the collectors used in this study were SEX and SIBX and were supplied in powder form from Senmin (Table 4.3). The collector dosages used in the factorial design of experiments were 50 g/t, 100 g/t and 150 g/t. A poly-glycol-ether, Dowfroth 200, which is commonly utilised for the flotation of PGMs was selected as the frother (Hadler et al., 2005) and was supplied in liquid form. Depramin 267 is a CMC depressant and was selected as it is suitable for the depression of talcaceous and carbonate gangue in PGM flotation (Karlkvist, 2017). It was supplied in powder form and dissolved in distilled water to prepare a 1% solution of depressant (Manono et al., 2018).

Table 4.3 shows these different reagents, their active content and source. The dosages for all experiments were adjusted to account for the active content (purity) of the reagents.

Table 4.3: Reagent types and dosages

Reagent	**Name**	**Dosage (g/t)**	**Active Content**	**Source**
Collectors	SIBX	Varied	98%	Senmin
	SEX	Varied	98%	Senmin
Frother	Dowfroth 200	40	99.9%	Senmin
Depressant	Depramin 267	100	79%	Akzo Nobel

4.2.2 Lab Scale Milling

A 1 kg laboratory stainless steel rod mill was used for the comminution of the ore. The mill characteristics are shown in Table 4.4. The mill was first dry milled for 5 min with silica to ensure there were no impurities present. Once the mill was rinsed and dried, 500 mL of the relevant water type was added to the mill with the 1 kg ore sample to form a slurry. The collector at the relevant dosage was added to the slurry and the mill was run for the milling time noted in Table 4.4. The mill speed and milling time achieved the required particle size distribution of 60% passing 75 μm, as seen in the milling calibration curve (Figure 4.1).

Table 4.4: Mill characteristics

Parameter	**Value**
Number of rods	20
Mill speed	256 rpm
Milling time	13.5 min
Composition of rods	Stainless steel

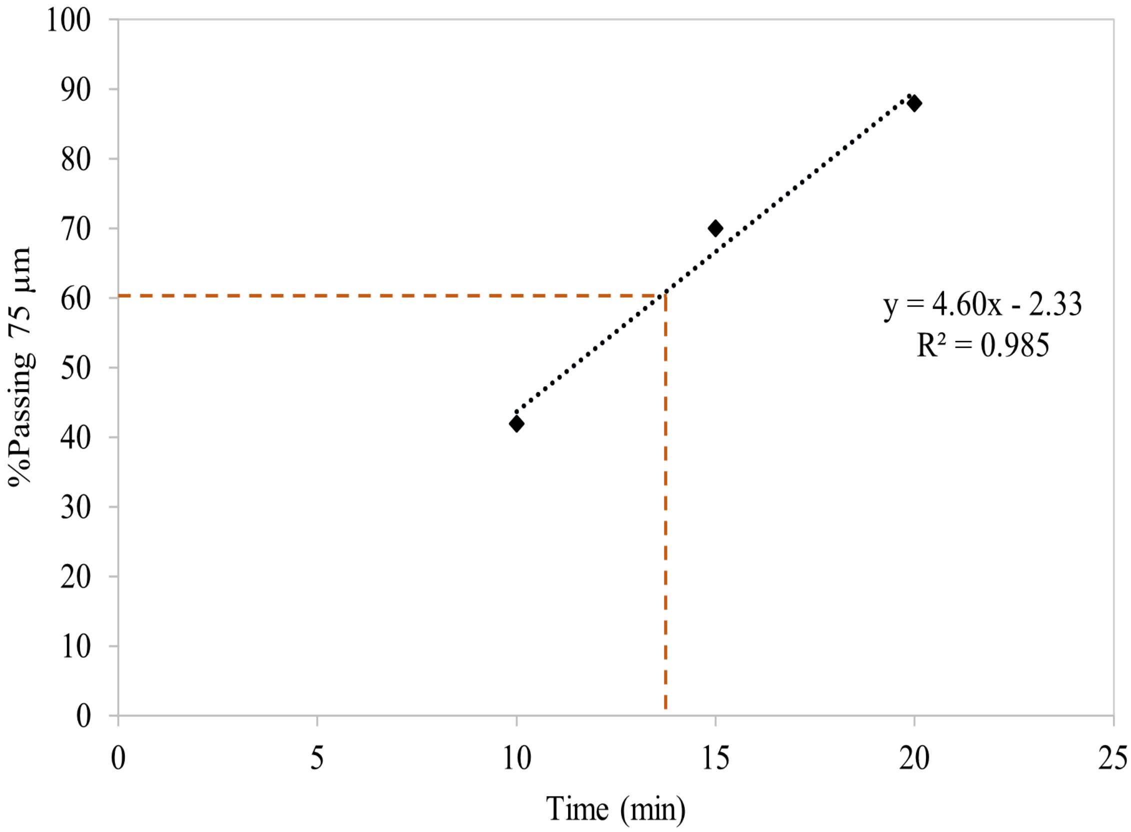


Figure 4.1: Milling calibration curve showing %passing 75 μm vs milling time

4.2.3 Synthetic Plant Water Preparation

To simulate the recycled process water and effectively compare the results of this study to previous studies, synthetic plant water (SPW) was used (Corin et al., 2011; Manono et al., 2018; Wiese, 2009). CMR at the University of Cape Town (UCT) developed a recipe that contains the inorganic ions and TDS that would be present in a singular Merensky concentrator (Manono et al., 2012; Wiese et al., 2005). 40 L of 1 SPW is prepared by the addition of inorganic salts to distilled water. 3 and 5 SPW are synthesised by multiplying the concentrations of the salts in 1 SPW by 3 and 5 respectively. These salts were sourced from Merck and were in powder form. Process water on a mineral processing site is typically at 3 SPW. Table 4.5 shows the ionic strengths of the different ions that the SPW contains.

Table 4.5: Concentrations of ions in different SPWs

Water	Ca^{2+} **(ppm)**	Mg^{2+} **(ppm)**	Na^{+} **(ppm)**	Cl^{-} **(ppm)**	SO_4^{2-} **(ppm)**	NO^{3-} **(ppm)**	CO_3^{2-} **(ppm)**	**TDS (mg/L)**	**IS [M]**
1 SPW	80	70	153	287	240	176	17	1023	0.0242
3 SPW	240	210	459	861	720	528	51	3069	0.0727
5 SPW	400	350	765	1435	1200	880	85	5115	0.1212

4.2.4 Batch Flotation

The standard batch flotation procedure utilised by CMR was implemented in this study in a 3 L Barker batch flotation cell (Figure 4.2). Once milled, the slurry was added to the cell and the relevant water type added to reach the 3 L mark, forming the pulp phase. The cell impeller was then turned on and set to 1200 rpm to agitate the pulp. Once a 50 mL feed sample was taken from the cell, the depressant, CMC, was added at the required dosage and conditioned for 2 min. The frother, Dowfroth 200 was then added to the cell and after a conditioning time of 1 min, air at a flow rate of 7 L/min was bubbled through the pulp. This air flow rate was maintained at this speed for all flotation experiments.

The froth was scraped into a concentrate collecting pan at 15 sec time intervals for 2, 4, 6 and 8 min respectively resulting in four concentrate samples. The water level in the cell was monitored and maintained at 3 L by the addition of the relevant water type throughout the experiment (Manenzhe et al., 2019).

Once the final concentrate sample was collected, the air was turned off and two tails samples were collected with 50 mL syringes. These tails samples were first utilised in the residual xanthate measurements as outlined in Section 4.2.8 and then the chemical analysis outlined in Section 4.2.5. 250 mL of the pulp was then collected for the sedimentation tests outlined in Section 4.2.7. The cell was then emptied to collect the remaining tails and the impeller was switched off. The cell was thoroughly rinsed with water to prevent contamination in further experiments.

The concentrates, tails and feed samples were weighed, filtered and dried overnight in an oven at 80°C. Once dry, the samples were re-weighed and sent for chemical analysis of copper and nickel by x-ray fluorescence (XRF).

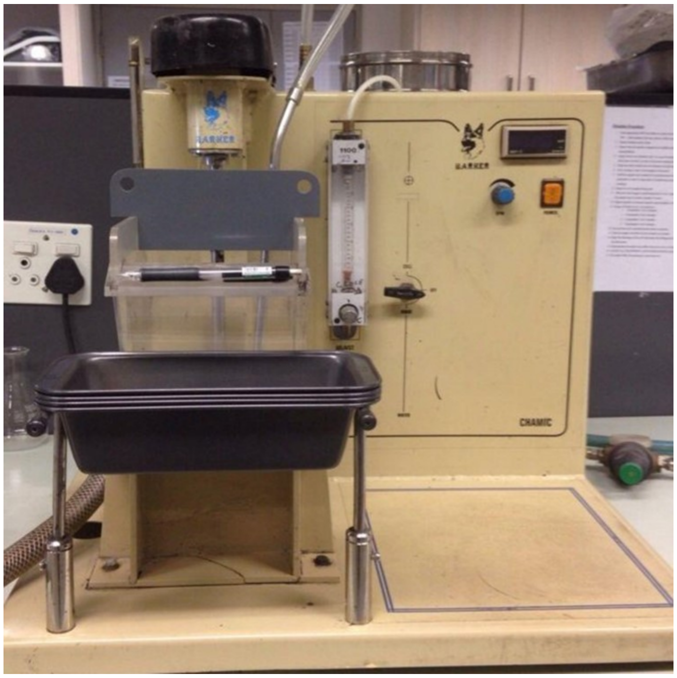


Figure 4.2: Batch flotation cell

4.2.5 Chemical Analysis of the Samples Using X-ray Fluoresence

The concentrations of copper and nickel in each of the samples were obtained utilising a Thermo-NITON XL3t 950 GOLD+ XRF spectrometer. The XRF spectrometer used a large area drift detector and a gold anode x-ray tube to acquire concentration data for 10, 20 and 30 s. These measurements were taken and averaged for each point using the Thermo Scientific NITON Data Transfer software suite. The data Cu and Ni from the XRF machine were in ppm units and these results were exported to Microsoft Excel. Once converted from ppm to percentage, the mineral grades and recoveries were calculated by multiplying the percentage by the mass of sample.

4.2.6 Determination of the Entrainment Factor

The entrainment factor was found utilising the method developed by Wiese (2009). This method assumes that at a depressant dosage of 300 g/t, all naturally floating gangue (NFG) is depressed and the remaining gangue recovered to the concentrates can be attributed to entrainment. Wiese (2009) found that at this high depressant dosage, the only gangue reporting to the concentrate would be due to entrainment and there would be no natural floating gangue (NFG). This method was selected as it does not require specialised equipment and is applicable to all particle sizes (Wiese et al., 2005; Wiese, 2009; Wiese et al., 2011).

A middle point dosage of 100 g/t of SIBX and SEX was used to determine the entrainment factor. All other factors such as flotation methodology and chemical analysis were kept the same as in Section 4.2.4 and 4.2.5.

4.2.7 Sedimentation Tests

To investigate whether coagulation occurred during the flotation process, sedimentation tests were conducted following the method used by Shibata and Fuerstenau (2003). In this method, the tailings taken from the pulp were added to a 250 mL conical flask. The test sample was then agitated by being covered with a stopper and inverted 15 times. After agitation, the flask was placed in front of an unmarked, white sheet of paper and a stopwatch started. The time taken for the sheet of paper behind the conical flask to be clearly visible through the supernatant was then recorded. This was done for each flotation test that was conducted. These tests were intended to obtain further insight into the behaviour of the fines in the flotation system.

4.2.8 Determination of Residual Xanthate in Solution

To determine residual xanthates in the tails samples, UV-Vis spectrophotometry was utilised. Calibration curves were created using each water type with known concentrations of the collector at different dosages (Figure 4.3).

After each flotation test, a 50 mL tails sample was centrifuged to separate the solid from the liquid material in the sample. The clear supernatant liquid was then dispensed into precision quartz cuvettes and read three times with respect to a blank in an Ultrospec UV-visible spectrophotometer (Wiese, 2009). This blank was the type of water used in the flotation test made according to the recipe described in Section 4.2.3.

Xanthate ions show an absorption peak at 301 nm (Agorhom et al., 2014). The average absorbance measurement at 301 nm from the three readings was recorded and the concentration of the residual collectors calculated using the calibration curves and Beer-Lambert's Law as shown in Equation 4.1 (Manenzhe et al., 2019; Muzinda and Schreithofer, 2018). A is the absorbance, l the path length of the cuvette, ϵ the molar absorptivity and c, the concentration. This equation is in the linear form $y = mx$ due to the term $\epsilon * l$ being constant as molar absorptivity for a given substance and path length of a cuvette do not change.

$$A = \epsilon * l * c \tag{4.1}$$

Therefore, the residual concentration is calculated using the slope of the calibration graph and the average absorbance of the tails sample at 301 nm. By quantifying the amount of residual xanthate in solution, information as to the amount of collector adsorbed in the flotation cell was provided.

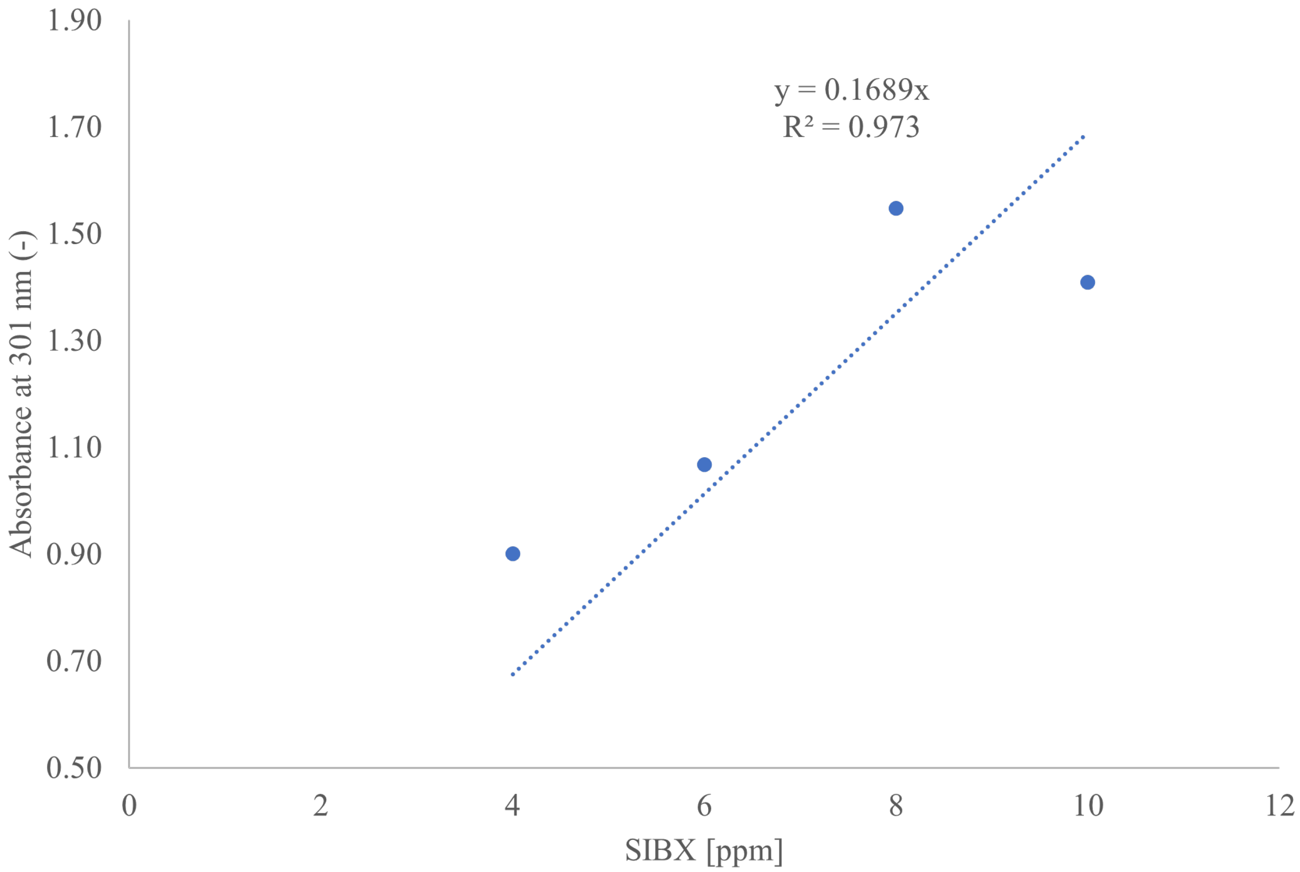


Figure 4.3: Calibration curves for tap for the SIBX concentration range of 4 to 10 ppm

4.2.9 Zeta Potential Measurements

Chalcopyrite is a mineral of interest within the Merenksy ore used in the study. It is also the most easily accessible as a pure natural mineral. Furthermore, chalcopyrite has been utilised in studies that were used allowing for comparison (Goktepe, 2001; October et al., 2020). The chalcopyrite used in the zeta potential studies was received in chunks from Ward's Natural Science Establishment. These chunks were hammered down and pulverised for 5 sec with a laboratory scale pulveriser. The chalcopyrite powder was dry sieved utilising a 38 μm screen to obtain a particle size fraction of <38 μm which was then used in the experiments (Mhonde et al., 2020).

60 mL of the specific water type was mixed with 0.075 g of the chalcopyrite particles and conditioned for 1 min. The pH was kept at the natural pH of the water as this was what was used in the batch flotation tests (City of Cape Town, 2021). This was then conditioned for

15 min and allowed to settle for 5 min. The collector was added and allowed to condition for another 5 min. Approximately 2-3 mL of the supernatant liquid was then utilised in the zetasizer cell and measurements were conducted using a Malvern Zetasizer (October et al., 2020). All tests were conducted in duplicates and the standard error calculated.

5. Results

This chapter details the results obtained from the batch flotation experiments, the entrainment studies, and the zeta potential studies. To illustrate the flotation performance of the collectors at different dosages and different ionic strengths of water, solids, water, copper, and nickel recovery, and copper and nickel grades were plotted.

5.1 Reproducibility

The batch flotation experiments were conducted in duplicates. To evaluate the precision of the experiments, the standard error between the duplicate tests was determined. As shown in Equation 5.1, the standard error is calculated by the standard deviation divided by the root of the number of samples. This standard error is represented by the error bars on the graphs.

$$SE = \frac{\sigma}{\sqrt{n}} \tag{5.1}$$

5.2 Effect of Water Quality and Collector Chain-Length on Solids and Water Recoveries

Figure 5.1 shows the cumulative solids recovery as a function of flotation time. As the ionic strength of the water increased, there was an increase in the recovered solids obtained for both collectors. Figure 5.1 also shows all dosages of SEX at 0 and 3 SPW recover a higher mass of solids than the same dosages of SIBX. However, this pattern is not observed at the highest ionic strength of 5 SPW. The highest solids recovery occurred with SIBX at a dosage of 100 g/t and at 5 SPW. However, at the highest ionic strength and dosage of SIBX, there is a decrease in the recovery of the solids. The same observation is made at the highest dosage of SEX.

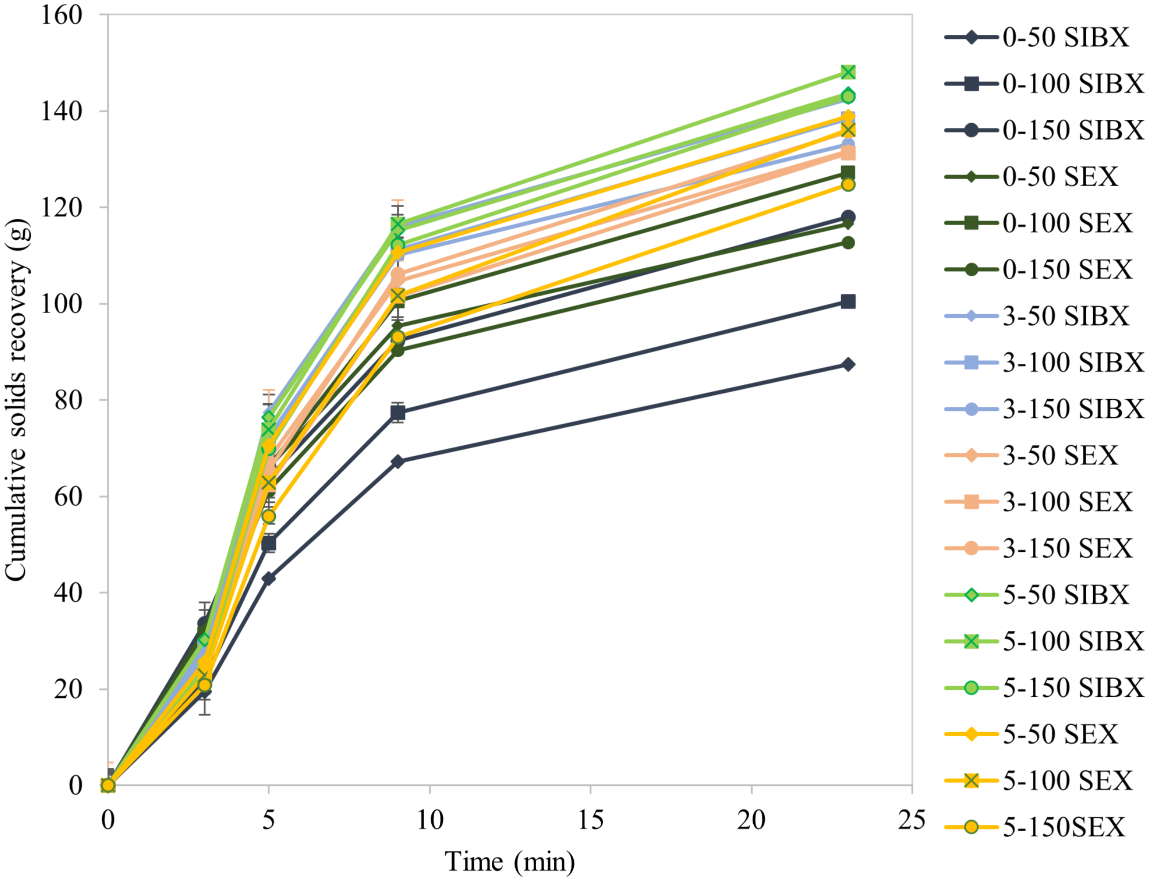


Figure 5.1: Cumulative solids recovered vs. flotation time. Error bars represent the standard error between duplicate tests.

Figure 5.2 shows the cumulative water recovery as a function of flotation time. At 0 SPW, both collectors showed an increase in water recovery with an increase in dosage. However, at 3 and 5 SPW, the collectors both recovered more water at dosages of 50 g/t. The mass of water recovered increases with an increase in ionic strength for both collectors. SIBX recovered more water than SEX at 0 and 5 SPW, however, at a dosage of 50 g/t and an ionic strength of 5 SPW, SEX achieved the highest water recovery.

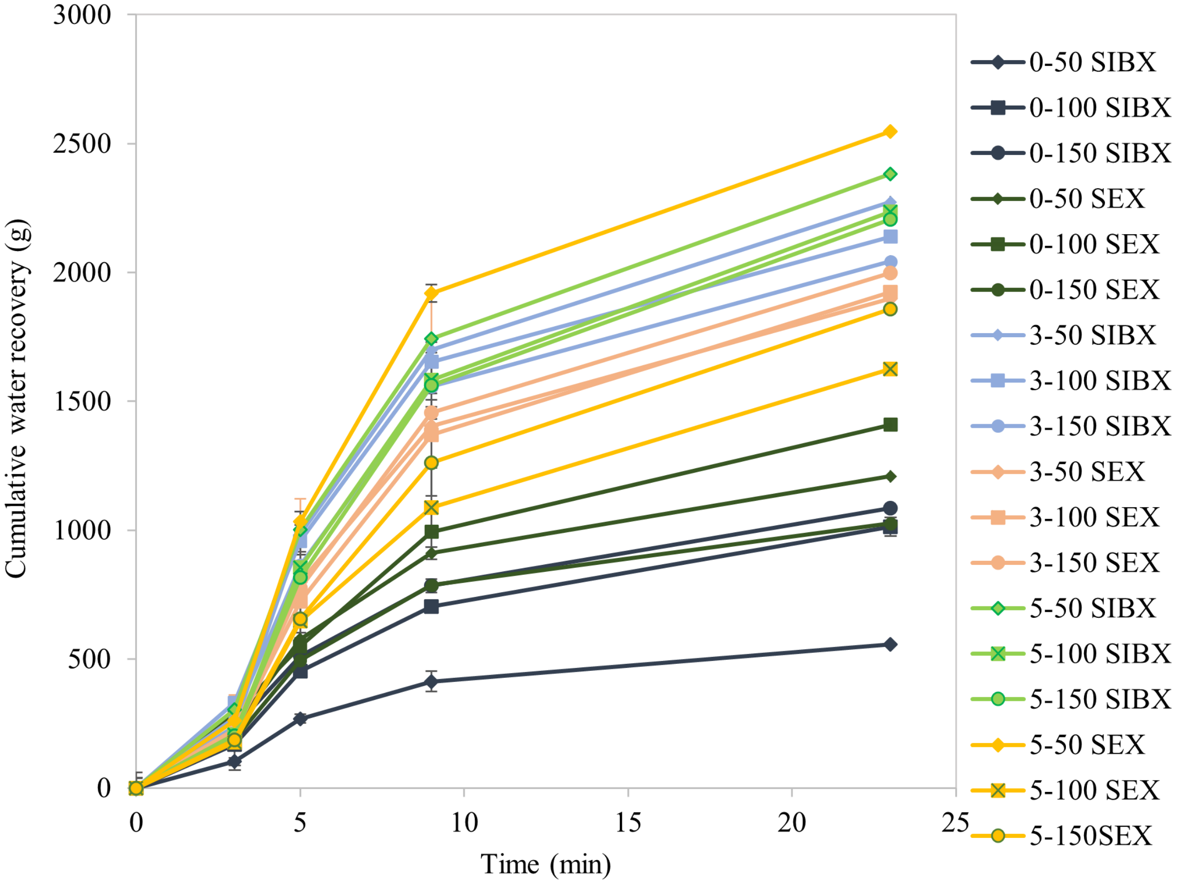


Figure 5.2: Cumulative water recovered vs. flotation time. Error bars represent the standard error between duplicate tests.

Figure 5.3 shows the cumulative solids recovery as a function of cumulative water recovery. As shown in the figure, the general pattern indicates an increase in solids recoveries also reflected in increased water recoveries. However, the highest water recovery is at a condition of 5 SPW and 50 g/t of SEX. The lowest solids and water recovery both occurred at 0 SPW and at a dosage of 50 g/t of SIBX. Although SEX at a dosage of 50 g/t and at 5 SPW achieved the highest water recovery, the condition achieved a lower recovery of solids, than the other dosages at that ionic strength.

SIBX exhibits a greater increase in solids recovery, from 0 SPW to 3 & 5 SPW, compared to SEX. This is attributed to SIBX's stronger collecting capability, which brings a higher quantity of hydrophobic particles into the froth and enhances its stability for improved water recovery (Goktepe, 2001; Rao and Finch, 1989).

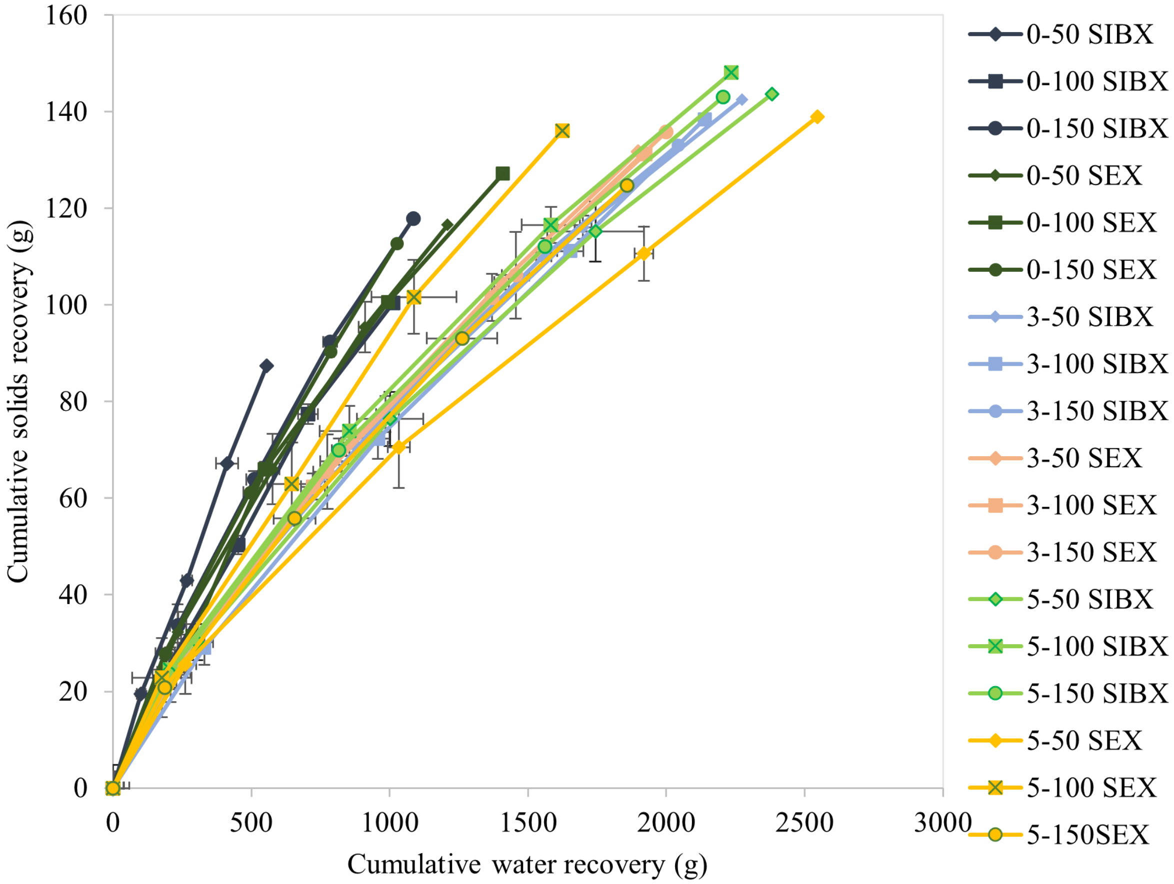


Figure 5.3: Cumulative solids recovered vs. cumulative water recovered. Error bars represent the standard error between duplicate tests.

Figure 5.4 shows the final solids and water recovered at the three ionic strengths for SIBX and SEX at a dosage of 50 g/t. Both collectors showed an increase in solids and water recoveries with an increase in ionic strength from 0 to 3 SPW. At 0 SPW, SEX recovered 33% more solids than SIBX. However, SIBX at the higher ionic strengths recovered more solids than SEX. At 50 g/t, the difference in the performance of the two collectors decreased as the ionic strength of the water increased. The difference in solids recovered at 0 SPW further decreased to 8% at 3 SPW, and finally, 3% at 5 SPW. The water recoveries increased with an increase in the ionic strength of the water. At 0 and 5 SPW, SIBX recovered less water than SEX. However, at 3 SPW, SEX recovered 20% less water than SIBX.

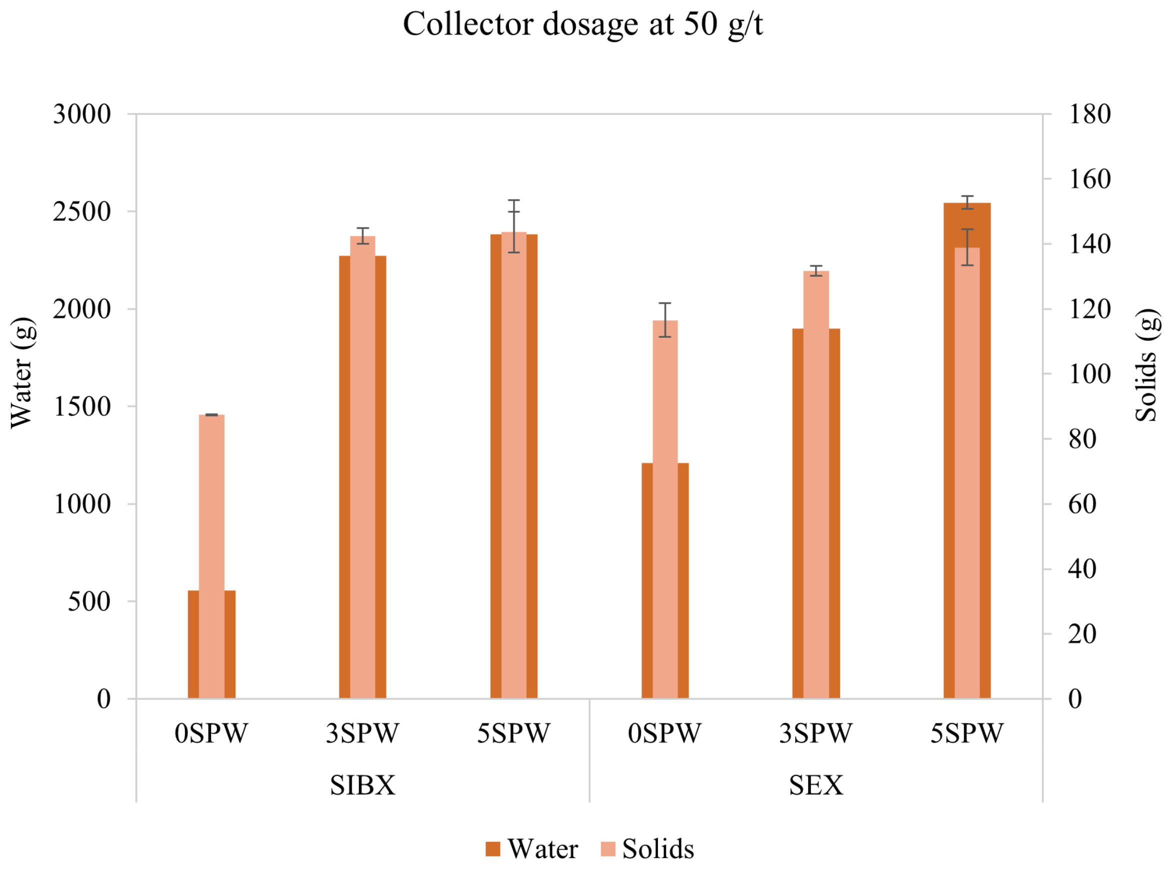


Figure 5.4: Solids and water recoveries under 0, 3 and 5 SPW at a collector dosage of 50 g/t. Error bars represent the standard error between duplicate tests.

At 0 SPW, increasing collector dosage improved both solid and water recoveries for both collectors. However, at 3 SPW, the impact on recoveries with increasing dosage was minimal for both collectors. At 5 SPW, SIBX showed little change in recoveries, while SEX displayed a decrease in recoveries with higher collector dosage. This could be due to potential competition for the mineral surface between the collector and the ions in the SPW (Ikumapayi et al., 2012).

Figure 5.5 presents the final solids and water recoveries at a collector dosage of 100 g/t. The lowest solids and water recoveries occurred with SIBX at 0 SPW. As the ionic strength of the water increased, the solids recoveries for both collectors increased as well. As observed at a collector dosage of 50 g/t, solid recoveries with SIBX at 3 and 5 SPW were higher than recoveries with SEX. Unlike at the 50 g/t dosage however, the difference between the collector performance did not decrease with an increase in the ionic strength of the water. The water recoveries for SIBX increased with an increase in ionic strength. Aside from 0 SPW, SIBX had higher water recovered than SEX. SEX had an increase in the water recovered when the synthetic plant water strength was increased from 0 to 3 SPW. However, at 5 SPW, there was a 15% decrease in the water recovered by SEX in comparison to 3 SPW.

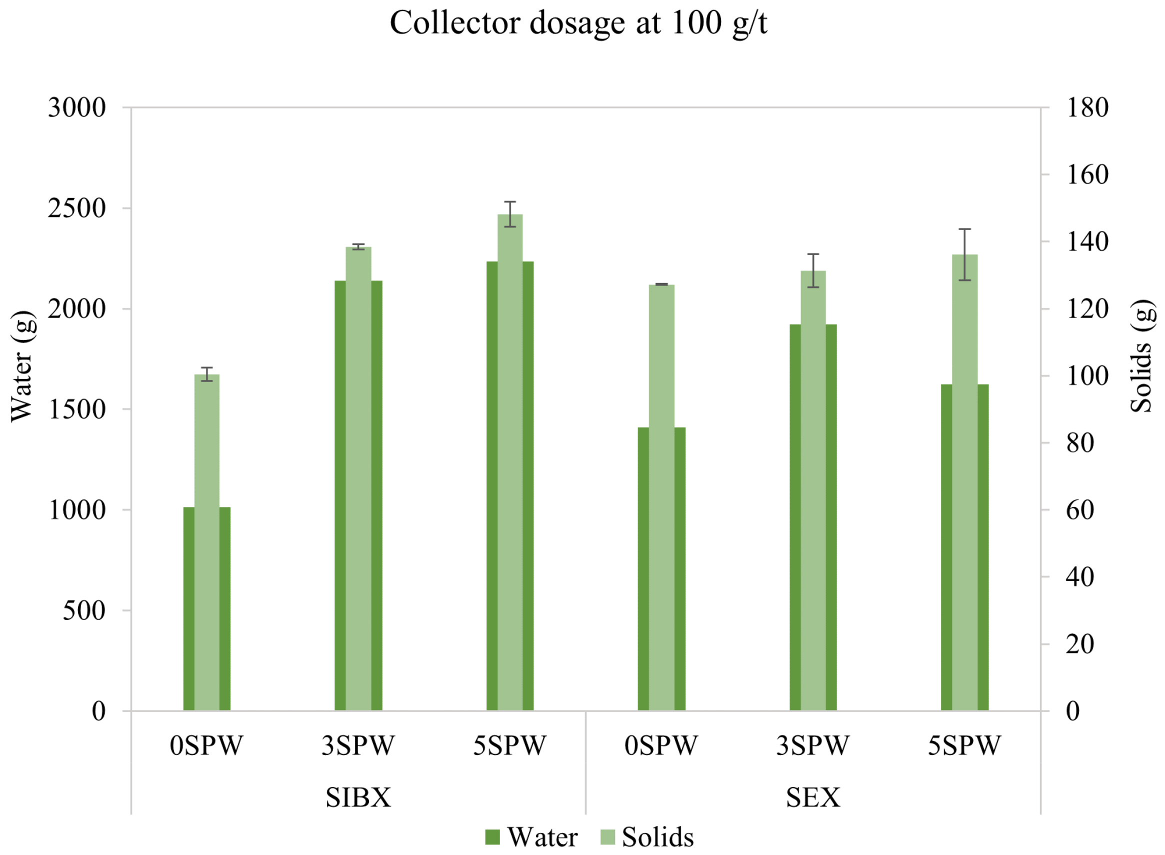


Figure 5.5: Solids and water recoveries under 0, 3 and 5 SPW at a collector dosage of 100 g/t. Error bars represent the standard error between duplicate tests.

Figure 5.6 shows the solids and water recoveries at a collector dosage of 150 g/t. As the ionic strength of the water increased, the solids and water recoveries increased as observed for the lower dosages. However, for SEX at 5 SPW, there is a decrease in both the water and solids recoveries. Therefore, as observed at 100 g/t, the highest water and solids recoveries observed for SEX occurred at 3 SPW. Another difference observed is at this higher dosage, SIBX and SEX had similar solids and water recoveries at 0 SPW in comparison to lower dosages, where SIBX had a lower performance in comparison to SEX at the lower ionic strength.

At 0 SPW an increase in collector dosage resulted in an increase in both solid and water recoveries for both collectors. At 3 SPW however, the differences in solid and water recoveries as collector dosage increased was negligible for both collectors. At 5 SPW, SIBX once again had a negligible change in recoveries. However, a decrease in recoveries with an increase in collector dosage was observed for SEX.

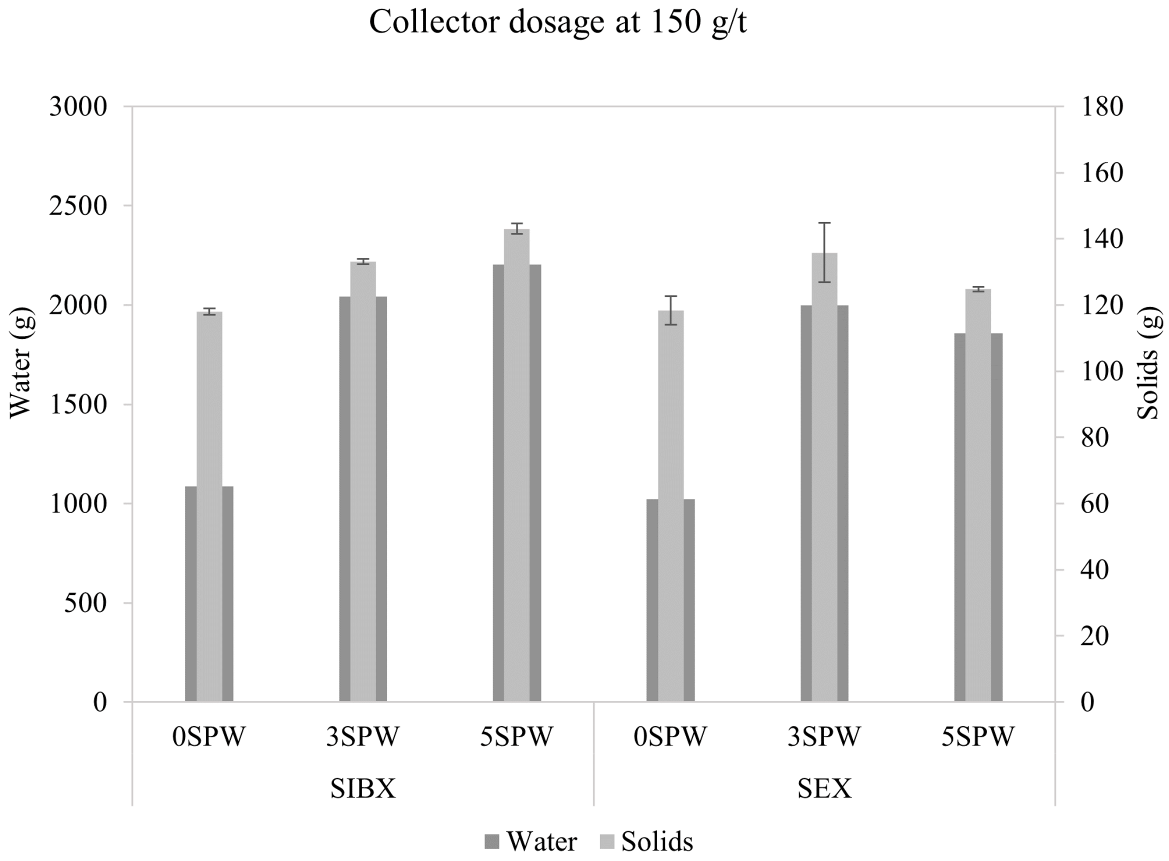


Figure 5.6: Solids and water recoveries under 0, 3 and 5 SPW at a collector dosage of 150 g/t. Error bars represent the standard error between duplicate tests.

5.3 Effect of Water Quality and Collector Chain-length on Copper Recoveries and Grades

The Klimpel model shown in Equation 5.2 was selected to model the copper recovery as it has been used extensively in literature to describe flotation data (Sahoo et al., 2017; Vinnett and Waters, 2020). The recovery differences were sufficiently small to represent the recovery rate using this model. R is the recovery of the mineral at a given time (t), R∞ is the maximum recovery that can be reached at equilibrium (an infinite time), and k is the rate constant (Sahoo et al., 2017).

$$R = R_{\infty}[1 - \frac{1}{kt}][1 - exp(-kt)] \tag{5.2}$$

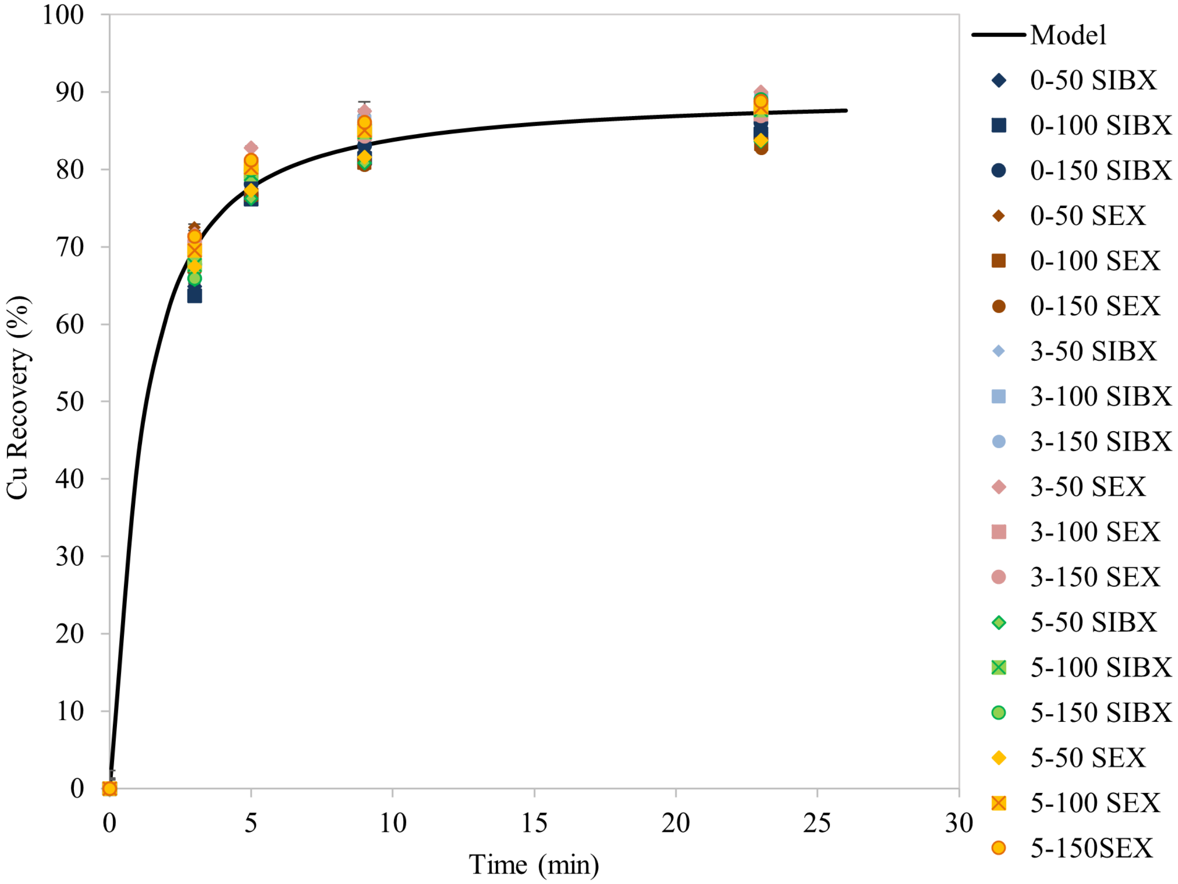


Figure 5.7: Cumulative copper recovered vs. flotation time. Error bars denote the standard error between duplicate tests (they are too minute to be visible).

Figure 5.7 shows the recovery of copper as a function of time. It is observed from the figure that the floatability of copper per minute is the same for all experimental conditions with a rate constant of 1.46 min^{-1}.

Both collectors had lower water recoveries with a decrease in ionic strength as it was observed that an ionic strength of 0 SPW and 50 g/t of SIBX had the lowest water recovery. Furthermore, 5 SPW a dosage of 50 g/t of SEX had the highest water recovery as expected. At all ionic strengths, SEX achieves similar copper recoveries to that of SIBX, however, the water recoveries observed with SEX are higher.

Despite recovering the least amount of water, 50 g/t of SIBX at 0 SPW did not achieve the lowest copper recovery. The lowest copper recovery and the highest water recovery occurred at 50 g/t SEX at 5 SPW.

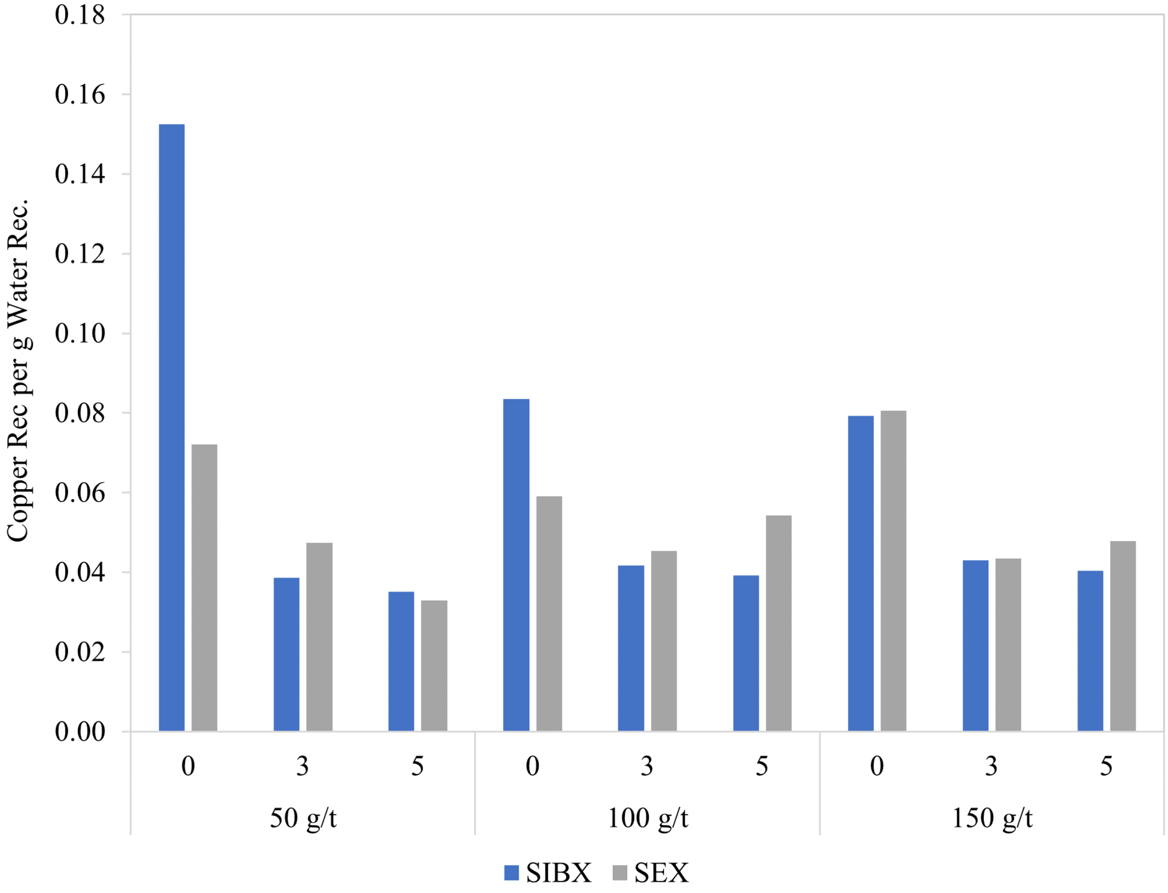


Figure 5.8: Copper recovered per g of cumulative water recovered.

As shown in Figure 5.8 the copper recovered per g of cumulative water recovered, 0 SPW and 50 g/t of SIBX had the highest value with almost twice the amount of copper recovered per g of water. And as shown in Figure 5.9, this is due to this condition having the lowest water recovered, and not due to a higher amount of copper being recovered. There was an decrease in copper recovered per g of water as the ionic strength increased at all dosages of

SIBX. This is expected as studies have shown the mass of water recovered increases with an increase in ionic strength of water. However, SEX only produced this trend at 50 g/t, at the other dosages, 3 SPW recorded the lowest copper recovered per g of water. From Figure 5.9, at 3 SPW, SEX at 100 g/t and 150 g/t achieved a similar recovery of copper as 5 SPW, however, recovered more water.

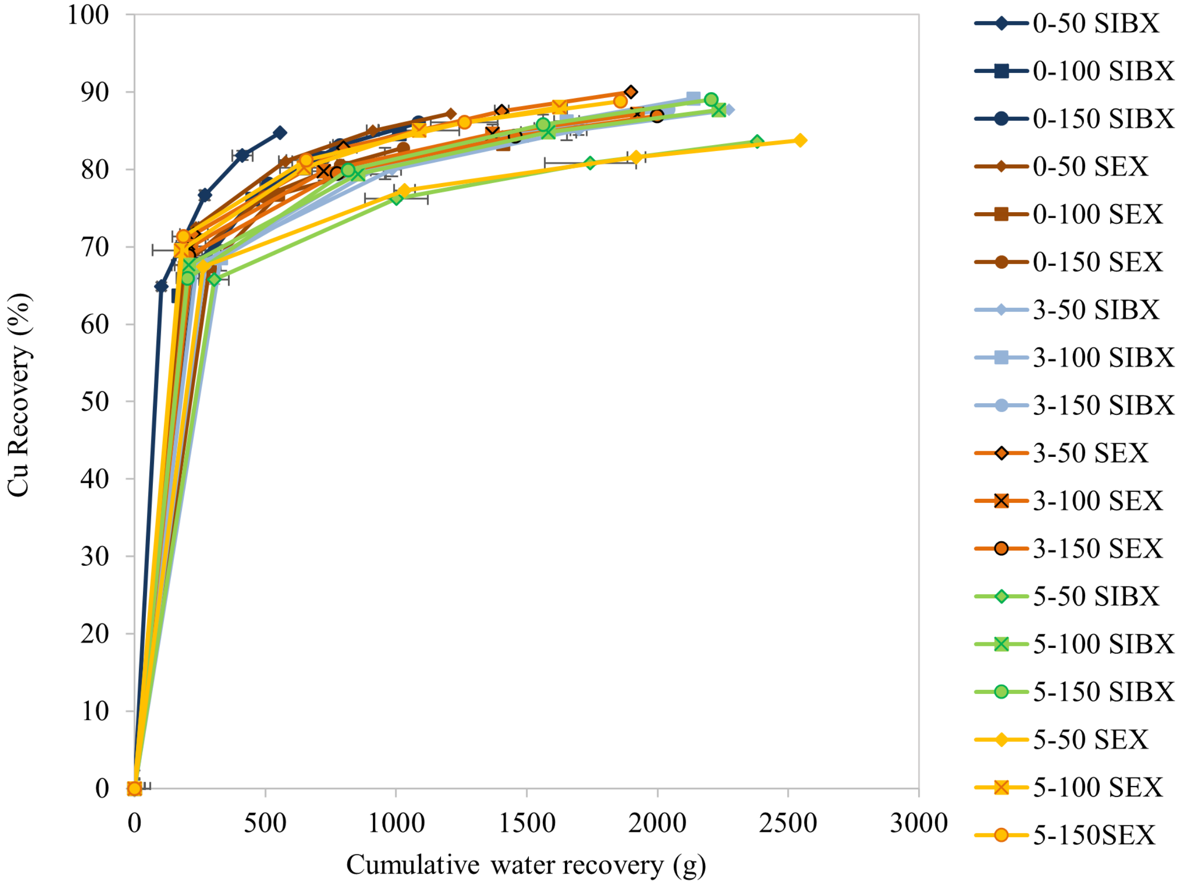


Figure 5.9: Cumulative copper recovered vs. cumulative water recovered. Error bars represent the standard error between duplicate tests

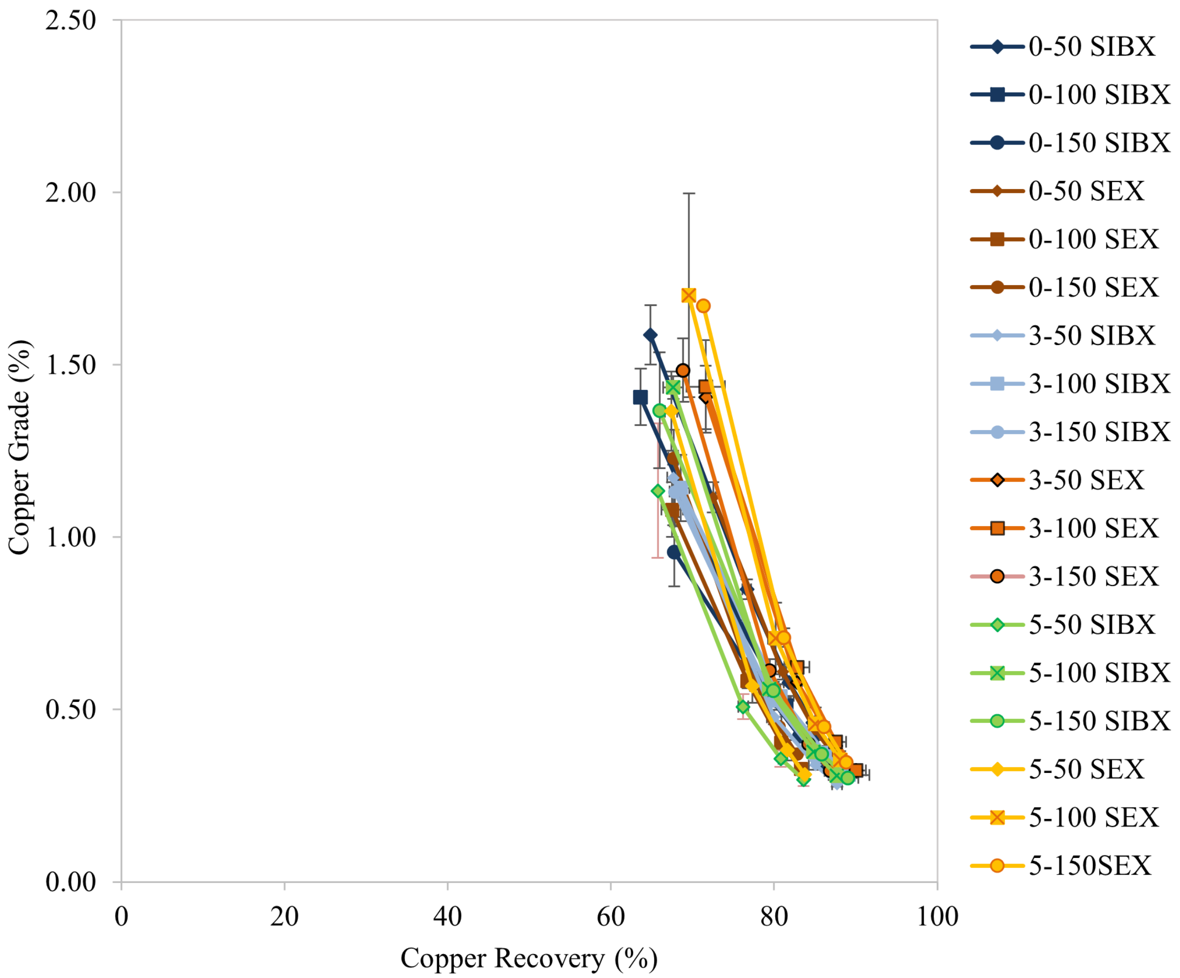


Figure 5.10: Cumulative copper grade vs. cumulative copper recovered. Error bars represent the standard error between duplicate tests

The relationship between the cumulative copper grade and the cumulative copper recovery is shown in Figure 5.10. The range of final recoveries ranged between 83-90%. This is similar to what was observed in the copper recoveries.

The total copper recoveries and grades for all conditions at a collector dosage of 50 g/t are shown in Figure 5.11. There is no variation in the recoveries obtained as the ionic strength of water is increased between the two collectors. SEX obtained slightly higher grades than SIBX, however, the difference is minimal in comparison to the noticeable difference of SIBX in tap water which obtained the highest grade of 3.5%. The rest of the experimental conditions achieved grades that were lower at less than 3%.

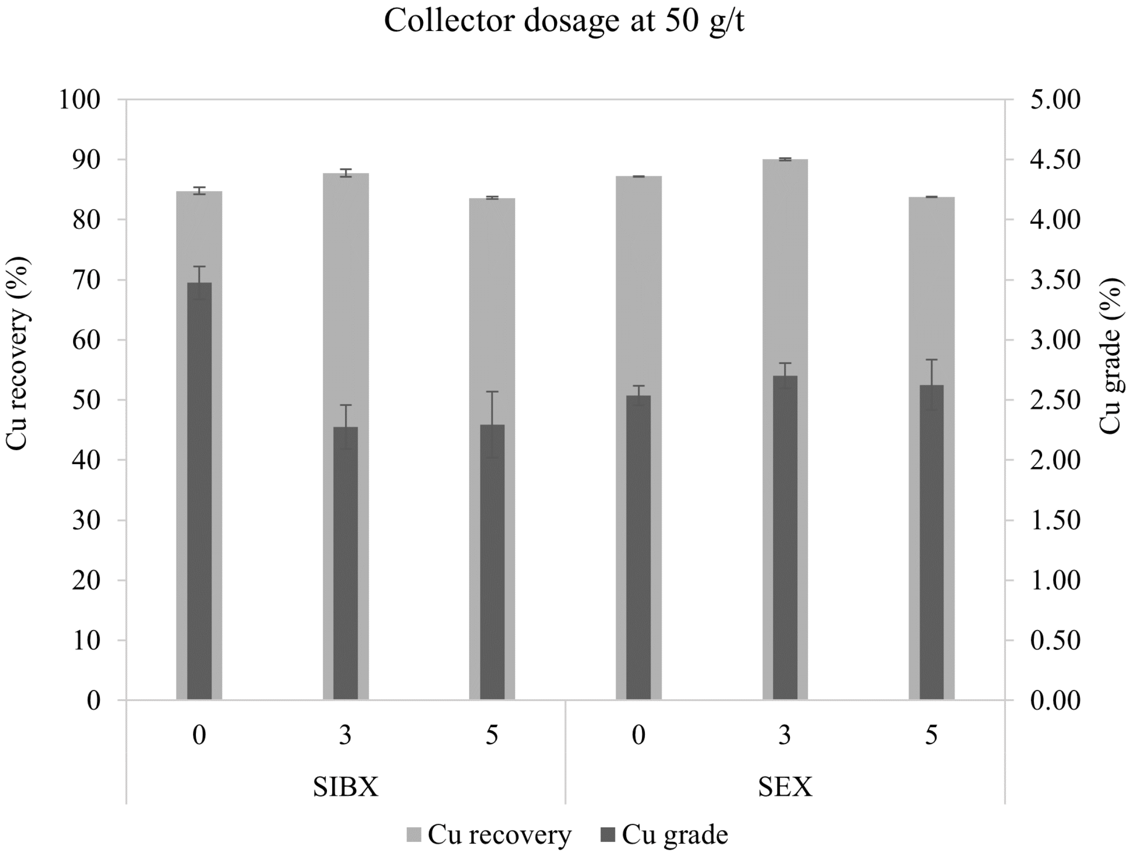


Figure 5.11: Copper recoveries and grades in 0, 3 and 5 SPW at a collector dosage of 50 g/t. Error bars represent the standard error between duplicate tests

Figure 5.12 shows the copper recoveries and grades for each ionic strength of water at 100 g/t of collector. At this dosage, there is also no difference in the copper recoveries obtained with neither an increase in the ionic strength of water nor an increase in collector chain-length.

However, at this dosage the difference in grade is more pronounced than at 50 g/t of collector. SEX obtains a higher grade than SIBX in tap water and 5 SPW. The highest grade is obtained by SEX in tap water and is approximately 3.5%. At 3 SPW the grade is the same for both collectors. There is also a slight decrease in grade at 3 SPW between tap water and 5 SPW for both collectors.

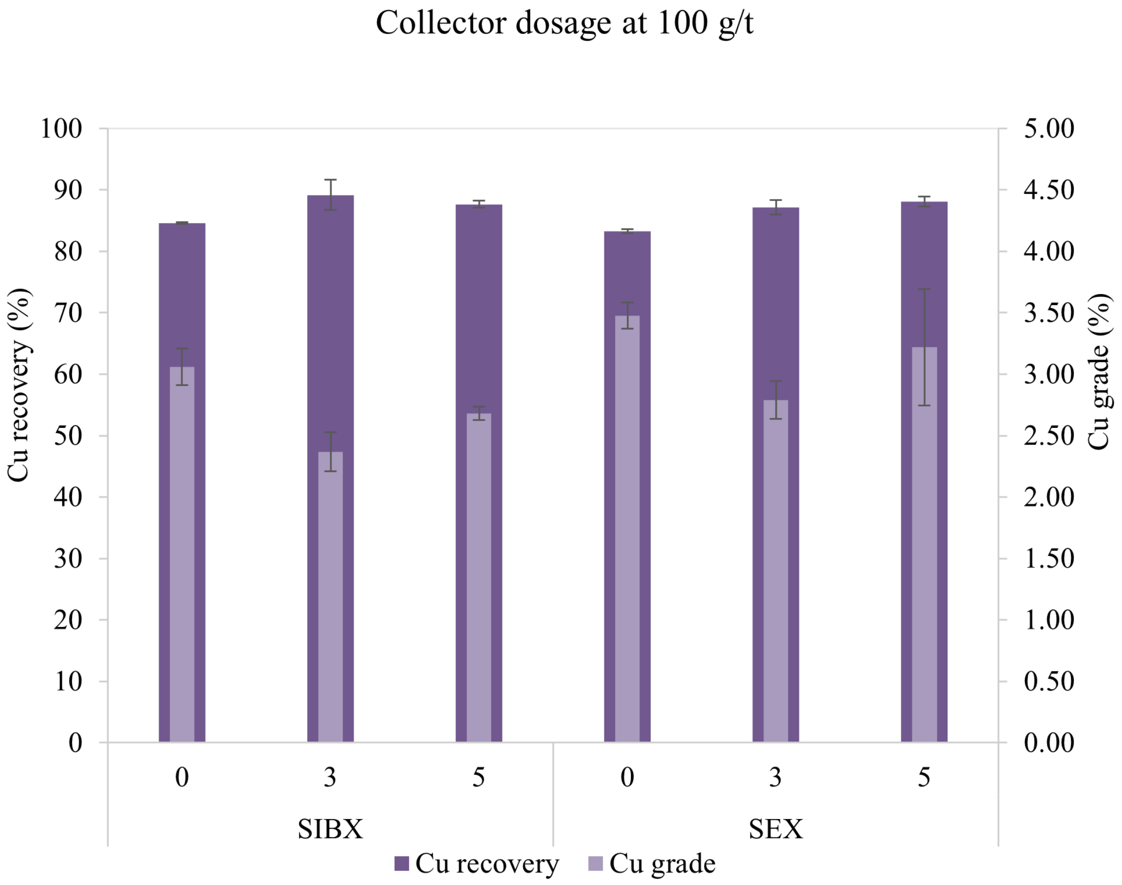


Figure 5.12: Copper recoveries and grades in 0, 3 and 5 SPW and at a collector dosage of 100 g/t. Error bars represent the standard error between duplicate tests

Figure 5.13 shows the copper recoveries and grades in all water types at a collector dosage of 150 g/t. As observed in both Figure 5.11 and Figure 5.12, the copper recovery does not vary significantly as ionic strength increases for either collector. The range of recoveries obtained is between approximately 82% - 88%. The grade obtained by SEX is higher than SIBX with the highest grade with SEX at 5 SPW, at slightly above 3%. There is also a slight increase in grade with an increase in ionic strength for all collectors at a dosage of 150 g/t.

Therefore, at all collector dosages, the copper recovery was within the same range, 80%-90%, and was unaffected by an increase in the ionic strength of the water and collector chain length. However, the grade did show some variation in behaviour across the dosages. At dosages of 100 g/t and 150 g/t, SEX generally obtained higher grades than SIBX when the grade at the same ionic strength was compared. However, SIBX at 50 g/t and tap water achieved the highest grade at that dosage. A dosage of 150 g/t recorded the lowest grade amongst the dosages as the grades were below 3% for all conditions aside from SEX at 5 SPW.

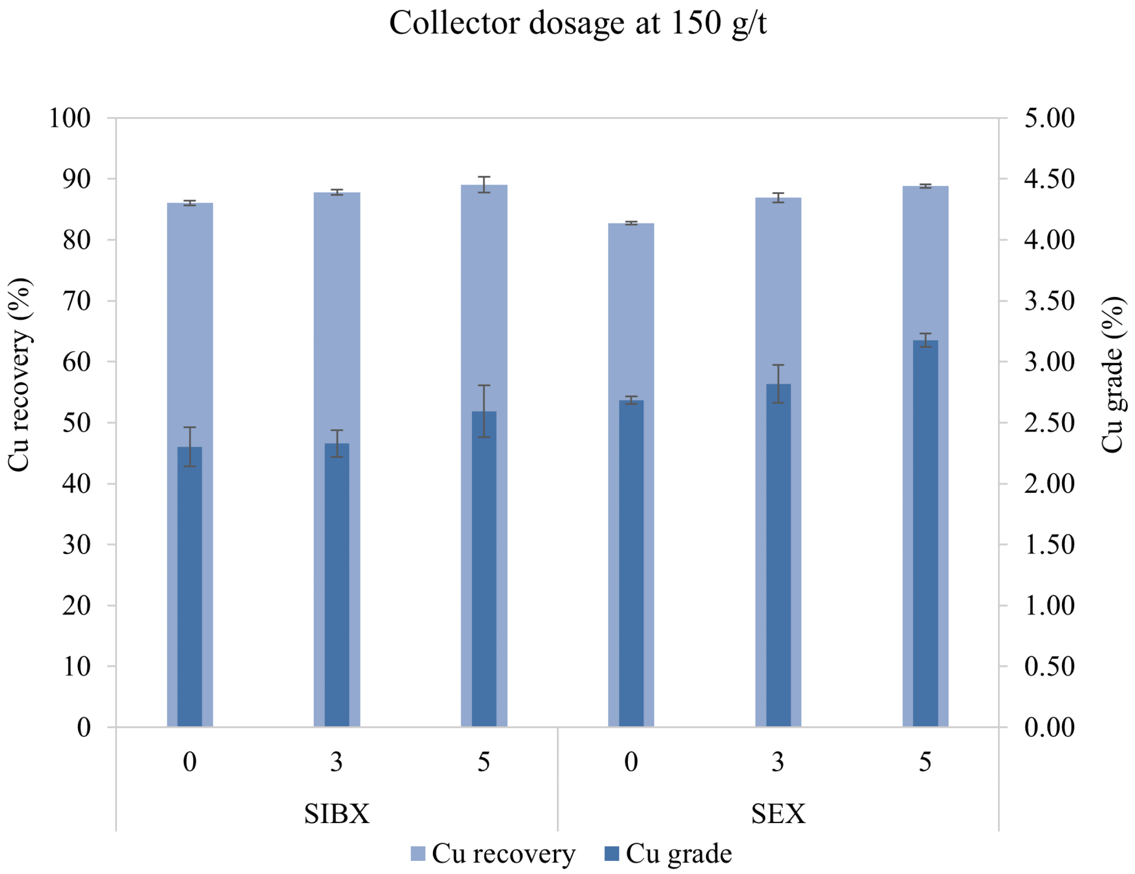


Figure 5.13: Copper recoveries and grades in 0, 3 and 5 SPW and at a collector dosage of 150 g/t. Error bars represent the standard error between duplicate tests

5.4 Effect of Water Quality and Collector Chain-length on Nickel Recoveries and Grades

The cumulative nickel recovery as a function of flotation time had the same model fit onto the data as shown in Figure 5.14, however, there are two trends present. The figure shows the floatability of nickel per minute (k_1) was higher at an ionic strength of 0 SPW and a dosage of 50 g/t of SEX, while all other conditions (k_2) could be considered to fall within one model line. When compared to Figure 5.7, the first-order flotation rate constant is higher for copper than it is for nickel, implying faster flotation kinetics for chalcopyrite than pentlandite. The first order for the curves was calculated as per Section 5.3.

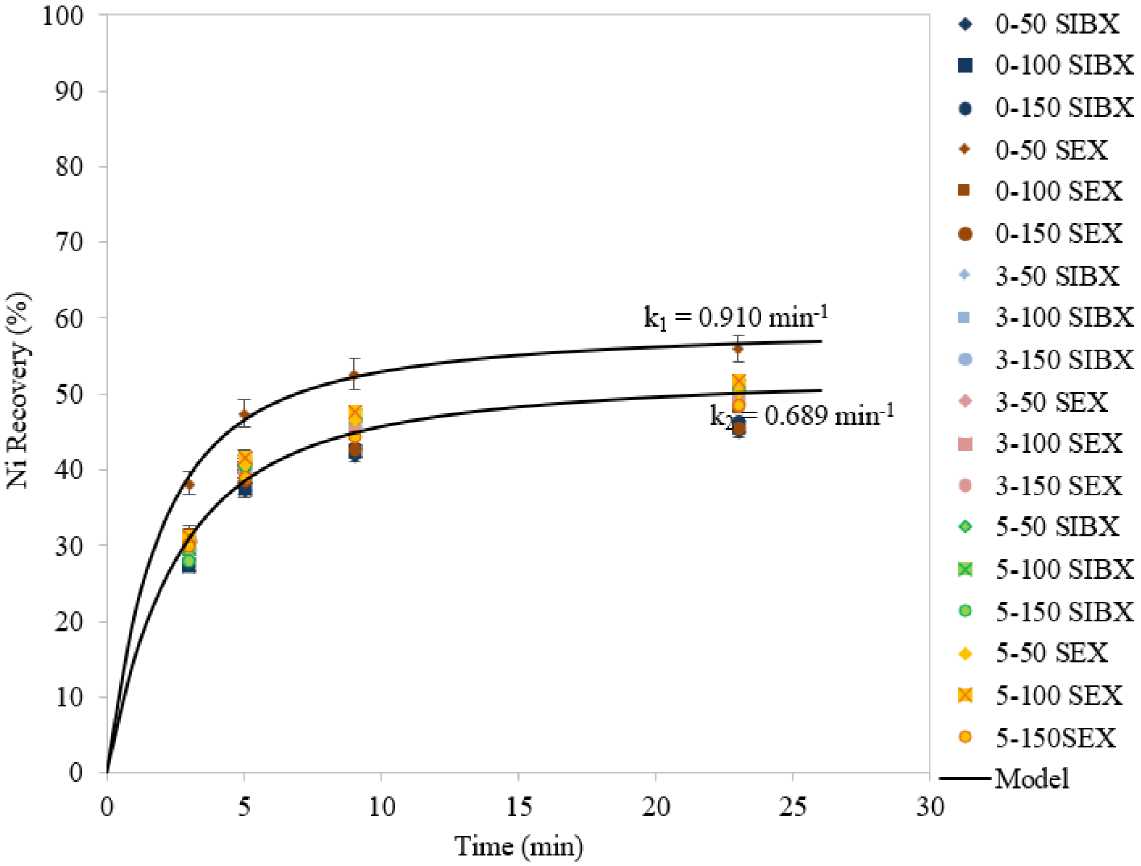


Figure 5.14: Cumulative nickel recovered vs. flotation time. Error bars represent the standard error between duplicate tests

Figure 5.15 shows the relationship between the cumulative nickel grade and nickel recovery. It was observed that just like in Figure 5.10, the difference between the highest and lowest nickel recovery was less than 10% for the experimental conditions regardless of ionic strength and collector dosage.

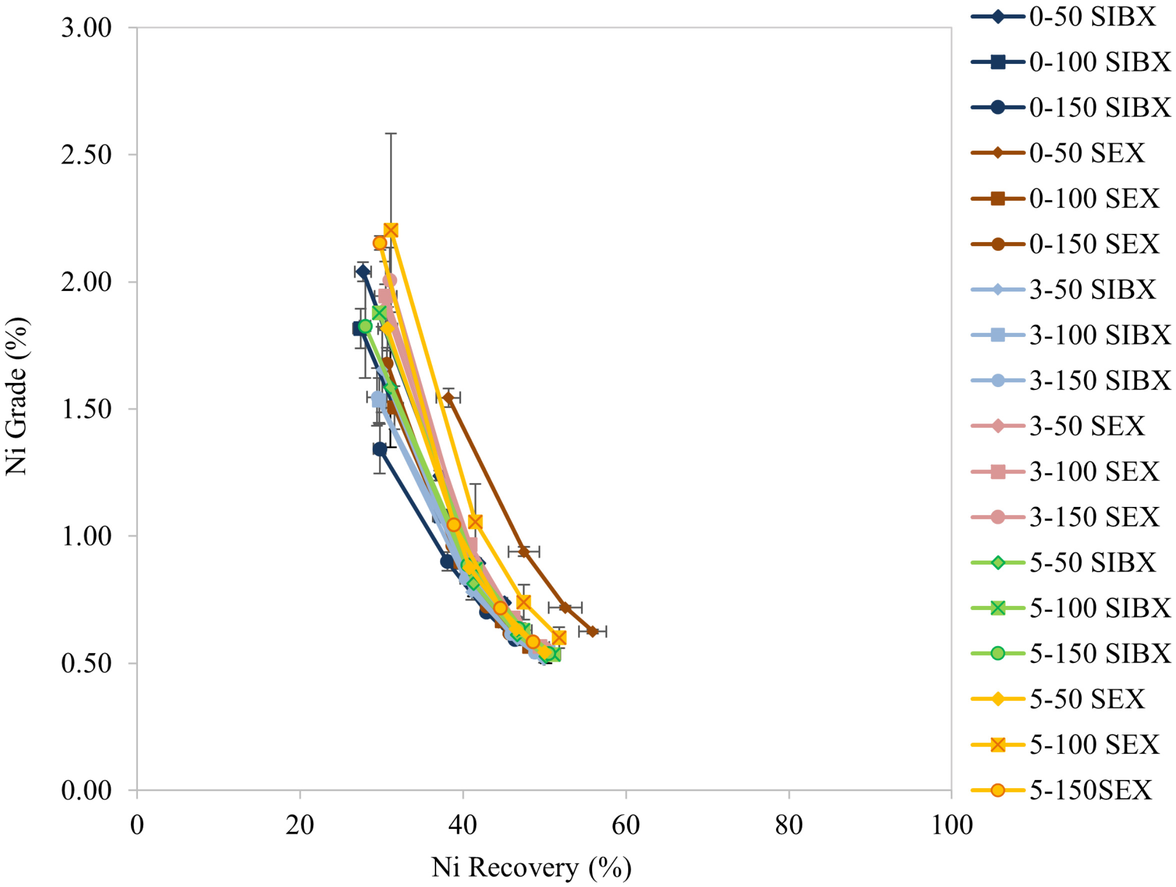


Figure 5.15: Cumulative nickel grade vs. nickel recovered. Error bars represent the standard error between duplicate tests

Figure 5.16 shows the nickel recoveries and grades for both 50 g/t of SEX and SIBX in water of varying ionic strengths. As the ionic strength of water increased, it was observed that the nickel recoveries were similar to each other, aside from in tap water. SIBX in tap water was the lowest at 45% and SEX the highest at approximately 55%.

Although there were no large differences in grade, it was noted that for both 3 and 5 SPW, SEX achieved higher grades than SIBX. However, in tap water, SIBX achieved the highest grade of approximately 4.8%, whilst achieving the lowest recovery. At 3 and 5 SPW, SIBX achieved the same grade, which was the lowest of the six conditions of 3.5%.

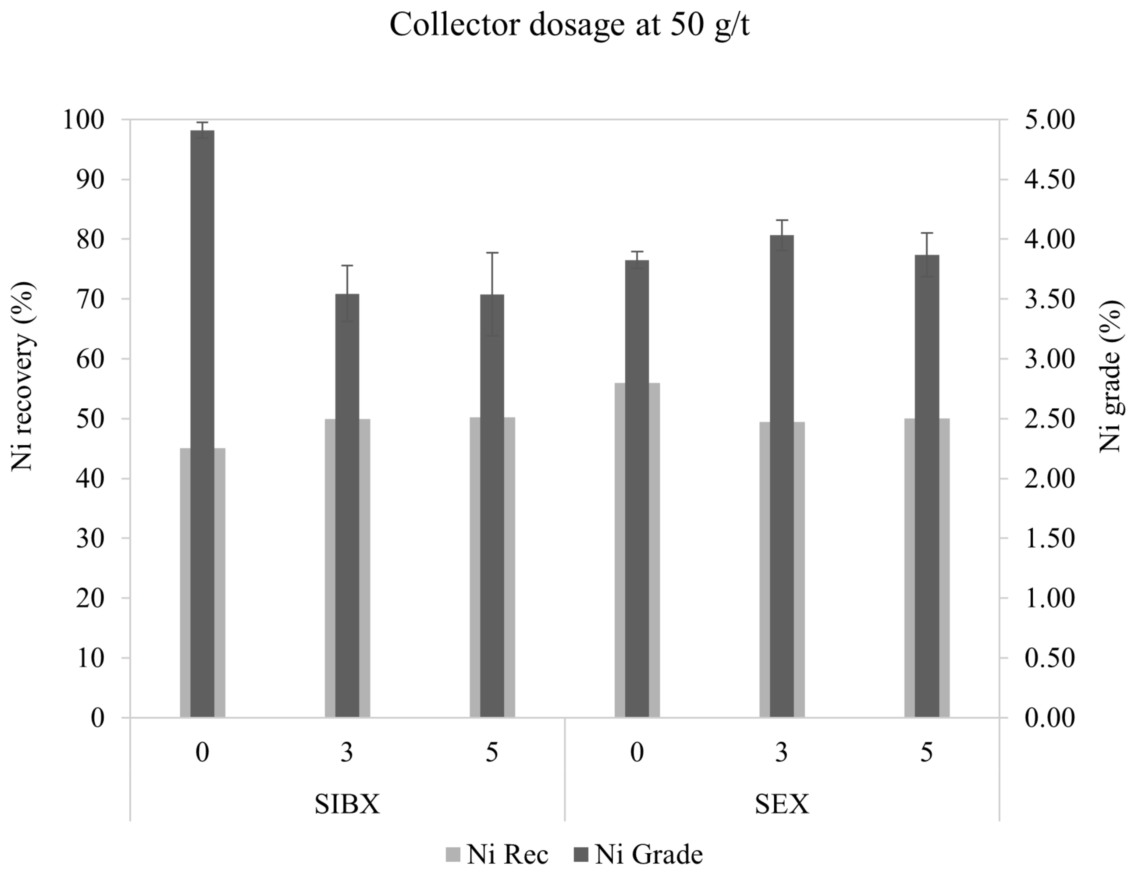


Figure 5.16: Nickel recoveries and grades under 0, 3 and 5 SPW at a dosage of 50 g/t. Error bars represent the standard error between duplicate tests

As shown in Figure 5.16, the lowest SEX grade obtained was approximately 3.8% and the highest, slightly above 4%, therefore, there was not much variation amongst the ionic strengths.

Figure 5.17. shows the nickel recovery and grade for both collectors at a dosage of 100 g/t. The nickel recovery was unaffected by changes in ionic strength and collector chain length as the recovery was approximately 50% for all conditions. This was aside from SIBX in tap water that obtained a recovery of approximately 45%.

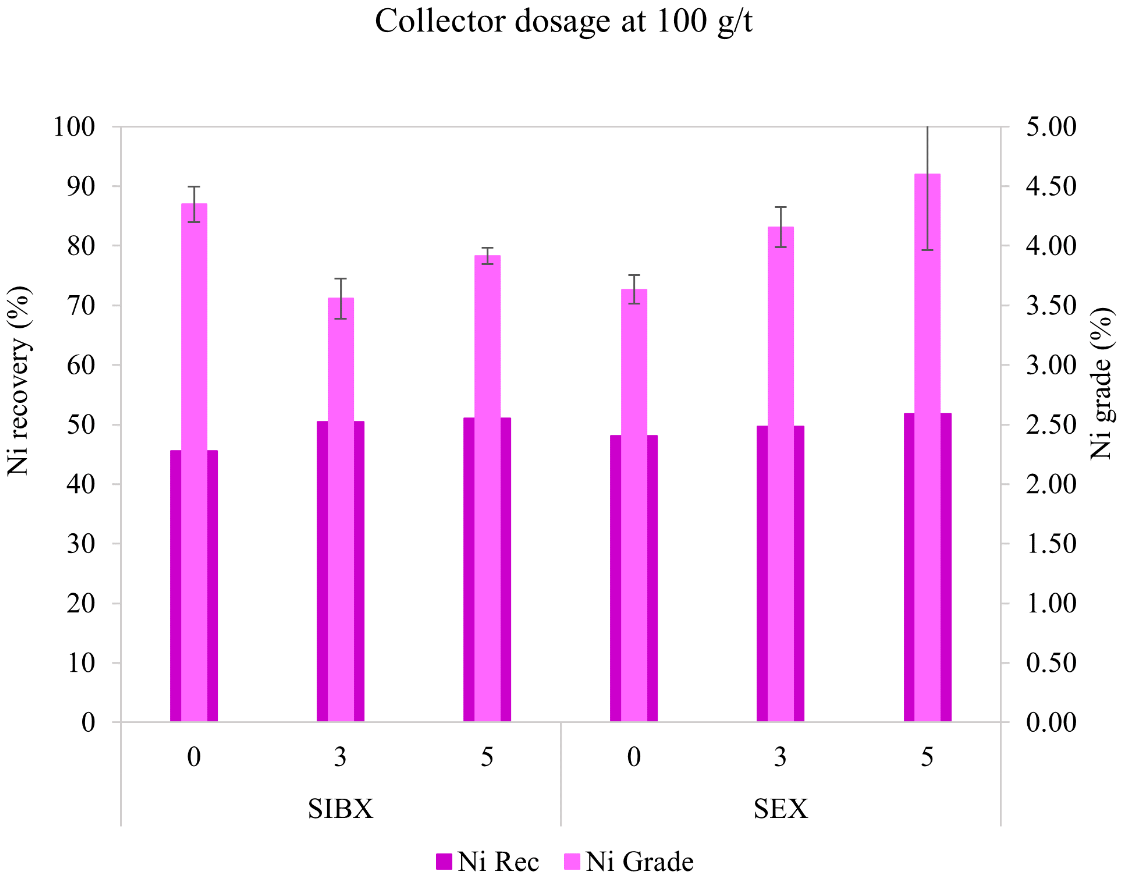


Figure 5.17: Nickel recoveries and grades under 0, 3 and 5 SPW at a dosage of 100 g/t. Error bars represent the standard error between duplicate tests

It was observed that SEX had an increase in grade with an increase in the ionic strength of the water with 5 SPW obtaining the highest grade of approximately 4.6%. At 3 and 5 SPW, SEX obtained a higher grade than SIBX at the same conditions, however, SIBX in tap water obtained higher than SEX. SIBX in 3 SPW and SEX in tap water obtained the lowest grade of slightly about 3.7%.

As shown in Figure 5.18, at a collector dosage of 150 g/t, the nickel recovery did not change with an increase in the ionic strength of the water. SEX obtained higher grades in comparison to SIBX in the same water type. There was also an increase in the grade observed with an increase in ionic strength for both collectors; aside from SIBX in 0 and 3 SPW where the achieved grade was similar at approximately 3.5%.

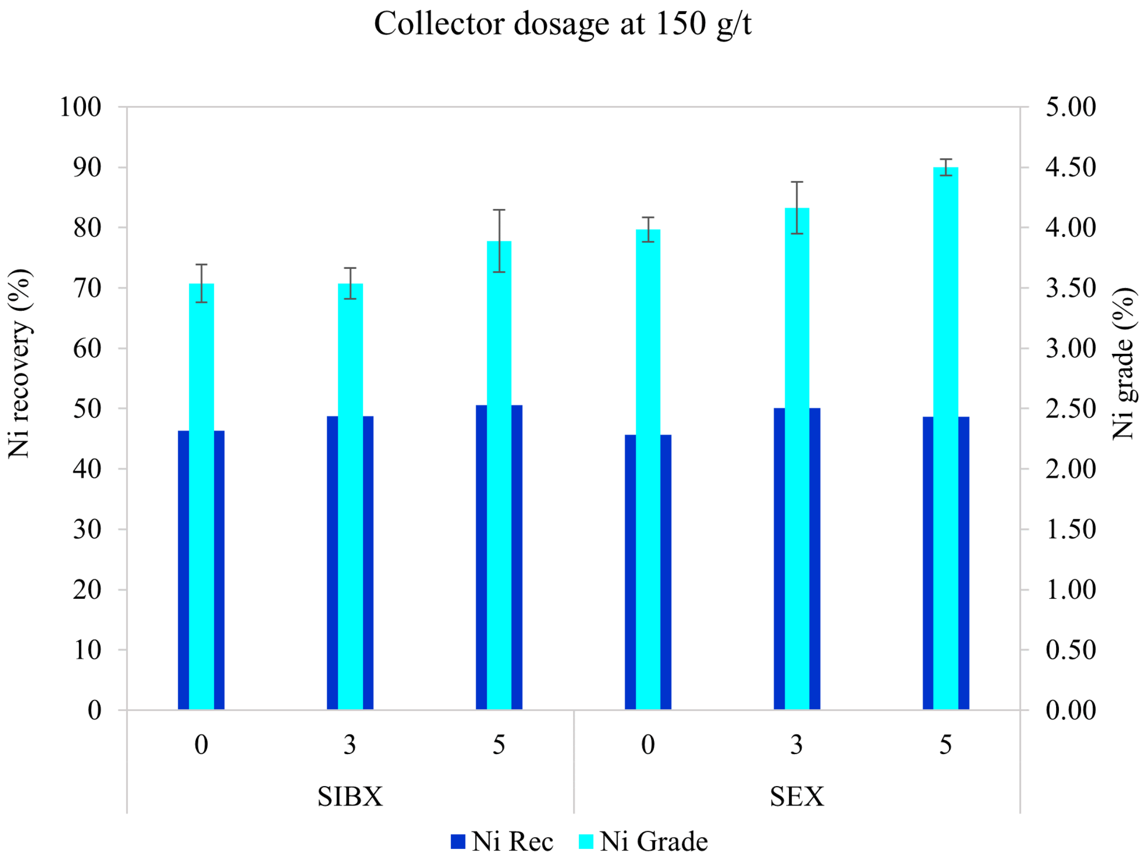


Figure 5.18: Nickel recoveries and grades under 0, 3 and 5 SPW at a dosage of 150 g/t. Error bars represent the standard error between duplicate tests

Therefore, based on the findings presented in Section 5.4 and Section 5.3, 50 g/t of SEX in tap water demonstrates the highest nickel recovery, while tap water at 50 g/t of SIBX results in the highest grade. For copper, the best recovery of 90% was at 3 SPW with 50 g/t of SEX, and the highest grade of 2.2% was at 50 g/t in 3 SPW.

5.5 The Entrainment Factor

Wiese et al. (2005) observed that at a dosage of 300 g/t of CMC depressant, all the gangue that reports to the concentrate can be attributed to entrainment. A middle point collector dosage of 100 g/t was utilised to determine the difference in entrainment in the different water types for the collectors. Figure 5.19 shows the total gangue versus cumulative water recovered for the batch flotation tests that utilised SEX and SIBX at a dosage of 100 g/t and CMC at 300 g/t in 3 SPW and 5 SPW.

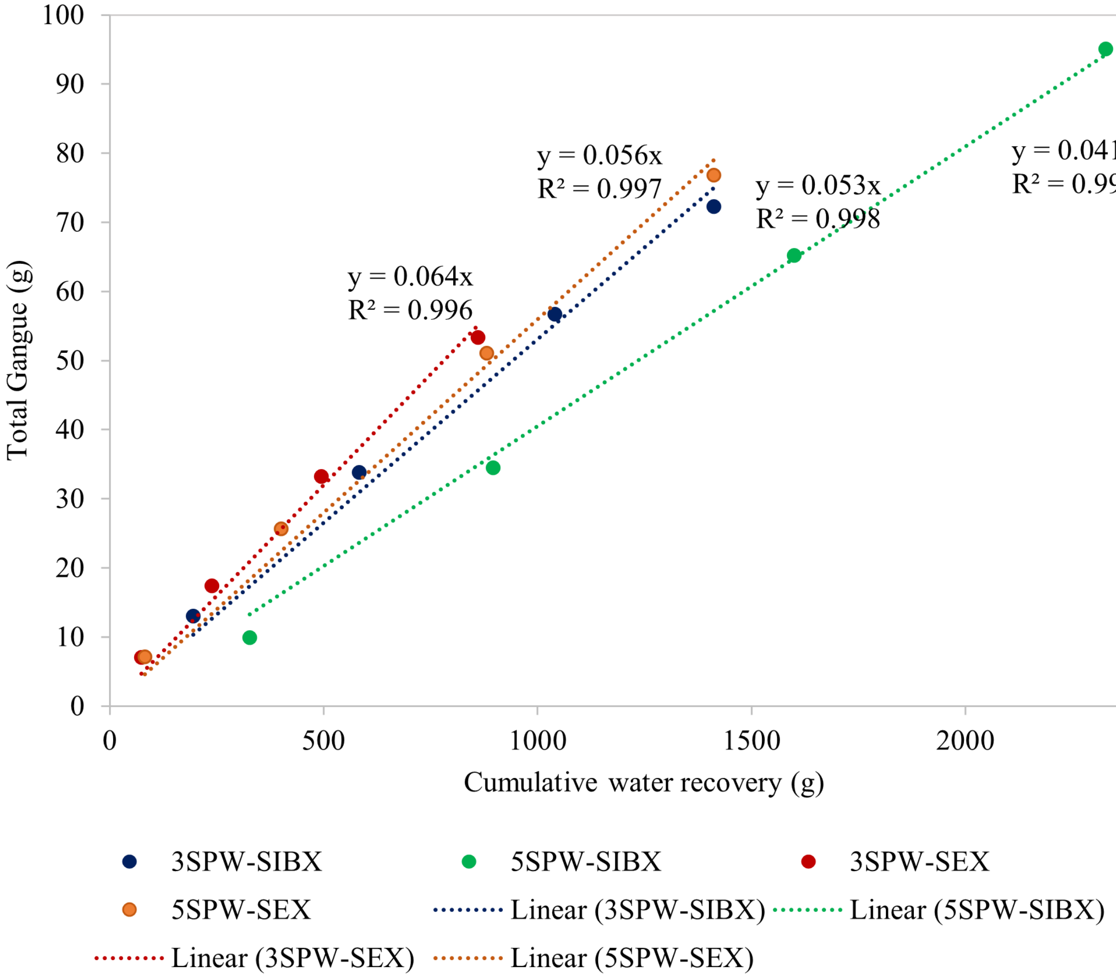


Figure 5.19: Total gangue vs. cumulative water recovered for SIBX and SEX at a dosage of 100 g/t and a CMC dosage of 300 g/t.

To calculate the total gangue, the mass of solids, mass of copper and mass of nickel was obtained from the batch flotation and XRF methodology outlined in Chapter 4. The gangue is then equivalent to the mass of solids minus the mass of copper and nickel as they are the target minerals.

At a dosage of 300 g/t of CMC in 0 SPW, neither collector was able to recover a mass of solids and water that would be sufficient to conduct a chemical analysis. Therefore, only the entrainment factors at 3 and 5 SPW were analysed.

The gradients are indicative of the entrainment factor, therefore, SEX in 3 SPW had an entrainment factor of 0.064, therefore, 0.064 g of solid material was entrained per 1 ml of recovered water. SEX in 3 SPW had the highest entrainment factor whilst SIBX in 5 SPW had the lowest with 0.041 g. SIBX had a lower entrainment factor in comparison to SEX in both water conditions. Both collectors had a decrease in the entrainment factor with an increase in ionic strength.

5.6 Zeta Potential Measurements

Figure 5.20 shows the zeta potential measurements for SEX and SIBX on chalcopyrite at a natural pH in water of varying ionic strengths. As shown in the figure, the zeta potential becomes less negative with an increase in ionic strength for all conditions.

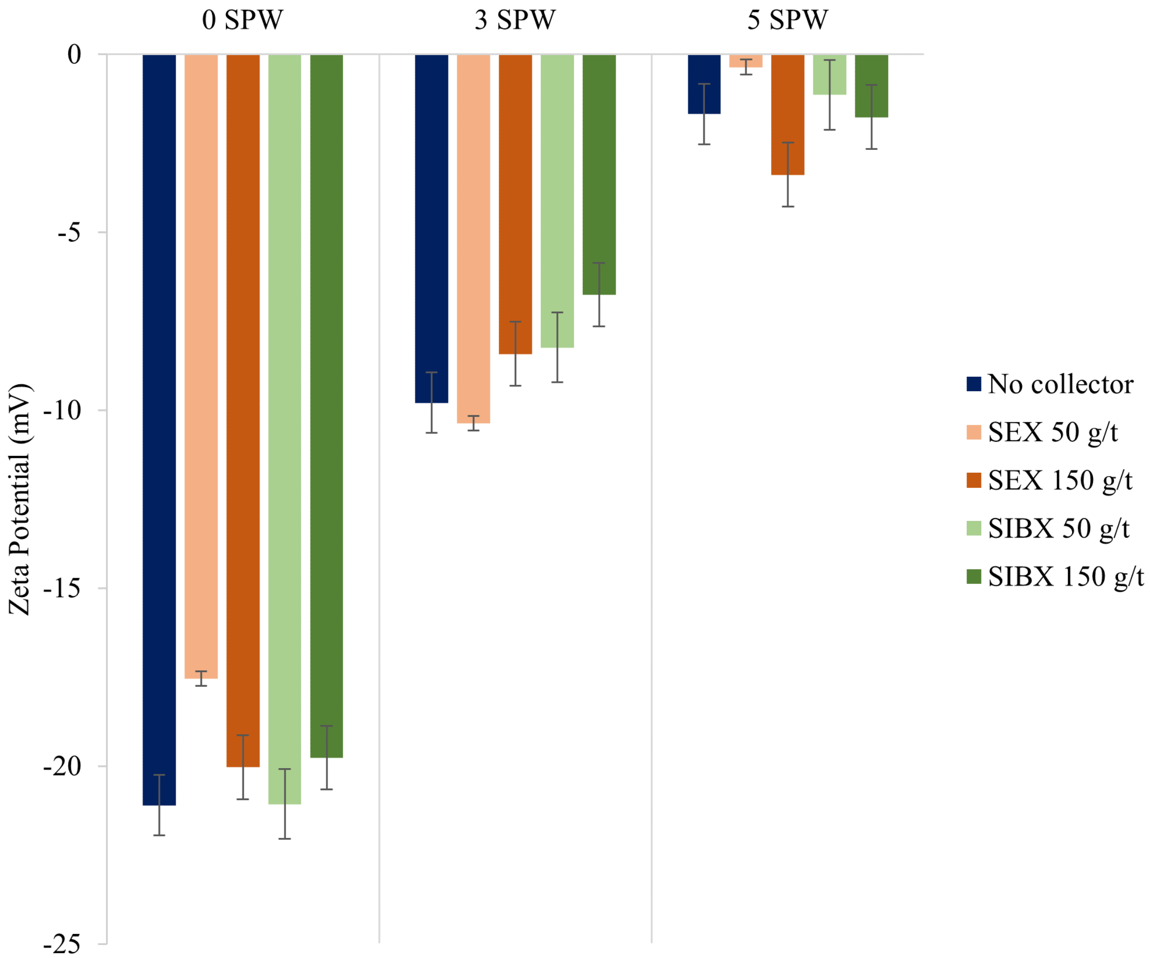


Figure 5.20: Chalcopyrite zeta potential measurements for SEX and SIBX at a natural pH in water of varying ionic strengths

It was expected that owing to the smaller molecule size, and lower steric hinderance due to the absence of a branched chain, SEX would be able to coat the chalcopyrite more easily than SIBX, resulting in larger changes in zeta potential in comparison to SIBX (Özün and Ergen, 2019).

In 0 SPW and 5 SPW, 50 g/t of SEX had the least negative zeta potential, whilst in 3 SPW, 150 g/t of SIBX had the least negative result. The largest change in zeta potential is also observed at a dosage of 50 g/t of SEX when the ionic strength of water was increased from 3 to 5 SPW. It was also observed that in 5 SPW, SEX had the sharpest decrease in zeta potential when the dosage of the collector was changed from 50 g/t to 150 g/t. 50 g/t of SEX had a zeta potential value of -0.36 MV, almost a tenth of what was observed at 150 g/t (-3.39 MV). The difference in the zeta potential observed between the two dosages of SIBX in 5 SPW, however, was not as large. In 0 SPW, 50 g/t of SIBX had a similar zeta potential value to no collector in 0 SPW.

5.7 Concentration of Residual Xanthates in the Tailings

The concentration of residual xanthate collectors in each tailing sample is shown in Figure 5.21. The highest residual concentration is at 50 g/t and 100 g/t of SIBX in 0 SPW. At a dosage of 150 g/t, there is a sharp decrease in the SIBX indicating that more of the collector was adsorbed onto the minerals. This increase in adsorption continues as the residual concentration of SIBX decreases further in 3 SPW. The trend of the residual concentration of SIBX changes as there is an increase in the concentration with an increase in dosage. This trend is observed in 5 SPW as well with the concentration at each dosage being similar to what was observed in 3 SPW.

The trend of residual collector with increasing collector concentration is the same across all three IS for SEX.

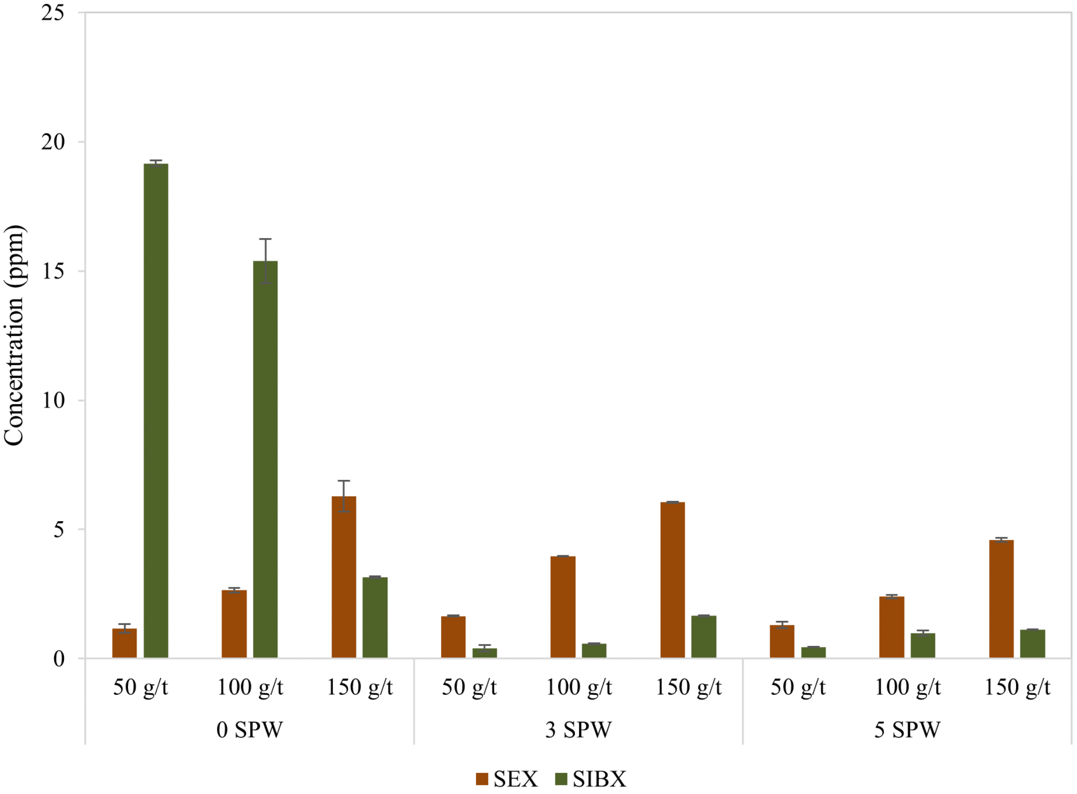


Figure 5.21: Concentration of residual xanthates in the tailings for each batch flotation condition. The error bars represent the difference between two flotation runs.

5.8 Settlement Tests

A lower settling time implies that there is flocculation of particles. As shown in Figure 5.22, the settling times for each of the samples taken from the tailings is shown. A decrease in settlement times for both collectors is observed when moved from 0 SPW to 3 SPW. However, for both collectors, there is an increase in the settling times for 50 g/t and 100 g/t. Furthermore, a decrease in the times is observed at a dosage of 150 g/t and at 5 SPW.

At all ionic strengths, 100 g/t of SEX has a longer settling time than SIBX, however, this is not the case for either of the other dosages. However, at 5 SPW, there is a steady decrease in settling times for SIBX with an increase in collector dosage. However, the longest settling for SEX was at the midpoint dosage of 100 g/t and this is the trend across all ionic strengths with the trend most pronounced in 5 SPW.

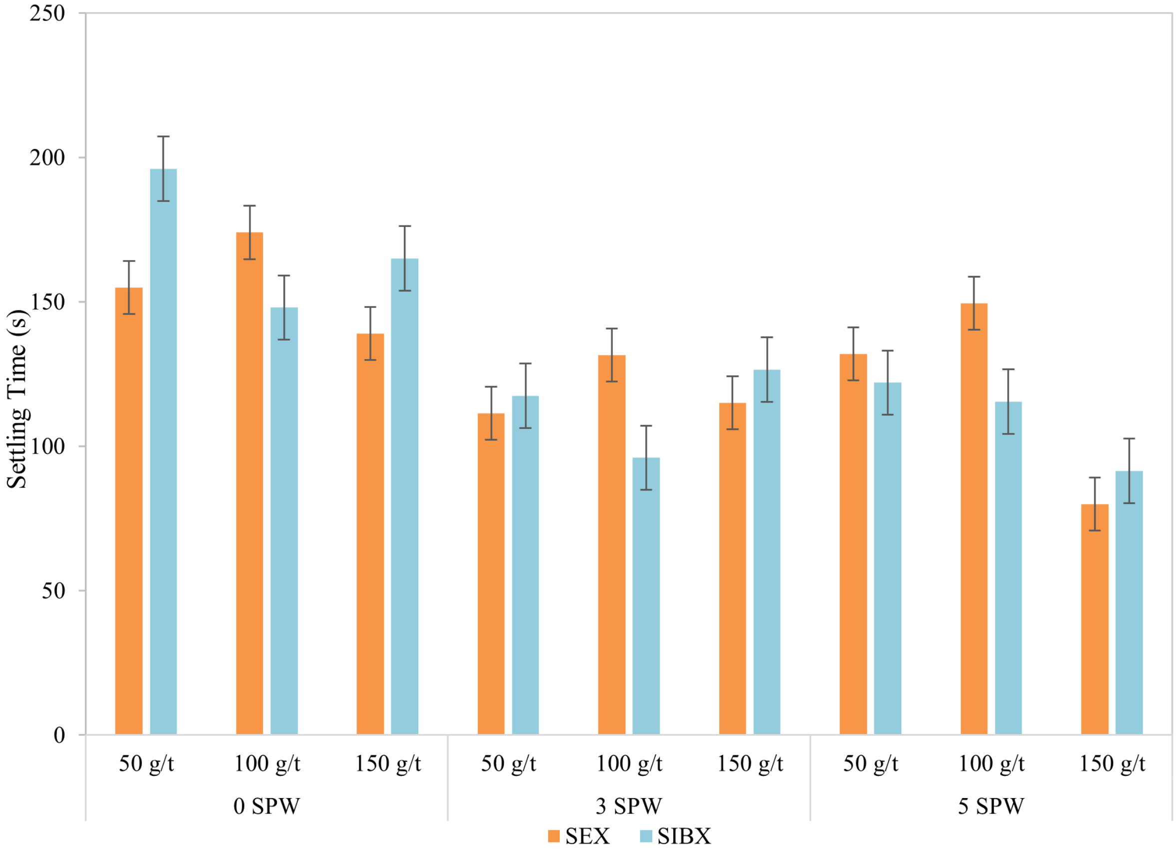


Figure 5.22: Settling time of solids in the tailing samples taken for each flotation condition

5.9 Key Observations

A summary of the key observations from the results described in this chapter are as follows:

5.9.1 Solids and Water Recoveries

- There was an increase in the recovery of solids and water with an increase in the ionic strength for both collectors.
- SEX had higher solids and water recoveries at 0 SPW than SIBX. As the ionic strength of the water increased there was a decrease in the difference in the recoveries. At the highest ionic strength (5 SPW), 100 g/t of SIBX had a higher solids recovery whilst a dosage of 50 g/t of SEX had the highest water recovery.
- A decrease in the solids and water recovery was observed at 150 g/t of SEX in 5 SPW and 150 g/t.
- Collector dosage had no apparent effect on the solids and water recoveries.

5.9.2 Copper and Nickel Recoveries and Grades

- Despite lower water recoveries than other conditions, 50 g/t of SIBX in 0 SPW recovered a similar amount of copper to the other conditions.
- 50 g/t of SIBX in 0 SPW also obtained the highest copper and nickel grade .
- The copper recoveries were not affected by any changes made to the collector chain length, dosage and ionic strength.
- The nickel recoveries had two flotation rate constants with 50 g/t of SEX in 0 SPW achieving a higher rate constant than the other conditions.
- The flotation rate constants were higher for copper than for nickel.

5.9.3 Zeta Potential Measurements

- The zeta potential became less negative with an increase in ionic strength for all conditions.
- 0 and 5 SPW recorded similar trends with respect to changes to the zeta potential with a change in collector chain length and collector dosage.

5.9.4 Entrainment

- SEX had a higher entrainment factor than SIBX in both 3 and 5 SPW.
- A decrease in the entrainment factor was seen with an increase in ionic strength for both collectors.

5.9.5 Residual Xanthate Concentrations in the Tails

- The highest residual xanthate concentration was observed when 50 and 100 g/t of SIBX were used in 0 SPW. These concentrations were significantly higher than what was observed with the other conditions.
- The trend in residual concentration with an increase in dosage was the same for all conditions aside from SIBX in 0 SPW.
- Residual concentrations of SIBX in 3 and 5 SPW had the same trend as SEX, indicating ionic strength had no effect.

5.9.6 Settlement of Tailings

- There was no definitive trend observed for SIBX with respect to the settling time.
- At all ionic strengths, the tails samples from the flotation experiments that used a dosage of 100 g/t SEX had the highest settling time in comparison to other SEX dosages.

Further explanation of these key observations is detailed in Chapter 6.

6. Discussion

The aim of this study was to investigate the effects of increasing collector chain length, collector dosage and ionic strength on flotation performance. In addition to this, the study investigated whether interactive effects existed among the three factors.

This chapter discusses and explains the key observations made on the results that were described in Chapter 5.

6.1 The Effect of Varying Ionic Strength on the Water and Solids Recoveries and Copper and Nickel Recoveries and Grades

In Section 5.2, it was observed that as the ionic strength of the water increased, the solids and water recoveries increased for both collector types. An increase in solids recovery is typically a result of increased water recovery which is attributed to an increase in the stability of the froth (Corin et al., 2011; Wiese, 2009).

The role of frothers as reagents in flotation is to increase the stability of the froth by decreasing the bubble size and inhibiting bubble coalescence (Rao, 2004). Studies found salts can also hinder bubble coalescence due to the electrical repulsive forces present when bubbles are brought into contact by the motion of the liquid (Lessard and Zieminski, 1971; Manono et al., 2013; Marrucci and Nicodemo, 1967). To indirectly measure bubble size, gas holdup measurements can be utilised as an increase in gas holdup occurs when bubble size decreases (Quinn et al., 2007). Quinn et al. (2007) found that an increase in the concentration of sodium chloride resulted in an increase in the gas holdup, indicating the salt had the ability to decrease the bubble size.

This decrease in bubble size also explains the increase in the solids recovered as a decrease in bubble size leads to an increase in the surface area available for bubble-particle attachment, leading to more particles attaching to the bubbles (Hewitt et al., 1994). Bubble-particle attachment may also be increased when the electrical double layers undergo ion-induced compression, leading to an increase in the recovery of solids (Kurniawan et al., 2011; Li et al., 2017)

Despite the increase in the recoveries of solids with an increase in ionic strength, copper and nickel recoveries were not affected by changes to the ionic strength of the water, collector dosage and collector type by more than 20%. Figure 5.7 shows that at all experimental conditions, (water type, collector type and dosage), copper recovery as a function of time fits a first-order response. This trend in the recovery of copper with a change in ionic strength was also observed by Corin et al. (2011) which found chalcopyrite's recovery to be independent of ionic strength.

However, the zeta potential results in Figure 5.20 show that an increase in the ionic strength resulted in a less negative zeta potential on the chalcopyrite surface. This indicates that the electrostatic repulsion between the particle surfaces decreases with an increase in the presence of ions (Ikumapayi et al., 2012; Li et al., 2017). This decrease in electrostatic repulsion should result in an increase in the recovery of the chalcopyrite mineral (Li et al., 2017). A possible reason why there are no changes observed in the recovery is the fast floating nature of chalcopyrite which is not impacted by changes to the ionic strength, collector dosage and collector chain length (Corin et al., 2022).

Figure 5.14 shows Nickel had two first-order response curves with 50 g/t of SEX in 0 SPW water having a higher flotation rate than the other conditions; indicating that pentlandite (represented by nickel recovery) is partially affected by the changes in flotation conditions. 0 SPW is tap water from the City of Cape Town, therefore, there may be variations in the concentrations of the salts in the tap water (City of Cape Town, 2021). A decrease in the presence of calcium and magnesium ions in the tap water at low depressant dosages would increase the recovery of nickel (Afolabi et al., 2012; Ikotun et al., 2017; Rao, 2013). This is because the sensitivity of pentlandite to calcium and magnesium ion concentrations causes surface passivation (Bremmell et al., 2005; Hirajima et al., 2016). Conversely, an increase in sodium ions, known to activate mineral surfaces, could enhance their recovery (Li et al., 2017).

However, it is unlikely that the regulated Cape Town water supply could result in a variation large enough that would solely be responsible for the difference in flotation rate (Municipality, 2021). In addition to this, there was no variation in nickel recovery amongst the other 0 SPW runs. Therefore, the effect of dosage and the shorter, more selective collector may have had an effect that led to the increase in the nickel recovery. This will require further investigation.

It was noted in the key observations that for most conditions, the grade for copper was unaffected by the changes in ionic strength (Figures 5.11, 5.12 and 5.13). Nickel did vary between 0.5-1%, showing once again, pentlandite was slightly affected by the reagents chemistry. It was expected that an increase in the ionic strength would lead to higher froth stability, higher water recoveries and therefore, more entrainment resulting in a decrease in the grade of the valuable minerals (Corin et al., 2011, 2022; Wiese, 2009).

Furthermore, this expected increase in entrainment with an increase in ionic strength was not observed in Section 5.5 where entrainment was investigated. The results in Section 5.5 showed both collectors had higher water recoveries with an increase in ionic strength but recorded a decrease in the entrainment factor.

Studies have found these unexpected results may point towards interactive effects that exist between collector type, dosage and ionic strength that may have stabilised the grades despite the increase in water recovery (McFadzean et al., 2016). These possible synergistic effects will be discussed further in Section 6.4.

6.2 The Effect of Collector Chain-Length on the Water and Solids Recoveries and Copper and Nickel Recoveries and Grades

As described in Chapter 2.3, longer chained collectors have a larger contact angle on the bubble surface (Rao and Finch, 1989). This increase in the contact angle results in higher hydrophobicity and higher bubble-particle attachment efficiency (Goktepe, 2001; Xie et al., 2016). Therefore, in Section 3.3, it was hypothesised that SIBX would achieve higher solids and water recoveries than SEX due to the increase in hydrophobicity caused by an increase in the hydrophobic hydrocarbon chain length.

However, in this study, SIBX had lower solids and water recoveries than SEX, and this was more pronounced at low ionic strengths. As explained in the discussion on the effects of ionic strength on flotation performance in Section 6.1, lower water recoveries imply lower froth stabilities (Corin et al., 2011; Wiese, 2009). Wiese et al. (2011) had observed a similar trend with SIBX consistently achieving lower solids and water recoveries than SEX at low depressant dosages in 1 SPW. Dippenaar (1978) found that when SIBX and SEX were compared in the flotation of galena, SEX's contact angle of 60° had a higher froth stability than SIBX. The 70° contact angle from SIBX led to a destabilisation of the froth. The size of the contact angle was too large and resulted in the rupture of bubbles, decreasing the froth stability.

Park et al. (2018) found that an increase in contact angles resulted in an increase in the froth stability up until a maximum contact angle of 70°. The study found that a contact angle of $\theta = 85°$ was a critical contact angle as there was a substantial decrease in froth stability after the angle. Investigations by Schwarz and Grano (2005) and Johansson and Pugh (1992) found that froth stability reaches its maximum at contact angles significantly below 90°.

Some base metal sulfides have a degree of natural hydrophobicity that has previously been found to destabilize froths (Gardner and Woods, 1979; Huang et al., 2019; Mendiratta, 2000; Pugh, 1996). However, these froth destabilisation effects are significantly diminished at particle sizes greater than 74 μm (Johansson and Pugh, 1992). Therefore, at the grind size used in this study of 60% passing 75 μm, the hydrophobicity of the mineral surfaces on their own may not have had a significant effect. However, there may have been coupled secondary effects of particle hydrophobicity and a longer chain length that led to the destabilisation of the froth as the critical contact angle may have been surpassed, resulting in lower solids and water recoveries (Bradshaw et al., 2005).

As shown in Figures 5.11 and 5.16, the highest grades for both nickel and copper observed at 50 g/t of SIBX in 0 SPW. This condition also recorded the lowest water recovery as shown in Figure 5.4 and the highest residual xanthate concentration(Figure 5.21). As lower water recoveries are typically associated with lower entrainment, the decrease in the presence of gangue in the concentrate would lead to higher grades. This difference in entrainment is further illustrated in Figure 5.19 which shows SIBX obtained a lower entrainment factor than SEX.

It was expected that as SEX had higher solids and water recoveries, there would be a decrease in the grades observed. However, The bar graphs in Sections 5.3 show that aside from 50 g/t of SIBX in 0 SPW, there was no significant difference between the collectors in the copper grades obtained. However, as seen in Figure 5.18, increasing collector chain length partially affected the nickel grades as aside from 50 g/t in 0 SPW, the lowest grades were consistently observed with SIBX. Ikotun et al. (2017) found SEX had higher nickel grades than SIBX due to its ability to form complex metal complexes with the mineral surfaces, increasing the collector's selectivity towards nickel. The added ability of the longer chained collector to adsorb onto mineral surfaces due to more efficient bubble-particle attachment efficiency further decreases its ability to be selective towards the valuable mineral in the study (Huang et al., 2019).

The recovery remained unaffected by the change in collector type, potentially indicating that the minerals had reached their maximum liberation, allowing for the recovery of nearly all available particles regardless of the collector used (Moimane, 2015).

The zeta potential results in Figure 5.20 show differences in the surface potential in comparison to the condition with no collector. This indicates adsorption onto the chalcopyrite surfaces (Ikumapayi et al., 2012; Huang et al., 2019). However, SIBX in 0 SPW did obtain a potential that was not significantly different to the potential with no collector. Therefore, SIBX in 0 SPW may have not adsorbed as efficiently as SEX onto the mineral surfaces leading to higher residual xanthate concentrations in the tailings as shown in Figure 5.21. There was a significant decrease in the concentration of residual SIBX in 3 and 5 SPW. This decrease may indicate an increase in the adsorption of collector due to the increase in the presence of ions that may have improved the adsorption (Goktepe, 2001; Ikumapayi et al., 2012).

In Figure 5.22, distinct settling time trends are observed for the two collectors, SIBX and SEX. Initially, an increase in collector dosage leads to a decrease in settling time for SIBX, but at 150 g/t, settling time increases. This implies that there is a decrease in flocculation at the higher dosage. This behavior is consistent for 0 and 3 SPW, except for 5 SPW, where settling time decreases at 150 g/t.

In contrast, SEX exhibits the opposite trend: settling time increases at 100 g/t but decreases at 150 g/t. These trends are consistent across all three ionic strengths, highlighting the complex and contrasting effects of collector dosage on settling time. Flocculation affects downstream processes such as dewatering, therefore, dosage optimization is required to acheive the desired settling characteristics in the flotation process (Amarjargal and Taşdemir, 2023).

6.3 The Effect of Collector Dosage on Water and Solids Recoveries and Copper and Nickel Recoveries and Grades

Studies have shown an increase in collector dosage can lead to an increase in mineral recovery as there is more collector available to retrieve the valuable minerals from the pulp (Langa et al., 2014; Mpongo and Siame, 2010).

Ostadrahimi et al. (2021) found that an increase in collector dosage resulted in higher froth recoveries, indicating a more stable froth (Farrokhpay, 2011). This increase in froth stability was due to the increase in the number of hydrophobic particles in the froth. Therefore, it would be expected that an increase in collector dosage would result in higher solids and water recoveries due to the increase in hydrophobic particles reporting to the froth and the subsequent froth stability.

However, as seen in Figures 5.1 and 5.2, there was no clear trend in the solids and water recoveries for either collector when the dosage was increased implying collector dosage had little or no effect on the froth stability under the conditions used within this study. Figures 5.7 and 5.14 show similar results as the recoveries of the minerals did not increase. This can be explained by the allotted time being sufficient for the collection of all the minerals as discussed in Section 6.1 and 6.2.

Figure 5.21 shows that there was an increase in the residual xanthate with an increase in the dosage of SEX across all ionic strengths. This suggests the degree of adsorption did not change with dosage and the usage of SEX can be decreased for reagent optimisation. SIBX in 0 SPW follows a different trend with there being a significant decrease in residual xanthate concentration as the dosage increases from 50 g/t to 150 g/t. However, the residual SIBX concentration increases with an increase in collector dosage in 3 and 5 SPW, similar to what was observed with SEX. However, despite the lack of adsorption of SIBX in 0 SPW, the condition still achieved similar grades to the other flotation conditions and the highest copper and nickel grades.

Furthermore, in Figure 5.22, it is shown that collector dosage does not affect the settlement time of the solids in the tailings. This implies there are no changes in the flocculation of solids in the tailings.

6.4 The Interactive Effects of Ionic Strength, Collector Chain-Length and Dosage on the Water and Solids Recoveries and Copper and Nickel Recoveries and Grades

Studies show both longer collector chain length and ionic strength can improve the froth stability by increasing the number of particles in the froth by increasing their hydrophobicity (Rao and Finch, 1989; Goktepe, 2001) and decreasing bubble size resulting in an improvement in the bubble-particle attachment efficiency (Kurniawan et al., 2011; Li et al., 2017; Hewitt et al., 1994; Quinn et al., 2007). However, longer chained collectors have been found to destabilise froths as they can surpass critical contact angles.

In the figures in Section 5.2 that show the solids and water recoveries, it appears simultaneously increasing the ionic strength and collector chain length resulted in the ions offsetting the froth-destabilising effect of SIBX. This is shown by the difference in the trends in water recovery as 50 g/t and 100 g/t of SIBX have a significantly lower recovery than SEX, whilst in 3 and 5 SPW, the difference in results is lower and SIBX recovers more than SEX.

Furthermore, the solids recoveries follow a similar pattern with SEX at 50 and 100 g/t achieving higher recoveries than SIBX in 0 SPW. However, once the ionic strength is increased to 3 SPW and 5 SPW, there is a significant increase in the water recovered. An increase in the concentration of ions such as Na^+ have been found to decrease the bubble size leading to greater froth stability (Marrucci and Nicodemo, 1967; Quinn et al., 2007).

A simultaneous increase in the ionic strength and dosage of SEX in 3 and 5 SPW resulted in a decrease in the solids and water recovery that was not observed with SIBX. This may be a result of froth destabilisation due to exceeding the critical contact angle that could not be overcome by the stabilising effect of the ions. In addition to this, studies have found that superhydrophobicity can occur at contact angles that are greater than 150° (Law, 2014). However, the changes to the wetting and adhesion interactions have been found to change before this and can contribute to an unpredictable froth phase (Law, 2014; Celia et al., 2013; Samuel et al., 2011).

Simultaneously increasing the collector chain length and ionic strength did lead to lower nickel grades as seen in other studies (Ikotun et al., 2017). SIBX at 50 g/t in 0 SPW achieved the highest grades in comparison to the other conditions. However, at higher ionic strengths, the usage of SIBX resulted in lower nickel grades than what was observed with SEX. However, the entrainment factor was observed to decrease with an increase in ionic strength and collector chain length (Figure 5.19). Therefore, the decrease in grades may have been due to the true flotation of gangue particles owing to the lower selectivity of SIBX (Xie et al., 2016).

7. Conclusions

It is known that collectors are used to selectively alter the hydrophobicity of valuable mineral surfaces to improve their recovery. However, their effectiveness has been thought to be affected by their type, dosage and pulp conditions like the concentrations of ions.

This study aimed to determine both the individual and simultaneous effects of changing the ionic strength of plant water, collector chain length and collector dosage on the flotation response of a Merensky ore. This was to investigate how the flotation performance can be maintained or improved with the usage of collectors under conditions of varying ionic strength of plant water. It was hypothesised that the simultaneous usage of a longer chained collector, higher collector dosage and increased ionic strength would lead to higher solids recovery and a lower grade of concentrate.

Therefore, the final conclusions are in the following sections.

7.1 Individual and Interactive Effects of Collector Type, Dosage and Ionic Strength on the Solids and Water Recoveries

- At low ionic strengths, the longer chained collector, SIBX, results in lower solids and water recoveries than SEX. This is due to the froth-destabilising abilities that longer chained collectors have been observed to portray when utilised at low depressant dosages.

- An increase in ionic strength offsets the froth-destabilising effects caused by the longer chained collector. This results in SIBX following the expected trend of obtaining higher solids and water recoveries than SEX.

- SEX has an increase in solids and water recovered with an increase in ionic strength. However, at high dosages, and in higher ionic strengths of SPW, a decrease in the recoveries is observed. This implies the froth may have been destabilised by hydrophobic conditions that exceed the critical contact angle.

- Individually, collector dosage did not appear to have a significant effect on the solids and water recoveries.

- Collector dosage showed interactive effects with high ionic strength of SPW and shorter collector chain length.

- Collector chain length did not have a discernable trend in the settlement times, implying the composition of the tailings is not significantly impacted by changing the collector. This is a positive outcome as there may be no changes required to downstream dewatering processes if the collector needs to be changed.

7.2 Individual and Interactive Effects of Collector Type, Dosage and Ionic Strength on Copper Recoveries and Grades

- The copper recovery and grades are independent of the changes made to ionic strength of SPW, collector chain length and dosage. All conditions fit onto a first-order kinetics model. This is despite the zeta potential measurements showing a decrease in the negativity of the chalcopyrite surface potential with an increase in ionic strength, indicating increased hydrophobicity. Therefore, this indicates the lack of variation in the copper recovery is due to all the available copper having been collected in the allotted time, regardless of condition and this can be attributed to the fast-floating nature of chalcopyrite.

7.3 Individual and Interactive Effects of Collector Type, Dosage and Ionic Strength on the Nickel Recoveries and Grades

- The nickel recovery and grades are slightly affected by changes in collector chain length and ionic strength of SPW as there were two flotation recovery rate responses.
- 50 g/t of 0 SPW achieved the highest nickel grade due to the lower water recoveries which led to less gangue being recovered in the concentrate.
- Aside from 50 g/t in 0 SPW, the lowest nickel grades were consistently observed with SIBX. The degree of entrainment decreased with an increase in collector chain length, therefore, the lower nickel grade obtained is due to the lower selectivity towards copper and nickel of the longer chained collector.

7.4 Amongst the Collector Chain Length, Dosage and Ionic Strength of SPW, Which Factor Had the Largest Impact on the Flotation Response on the Merenksy Ore?

- The study found increases in the ionic strength led to the strongest responses in terms of solids and water recoveries, zeta potential and entrainment. Ionic strength also had an effect on the performance of the collectors as an increase in the ionic strength of SPW improved the solids and liquid recoveries of the longer chained collector. Therefore, amongst the factors, collector chain length, dosage and ionic strength of SPW, the ionic strength of SPW would have the largest impact on flotation performance. However, the effects of the collector chain length and dosage should not be ignored. There are interactive effects with ionic strength that can destabilise the froth phase and lead to lower solids recovery and grades.

The conclusions of this study re-emphasise the importance of understanding the impact of varying water quality in the flotation process. The ionic strength, a component of water quality, seemed to have more pronounced effects on flotation performance than changes to collector chain length and dosage. Additionally, the interactive effects observed show ionic strength can influence the behaviour of the collector. Therefore, further investigation into the recirculation of process water and its components could provide the mineral processing industry with more control over the flotation system when water is recycled.

8. Recommendations

Based on the results and conclusions of this study, the following recommendations are made:

- Future work needs to evaluate whether the observations of this study are unique to the Merensky ore, different ore types should be used for the same study.
- Longer, straight-chained collector such as PAX would be useful in determining whether there are any steric hindrances from the structure of the branched collector that may have led to the initial froth-destabilisation observed with SIBX at low ionic strengths of SPW.
- Consider changing the concentration of specific ions to determine if they have an effect in xanthate adsorption studies on pentlandite and chalcopyrite surfaces.
- To obtain a deeper understanding of the effects of water recycling on flotation performance, this study can be broadened to include more pollutants e.g. organics.

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Appendix A: Merensky Ore Batch Flotation Raw Data

Table 8.1: Raw batch flotation data for 50 g/t of SIBX in 0 SPW

Reagents	**Type**	**Dosage**						
SPW	0 SPW							
Frother	Dow200	40	g/t					
Collector	SIBX	50	g/t					
Depressant	CMC	100	g/t					
Run 1								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	28.04	33.16	34.54	29.27	27.71	23.51	28.31	873.87
Paper	9.35	9.45	9.35	9.61	9.83	9.85	9.67	25.91
B + H_2O	678.95	682.77	676.77	676.93				
Bottle	550.08	445.39	293.71	271.27				
D + C + H_2O	482.37	597.13	722.21	737.89				
Dish	232.85	184.93	171.47	191.98				
Run 2								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	30.04	32.85	33.13	30.47	25.32	24.32	25.80	868.12
Paper	9.79	9.61	9.80	9.74	9.56	9.45	9.65	30.20
B + H_2O	676.66	686.68	682.79	680.50				
Bottle	526.53	461.62	368.19	241.26				
D + C + H_2O	505.49	614.37	655.38	817.54				
Dish	232.69	184.69	171.12	191.96				
	Mass of Solids (g)					**Mass of Water (g)**		
	Run 1	Run 2	Average			Run 1	Run 2	Average
C1	18.69	20.25	19.47			101.96	102.42	102.19
C2	23.71	23.24	23.48			142.49	146.33	144.41
C3	25.19	23.33	24.26			151.11	181.38	166.25
C4	19.66	20.73	20.20			120.59	165.61	143.10
F	967.51	956.49						
T	847.96	837.92						
T2	13.66	14.87						
T3	18.64	16.15						

Table 8.24: Raw batch flotation data for 100 g/t of SIBX in 0 SPW

Reagents	**Type**	**Dosage**						
SPW	0 SPW							
Frother	Dow200	40	g/t					
Collector	SIBX	100	g/t					
Depressant	CMC	100	g/t					
Run 1								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	30.83	38.31	35.54	32.76	28.4	29.29	27.43	848.6
Paper	9.73	9.78	9.73	9.85	9.45	9.53	9.49	16.18
B + H_2O	681.65	681.59	673.93	665.68				
Bottle	609.46	532.54	377.84	332.29				
D + C + H_2O	476.86	653.18	733.18	842.22				
Dish	232.63	184.25	171.02	191.13				
Run 2								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	32.40	37.59	38.10	32.84	28.35	24.93	26.42	846.80
Paper	9.56	9.44	9.72	9.74	9.62	9.50	9.56	16.23
B + H_2O	669.10	687.92	622.40	673.30				
Bottle	612.26	467.90	276.12	237.43				
D + C + H_2O	498.81	709.63	808.05	973.46				
Dish	232.82	184.27	171.20	191.15				
	Mass of Solids (g)					**Mass of Water (g)**		
	Run 1	Run 2	Average			Run 1	Run 2	Average
C1	21.10	22.84	21.97			150.94	186.31	168.63
C2	28.53	28.15	28.34			240.26	262.19	251.23
C3	25.81	28.38	27.10			291.35	277.19	284.27
C4	22.91	23.10	23.01			294.79	323.34	309.06
F	968.47	965.33						
T	832.42	830.57						
T2	19.76	15.43						
T3	17.94	16.86						

Table 8.3: Raw batch flotation data for 150 g/t of SIBX in 0 SPW

Reagents	**Type**	**Dosage**						
SPW	0 SPW							
Frother	Dow200	40	g/t					
Collector	SIBX	150	g/t					
Depressant	CMC	100	g/t					
Run 1								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	46.43	39.07	37.2	34.6	27.53	24.56	28.22	830.56
Paper	9.56	9.3	9.74	9.77	9.39	9.35	9.70	38.65
B + H_2O	665.24	662.37	680.52	647.23				
Bottle	581.06	490.01	421.02	320.67				
D + C + H_2O	610.04	670.62	731.45	840.35				
Dish	232.53	184.32	171.09	191.22				
Run 2								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	40.07	40.46	39.21	36.13	29.66	27.08	27.26	879.35
Paper	9.66	9.78	9.75	9.74	9.67	9.65	9.58	45.59
B + H_2O	663.02	679.90	679.46	678.40				
Bottle	601.45	529.08	442.17	397.16				
D + C + H_2O	540.18	631.60	712.78	802.98				
Dish	232.67	184.53	171.38	191.51				
	Mass of Solids (g)					**Mass of Water (g)**		
	Run 1	Run 2	Average			Run 1	Run 2	Average
C1	36.87	30.41	33.64			256.46	215.54	236.00
C2	29.77	30.68	30.23			273.40	274.66	274.03
C3	27.46	29.46	28.46			284.17	265.575	274.87
C4	24.83	26.39	25.61			297.74	303.84	300.79
F	944.57	985.81						
T	791.91	833.76						
T2	15.21	17.43						
T3	18.52	17.68						

Table 8.4: Raw batch flotation data for 50 g/t of SEX in 0 SPW

Reagents	**Type**	**Dosage**						
SPW	0 SPW							
Frother	Dow200	40	g/t					
Collector	SEX	50	g/t					
Depressant	CMC	100	g/t					
Run 1								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	39.11	40.32	37.24	32.58	21.18	14.98	27.72	867.18
Paper	9.67	9.39	9.45	9.42	9.50	9.58	9.70	17.21
B + H_2O	686	674.53	680.73	676.81				
Bottle	574.89	500.28	400.90	273.67				
D + C + H_2O	609.13	719.21	798.34	917.68				
Dish	232.52	184.15	171.04	191.01				
Run 2								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	33.63	38.00	40.68	30.48	26.78	25.64	17.60	851.00
Paper	9.20	9.36	9.03	9.06	9.53	9.58	9.52	17.37
B + H_2O	656.25	687.82	639.42	631.54				
Bottle	571.51	538.39	330.23	260.25				
D + C + H_2O	520.60	638.14	856.23	816.29				
Dish	233.14	185.02	172.68	191.84				
	Mass of Solids (g)					**Mass of Water (g)**		
	Run 1	Run 2	Average			Run 1	Run 2	Average
C1	29.44	24.43	26.94			236.06	178.29	207.17
C2	30.93	28.64	29.79			319.68	342.71	331.20
C3	27.79	31.65	29.72			329.88	275.05	302.47
C4	23.16	21.42	22.29			300.37	231.74	266.05
F	984.71	963.91						
T	849.97	833.63						
T2	5.40	16.06						
T3	18.02	8.08						

Table 8.5: Raw batch flotation data for 100 g/t of SEX in 0 SPW

Reagents	**Type**	**Dosage**						
SPW	0 SPW							
Frother	Dow200	40	g/t					
Collector	SEX	100	g/t					
Depressant	CMC	100	g/t					
				Run 1				
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	43.89	39.00	45.09	37.83	26.52	15.19	34.80	810.00
Paper	9.66	9.62	9.65	9.85	9.79	10.08	9.20	24.77
B + H_2O	657.39	665.02	670.54	669.31				
Bottle	573.83	539.05	402.50	343.76				
D + C + H_2O	628.98	628.30	908.96	947.57				
Dish	233.22	184.54	171.62	191.61				
				Run 2				
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	43.11	54.13	47.84	39.9	30.62	28.5	31.21	872.3
Paper	14.34	14.36	14.36	14.60	14.38	14.54	13.75	42.00
B + H_2O	567.62	462.09	661.49	583.97				
Bottle	497.82	293.01	413.01	281.94				
D + C + H_2O	628.98	628.30	908.96	947.57				
Dish	233.22	184.54	171.62	191.61				
	Mass of Solids (g)					**Mass of Water (g)**		
	Run 1	Run 2	Average			Run 1	Run 2	Average
C1	34.23	28.77	31.5			277.97	297.19	287.58
C2	29.38	39.77	34.57			433.86	455.38	444.62
C3	35.44	33.48	34.46			288.41	234.91	261.66
C4	27.98	25.3	26.64			402.43	428.63	415.53
F	942.97	989.04						
T	785.23	830.3						
T2	5.11	13.96						
T3	25.60	17.46						

Table 8.6: Raw batch flotation data for 150 g/t of SEX in 0 SPW

Reagents	**Type**	**Dosage**						
SPW	0 SPW							
Frother	Dow200	40	g/t					
Collector	SEX	150	g/t					
Depressant	CMC	100	g/t					
Run 1								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	37.97	43.72	40.65	34.08	29.16	29.74	29.54	882.72
Paper	10.79	10.73	10.73	10.88	9.70	10.82	10.88	34.63
B + H_2O	648.32	669.67	666.16	651.79				
Bottle	551.5	496.12	437.89	347.12				
D + C + H_2O	522.88	686.09	731.08	770				
Dish	232.73	184.16	171.43	191.19				
Run 2								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	39.23	44.61	38.98	32.42	27.04	28.12	26.45	866.55
Paper	10.74	10.79	10.74	10.72	9.72	10.79	10.8	40.74
B + H_2O	664.09	678.64	636.97	623.78				
Bottle	600.66	538.2	377.62	277.11				
D + C + H_2O	535.42	677.2	740.53	787.21				
Dish	232.73	184.16	171.43	191.19				
	Mass of Solids (g)					**Mass of Water (g)**		
	Run 1	Run 2	Average			Run 1	Run 2	Average
C1	27.18	28.49	27.85			166.15	210.77	188.46
C2	32.99	33.82	33.41			301.46	281.51	291.49
C3	29.92	28.24	29.08			295.39	318.78	307.09
C4	23.2	21.7	22.45			250.94	227.65	239.30
F	998.96	971.04						
T	848.09	825.81						
T2	18.92	17.33						
T3	18.66	15.65						

Table 8.7: Raw batch flotation data for 50 g/t of SIBX in 3 SPW

Reagents	**Type**	**Dosage**						
SPW	3 SPW							
Frother	Dow200	40	g/t					
Collector	SIBX	50	g/t					
Depressant	CMC	100	g/t					
Run 1								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	33.81	60.01	47.72	37.43	25.83	26.29	24.45	818.2
Paper	9.86	9.61	9.81	9.58	9.41	9.87	9.22	20.73
B + H_2O	660.56	655.66	622.64	681.05				
Bottle	563.92	546.8	391.42	353.81				
D + C + H_2O	580.27	1079.8	1336.01	1141.09				
Dish	232.9	184.76	364.48	208.78				
Run 2								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	39.77	60.19	49.17	35.08	28.36	26.01	25.69	819.25
Paper	9.71	9.82	9.8	9.93	11.01	11.01	10.94	20.11
B + H_2O	563.98	546.8	667.29	646.57				
Bottle	482.32	433.39	392.25	303.81				
D + C + H_2O	594.29	1107.36	1401.84	1148.63				
Dish	233.39	184.76	363.1	209.85				
	Mass of Solids (g)					**Mass of Water (g)**		
	Run 1	Run 2	Average			Run 1	Run 2	Average
C1	23.95	30.06	27.01			226.78	249.18	237.98
C2	50.4	50.37	50.39			702.4	724.33	713.37
C3	37.91	39.37	38.64			735.78	758.82	747.30
C4	27.85	25.15	26.5			577.22	570.87	574.05
F	969.23	973.84						
T	797.47	799.14						
T2	16.42	15						
T3	15.23	14.75						

Table C.8: Raw batch flotation data for 100 g/t of SIBX in 3 SPW

Reagents	**Type**	**Dosage**						
SPW	3 SPW							
Frother	Dow200	40	g/t					
Collector	SIBX	100	g/t					
Depressant	CMC	100	g/t					
Run 1								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	42.26	55.64	50.26	34.64	26.3	25.5	24.23	825.88
Paper	10.94	11.02	10.89	10.75	9.78	9.68	9.93	21.74
B + H_2O	618.63	483.43	633.57	666.07				
Bottle	560.03	361.52	388.35	412.34				
D + C + H_2O	647.44	996.59	1372.74	977.23				
Dish	232.95	184.36	363	208.94				
Run 2								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	36.68	51.73	47.92	40.24	27.4	21.2	26.23	865.09
Paper	9.83	9.86	9.61	9.58	10.87	9.68	9.64	44.86
B + H_2O	667.44	655.56	599.96	646.78				
Bottle	604.21	549.5	350.75	346.81				
D + C + H_2O	659.23	941.41	1124.51	1001.76				
Dish	232.95	184.36	171.9	191.1				
	Mass of Solids (g)					**Mass of Water (g)**		
	Run 1	Run 2	Average			Run 1	Run 2	Average
C1	31.32	26.85	29.09			324.57	336.20	330.39
C2	44.62	41.87	43.25			725.15	665.09	695.12
C3	39.37	38.31	38.84			645.70	609.12	627.41
C4	23.89	30.66	27.28			490.67	480.03	485.35
F	973.46	986.03						
T	804.14	820.23						
T2	15.82	11.52						
T3	14.30	16.59						

Table B.9: Raw batch flotation data for 150 g/t of SIBX in 3 SPW

Reagents	**Type**	**Dosage**						
SPW	3 SPW							
Frother	Dow200	40	g/t					
Collector	SIBX	150	g/t					
Depressant	CMC	100	g/t					
Run 1								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	36.32	56.43	51.82	36.34	26.4	27.22	24.25	832.18
Paper	10.99	11.91	12.03	12.08	9.61	9.00	9.49	20.45
B + H_2O	359.12	465.11	485.18	512.01				
Bottle	310.74	360.26	297.48	303.59				
D + C + H_2O	537.25	937.12	1082.44	939.82				
Dish	232.81	184.31	171.64	209.03				
Run 2								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	43.99	54.43	50.59	34.78	24.35	26.18	16.82	824.84
Paper	12.57	12.77	13.03	13.04	9.82	9.89	9.78	20.47
B + H_2O	211.1	338.87	631.00	636.48				
Bottle	167.51	236.83	462.88	456.75				
D + C + H_2O	619.41	910.8	1078.63	884.42				
Dish	232.62	184.26	171.50	208.98				
	Mass of Solids (g)					**Mass of Water (g)**		
	Run 1	Run 2	Average			Run 1	Run 2	Average
C1	25.33	31.42	28.38			230.73	311.78	271.25
C2	44.52	41.66	43.09			683.31	701.45	692.38
C3	39.79	37.56	38.675			603.44	582.84	593.14
C4	24.26	21.74	23.00			498.11	473.97	486.04
F	978.61	960.08						
T	811.73	804.37						
T2	18.22	16.29						
T3	14.76	7.04						

Table 8.10: Raw batch flotation data for 50 g/t of SEX in 3 SPW

Reagents	**Type**	**Dosage**						
SPW	3 SPW							
Frother	Dow200	40	g/t					
Collector	SEX	50	g/t					
Depressant	CMC	100	g/t					
				Run 1				
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	36.23	58.25	52.15	41.81	–	28.38	31.64	881.67
Paper	13.5	13.93	13.84	13.97	–	13.99	13.72	42.99
B + H_2O	582.18	490.95	421.26	662.44				
Bottle	506.46	341.43	202.83	345.28				
D + C + H_2O	537.62	916.67	1228.72	1072.43				
Dish	232.62	184.26	362.95	208.93				
				Run 2				
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	38.95	55.88	48.95	37.85	29.2	29.11	30.35	882.52
Paper	13.34	13.24	13.19	11.7	12.22	13.99	14.1	41.34
B + H_2O	648.92	633.3	663.03	661.08				
Bottle	582.18	490.95	421.26	341.41				
D + C + H_2O	572.37	974.75	1242.48	1023.87				
Dish	232.9	184.2	362.37	208.91				
	Mass of Solids (g)					**Mass of Water (g)**		
	Run 1	Run 2	Average			Run 1	Run 2	Average
C1	22.73	25.61	24.17			206.55	247.12	226.84
C2	44.32	42.64	43.48			609.03	602.58	605.81
C3	38.31	35.76	37.03			538.57	605.56	572.07
C4	27.84	26.15	27.00			518.5	469.14	493.82
F	1004.19	1002.71						
T	838.68	841.18						
T2	14.39	15.12						
T3	17.92	16.25						

Table S.11: Raw batch flotation data for 100 g/t of SEX in 3 SPW

Reagents	**Type**	**Dosage**						
SPW	3 SPW							
Frother	Dow200	40	g/t					
Collector	SEX	100	g/t					
Depressant	CMC	100	g/t					
Run 1								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	40.01	50.21	49.54	41.48	29.58	28.3	28.34	850.35
Paper	13.84	13.71	13.39	13.98	14.12	14.02	14.19	41.42
B + H_2O	570.85	674.25	673.03	681.95				
Bottle	495.67	554.95	469.79	395.54				
D + C + H_2O	589.43	862.94	1236.93	1054.13				
Dish	232.9	184.2	362.37	208.91				
Run 2								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	35.91	54.41	56.25	45.83	32.4	29.59	29.01	881.23
Paper	14.18	14.05	14.07	13.94	13.94	13.75	13.71	42.56
B + H_2O	495.67	554.95	677.23	682.81				
Bottle	423.35	406.01	450.08	391.16				
D + C + H_2O	502.44	865.83	1290.12	1106.89				
Dish	232.9	184.2	362.37	208.91				
	Mass of Solids (g)					**Mass of Water (g)**		
	Run 1	Run 2	Average			Run 1	Run 2	Average
C1	26.17	21.73	23.95			255.18	175.49	215.34
C2	36.50	40.36	38.43			635.17	658.42	646.80
C3	36.15	42.18	39.17			522.94	492.33	507.63
C4	27.50	31.89	29.70			531.31	574.44	552.88
F	963.68	1005.97						
T	808.93	838.67						
T2	14.28	15.84						
T3	14.15	15.30						

Table B.12: Raw batch flotation data for 150 g/t of SEX in 3 SPW

Reagents	**Type**	**Dosage**						
SPW	3 SPW							
Frother	Dow200	40	g/t					
Collector	SEX	150	g/t					
Depressant	CMC	100	g/t					
				Run 1				
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	34.15	51.67	51.56	41.32	30.16	29.11	25.88	859.89
Paper	13.06	12.94	12.94	12.92	12.75	13.49	13.36	41.11
B + H_2O	674.69	639.58	679.97	651.59				
Bottle	600.47	511.38	465.27	327.63				
D + C + H_2O	522.69	880.99	1294.95	1106.56				
Dish	232.63	184.15	362.19	208.82				
				Run 2				
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	38.92	58.26	56.07	43.74	0	30.04	30.92	891.22
Paper	13.16	12.95	13.3	12.85	0	12.7	13.24	41.3
B + H_2O	600.47	511.38	465.27	628.74				
Bottle	521.31	389.7	233.85	313.81				
D + C + H_2O	559.14	956.32	1318.54	1098.63				
Dish	233.37	184.79	362.95	211.95				
	Mass of Solids (g)					**Mass of Water (g)**		
	Run 1	Run 2	Average			Run 1	Run 2	Average
C1	21.09	25.76	23.425			194.75	220.85	207.8
C2	38.73	45.31	42.02			679.44	681.40	680.42
C3	38.62	42.77	40.70			529.91	604.54	567.22
C4	28.4	30.89	29.65			545.38	540.86	543.12
F	973.76	1029.67						
T	818.78	849.92						
T2	15.62	17.34						
T3	12.52	17.68						

Table 6.13: Raw batch flotation data for 50 g/t of SIBX in 5 SPW

Reagents	**Type**	**Dosage**						
SPW	5 SPW							
Frother	Dow200	40	g/t					
Collector	SIBX	50	g/t					
Depressant	CMC	100	g/t					
Run 1								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	44.43	54.6	49.91	38.56	30.21	28.36	28.23	820.13
Paper	9.52	9.34	9.28	9.45	9.64	13.38	13.51	21.05
B + H_2O	662.98	683.44	639.85	670.98				
Bottle	610.63	582.08	447.66	423.86				
D + C + H_2O	684.22	1024.72	1400.12	1178.08				
Dish	232.51	184.19	362.14	208.7				
Run 2								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	35.11	56.7	46.43	37.63	25.52	24.65	24.05	825.73
Paper	9.63	9.56	9.51	9.77	9.73	9.67	9.42	20.93
B + H_2O	610.63	582.08	447.66	423.86				
Bottle	554.38	466.13	220.65	145.36				
D + C + H_2O	558.57	1046.95	1306.42	1098.99				
Dish	232.63	184.18	362.33	208.92				
	Mass of Solids (g)					**Mass of Water (g)**		
	Run 1	Run 2	Average			Run 1	Run 2	Average
C1	34.91	25.48	30.20			364.45	244.21	304.33
C2	45.26	47.14	46.20			805.16	680.16	742.66
C3	40.63	36.92	38.78			693.91	699.68	696.80
C4	29.11	27.86	28.50			693.15	583.71	638.43
F	978.69	971.81						
T	799.08	804.8						
T2	14.98	14.98						
T3	14.72	14.63						

Table 8.14: Raw batch flotation data for 100 g/t of SIBX in 5 SPW

Reagents	**Type**	**Dosage**						
SPW	5 SPW							
Frother	Dow200	40	g/t					
Collector	SIBX	100	g/t					
Depressant	CMC	100	g/t					
Run 1								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	38.14	59.28	55.31	46.96	32.26	29.51	27.32	834.86
Paper	13.93	13.71	13.68	14.03	14.24	14.1	13.34	19.28
B + H_2O	554.38	466.16	655.77	656.9				
Bottle	488.33	351.01	454.94	383.12				
D + C + H_2O	525.86	932.94	1289.68	1169.14				
Dish	232.62	184.43	362.7	208.9				
Run 2								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	38.92	67.3	57.91	44.09	31.58	29.95	28.56	831.12
Paper	14.11	14.14	14.13	14.02	14.11	13.57	13.9	20.58
B + H_2O	488.33	648.7	636.26	557.65				
Bottle	418.84	532.63	419.55	300.84				
D + C + H_2O	537.51	1061.2	1396.71	1144.45				
Dish	232.87	184.43	362.85	209.09				
	Mass of Solids (g)					**Mass of Water (g)**		
	Run 1	Run 2	Average			Run 1	Run 2	Average
C1	24.21	24.81	24.51			202.98	210.34	206.66
C2	45.57	53.16	49.36			684.52	773.37	728.95
C3	41.63	43.78	42.705			587.79	707.54	647.67
C4	32.93	30.07	31.50			653.53	648.48	651.01
F	989.31	993.40						
T	815.58	810.54						
T2	15.41	16.38						
T3	13.98	14.66						

Table 8.15: Raw batch flotation data for 150 g/t of SIBX in 5 SPW

Reagents	**Type**	**Dosage**						
SPW	5 SPW							
Frother	Dow200	40	g/t					
Collector	SIBX	150	g/t					
Depressant	CMC	100	g/t					
Run 1								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	30.63	56.14	53.19	41.05	28.59	27.22	25.85	816.68
Paper	9.94	9.83	10.45	9.40	9.50	10.76	9.87	20.94
B + H_2O	663.4	686.47	607.17	638.01				
Bottle	595.22	589.03	385.13	378.54				
D + C + H_2O	485.91	939.6	1365.92	1173.49				
Dish	232.73	186.55	338.81	208.89				
Run 2								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	37.06	56.43	52.17	40.55	29.95	22.84	25.97	856.86
Paper	10.35	10.35	10.39	10.47	10.9	9.9	9.73	43.12
B + H_2O	475.05	607.83	596.51	637.43				
Bottle	411.57	482.52	362.46	311.37				
D + C + H_2O	569.12	977.16	1369.53	1179.84				
Dish	237.41	187.04	365.69	211.95				
	Mass of Solids (g)					**Mass of Water (g)**		
	Run 1	Run 2	Average			Run 1	Run 2	Average
C1	20.69	26.71	23.7			164.31	241.52	202.92
C2	46.31	46.08	46.20			762.33	728.01	745.17
C3	42.74	41.78	42.26			609.30	618.73	614.02
C4	31.65	30.08	30.87			673.48	611.75	642.62
F	969.57	987.57						
T	795.74	813.74						
T2	16.46	12.94						
T3	15.98	16.24						

Table 8.16: Raw batch flotation data for 50 g/t of SEX in 5 SPW

Reagents	**Type**	**Dosage**						
SPW	5 SPW							
Frother	Dow200	40	g/t					
Collector	SEX	50	g/t					
Depressant	CMC	100	g/t					
				Run 1				
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	37.83	58.13	51.9	34.77	25.77	25.00	25.61	834.98
Paper	9.85	9.39	9.46	9.37	9.62	10.16	10.12	31.29
B + H_2O	528.90	490.50	659.25	669.08				
Bottle	464.13	367.23	441.77	408.50				
D + C + H_2O	625.23	1128.57	1512.93	1115.65				
Dish	232.77	184.53	365.76	209.21				
				Run 2				
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	33.11	50.99	47.51	40.87	26.35	23.27	23.39	841.56
Paper	9.85	9.79	9.87	9.64	9.75	9.91	9.91	31.29
B + H_2O	464.13	367.23	646.43	666.67				
Bottle	389.08	234.63	422.18	376.76				
D + C + H_2O	555.54	1128.57	1512.93	1162.09				
Dish	232.84	184.53	365.76	208.93				
	Mass of Solids (g)					**Mass of Water (g)**		
	Run 1	Run 2	Average			Run 1	Run 2	Average
C1	27.98	23.26	25.62			299.71	224.39	262.05
C2	48.74	41.20	44.97			887.25	885.28	886.27
C3	42.44	37.64	40.04			772.03	770.24	771.14
C4	25.40	31.23	28.32			620.46	632.02	626.24
F	978.58	970.44						
T	803.69	810.27						
T2	14.84	13.36						
T3	15.49	13.48						

Table 8.17: Raw batch flotation data for 100 g/t of SEX in 5 SPW

Reagents	**Type**	**Dosage**						
SPW	5 SPW							
Frother	Dow200	40	g/t					
Collector	SEX	100	g/t					
Depressant	CMC	100	g/t					
Run 1								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	39.17	58.36	52.82	47.09	33.59	33.16	27.18	887.23
Paper	12.95	13.52	13.58	13.64	13.28	13.62	10.03	54.35
B + H_2O	652.3	667.16	634.73	644.05				
Bottle	582.29	540.76	413.99	379.74				
D + C + H_2O	565.62	873.16	1048.96	1108.11				
Dish	232.84	184.53	365.76	208.93				
Run 2								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	29.37	48.58	48.24	45.11	30.41	18.1	28.17	896.33
Paper	9.98	13.24	9.95	9.67	13.31	13.21	9.98	51.56
B + H_2O	582.29	540.76	633.82	561.57				
Bottle	499.5	395.01	373.02	272.81				
D + C + H_2O	453	787.03	929.26	991.26				
Dish	232.84	184.53	171.85	193.91				
	Mass of Solids (g)					**Mass of Water (g)**		
	Run 1	Run 2	Average			Run 1	Run 2	Average
C1	26.22	19.39	22.81			236.55	117.98	177.27
C2	44.84	35.34	40.09			423.22	458.32	440.77
C3	39.24	38.29	38.77			517.39	421.41	469.40
C4	33.45	35.44	34.45			601.42	473.15	537.29
F	1013.32	996.31						
T	832.88	844.77						
T2	19.54	4.89						
T3	17.15	18.19						

Table 8.18: Raw batch flotation data for 150 g/t of SEX in 5 SPW

Reagents	**Type**	**Dosage**						
SPW	5 SPW							
Frother	Dow200	40	g/t					
Collector	SEX	150	g/t					
Depressant	CMC	100	g/t					
Run 1								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	30.14	46.02	46.82	41.65	29.53	25.71	26.09	859.62
Paper	10.17	10.13	10.08	10.18	10.26	9.76	9.67	47.92
B + H_2O	598.09	666.15	645.66	645.07				
Bottle	545.23	540.76	434.45	409.07				
D + C + H_2O	494.97	856.3	1056.16	1109.18				
Dish	232.69	184.69	171.12	191.96				
Run 2								
Mass	Conc 1	Conc 2	Conc 3	Conc 4	Feed	Tails 1	Tails 2	Tails 3
C + Paper	31.65	44.42	47.87	42.16	26.58	27.54	26.53	876.3
Paper	10.06	10.27	9.97	10.37	10.63	10.32	9.67	47.73
B + H_2O	545.23	540.76	646.7	652.72				
Bottle	475.05	413.67	408.45	354.14				
D + C + H_2O	508.93	775.19	1020.00	1066.60				
Dish	232.69	184.69	171.12	191.96				
	Mass of Solids (g)					**Mass of Water (g)**		
	Run 1	Run 2	Average			Run 1	Run 2	Average
C1	19.97	21.59	20.78			189.45	184.47	186.96
C2	35.89	34.15	35.02			637.09	572.73	604.91
C3	36.74	37.90	37.32			510.33	429.26	469.80
C4	31.47	31.79	31.63			649.75	544.27	597.01
F	968.14	988.08						
T	811.70	828.57						
T2	15.95	17.22						
T3	16.42	16.86						

Mass balance summaries for the batch flotation tests in Section 5.2, 5.3 and 5.4

Reagents	Run no.	Sample	Time (min)	Cum Solids (g)	Cum Water (g)	Cum Copper Mass (g)	Ave Copper Grade (%)	Ave Copper Recovery (%)	Cum Nickel Mass (g)	Ave Nickel Grade (%)	Ave Nickel Recovery (%)
0 SPW 50 g/t SIBX	1	C1	2	18.69	101.96	31.28	1.59	64.85	38.84	2.04	27.73
		C2	4	42.40	253.07	37.21	0.85	76.65	53.27	1.24	37.13
		C3	6	67.59	395.56	39.73	0.58	81.79	60.50	0.89	41.93
		C4	8	87.25	516.15	41.17	0.46	84.77	64.96	0.74	45.07
		F					3.48			4.91	
		T									
		T2									
		T3									
		Cc+Tt				48.21			145.24		
		Mass Balance				106.24			104.18		
	2	C1	2	20.25	102.42	30.39			40.51		
		C2	4	43.49	283.80	35.67			53.00		
		C3	6	66.82	430.13	38.04			59.52		
		C4	8	87.55	595.74	39.44			64.05		
		F									
		T									
		T2									
		T3									
		Cc+Tt				46.87			141.04		
		Mass Balance				100.38			97.72		

Reagents	Run no.	Sample	Time (min)	Cum Solids (g)	Cum Water (g)	Cum Copper Mass (g)	Ave Copper Grade (%)	Ave Copper Recovery (%)	Cum Nickel Mass (g)	Ave Nickel Grade (%)	Ave Nickel Recovery (%)
0 SPW 100 g/t SIBX	1	C1	2	21.10	150.94	31.41	1.41	63.64	39.95	1.82	27.43
		C2	4	49.63	442.29	37.71	0.73	76.16	54.72	1.08	37.32
		C3	6	75.44	682.55	40.31	0.51	81.43	62.01	0.79	42.30
		C4	8	98.35	977.34	41.90	0.41	84.58	66.87	0.66	45.60
		F					3.06			4.35	
		T									
		T2									
		T3									
		Cc+Tt				49.47			150.71		
		Mass Balance				104.67			101.51		
	2	C1	2	22.84	186.31	30.26			39.72		
		C2	4	50.99	463.50	36.09			53.69		
		C3	6	79.37	725.69	38.60			60.87		
		C4	8	102.47	1049.03	40.06			65.59		
		F									
		T									
		T2									
		T3									
		Cc+Tt				47.43			140.06		
		Mass Balance				100.69			103.19		

Reagents	Run no.	Sample	Time (min)	Cum Solids (g)	Cum Water (g)	Cum Copper Mass (g)	Ave Copper Grade (%)	Ave Copper Recovery (%)	Cum Nickel Mass (g)	Ave Nickel Grade (%)	Ave Nickel Recovery (%)
0 SPW 150 g/t SIBX	1	C1	2	36.87	256.46	31.59	0.96	67.76	45.90	1.34	29.77
		C2	4	66.64	540.63	36.27	0.58	78.14	57.56	0.90	38.09
		C3	6	94.10	814.03	38.41	0.42	83.11	64.57	0.70	42.88
		C4	8	118.93	1111.77	39.66	0.34	86.05	69.74	0.59	46.36
		F					2.30			3.54	
		T									
		T2									
		T3									
		Cc+Tt				46.31			150.28		
		Mass Balance				100.46			102.78		
	2	C1	2	30.41	215.54	32.16			43.81		
		C2	4	61.09	481.11	37.25			57.26		
		C3	6	90.55	755.77	39.79			64.68		
		C4	8	116.94	1059.61	41.31			69.99		
		F									
		T									
		T2									
		T3									
		Cc+Tt				47.78			151.14		
		Mass Balance				99.33			99.04		

Reagents	Run no.	Sample	Time (min)	Cum Solids (g)	Cum Water (g)	Cum Copper Mass (g)	Ave Copper Grade (%)	Ave Copper Recovery (%)	Cum Nickel Mass (g)	Ave Nickel Grade (%)	Ave Nickel Recovery (%)
0 SPW 50 g/t SEX	1	C1	2	29.44	236.06	34.12	1.12	72.52	46.54	1.54	38.22
		C2	4	60.37	565.94	38.11	0.61	81.05	57.75	0.94	47.49
		C3	6	88.16	885.62	40.08	0.44	85.00	63.97	0.72	52.56
		C4	8	111.32	1185.99	41.23	0.37	87.21	68.64	0.62	55.92
		F					2.54			3.83	
		T									
		T2									
		T3									
		Cc+Tt				47.25			126.60		
		Mass Balance				101.88			102.85		
	2	C1	2	35.19	231.93	37.69			53.06		
		C2	4	71.72	588.87	42.15			66.03		
		C3	6	102.67	935.69	44.08			73.02		
		C4	8	121.79	1232.26	45.12			77.07		
		F									
		T									
		T2									
		T3									
		Cc+Tt				51.76			133.76		
		Mass Balance				107.11			108.13		

Reagents	Run no.	Sample	Time (min)	Cum Solids (g)	Cum Water (g)	Cum Copper Mass (g)	Ave Copper Grade (%)	Ave Copper Recovery (%)	Cum Nickel Mass (g)	Ave Nickel Grade (%)	Ave Nickel Recovery (%)
0 SPW 100 g/t SEX	1	C1	2	28.77	297.19	33.37	1.08	67.49	45.74	1.51	31.57
		C2	4	68.54	532.10	38.54	0.58	76.75	59.66	0.90	39.67
		C3	6	102.02	987.48	40.55	0.40	80.88	67.36	0.66	44.73
		C4	8	127.32	1416.11	41.82	0.33	83.26	72.42	0.57	48.11
		F					3.48			3.63	
		T									
		T2									
		T3									
		Cc+Tt				50.43			149.98		
		Mass Balance				101.99			101.09		
	2	C1	2	34.23	277.97	34.23			48.61		
		C2	4	63.61	566.38	38.34			58.89		
		C3	6	99.05	1000.24	40.47			66.33		
		C4	8	127.03	1402.67	41.59			71.37		
		F									
		T									
		T2									
		T3									
		Cc+Tt				49.75			148.88		
		Mass Balance				105.51			105.26		

Reagents	Run no.	Sample	Time (min)	Cum Solids (g)	Cum Water (g)	Cum Copper Mass (g)	Ave Copper Grade (%)	Ave Copper Recovery (%)	Cum Nickel Mass (g)	Ave Nickel Grade (%)	Ave Nickel Recovery (%)
0 SPW 150 g/t SEX	1	C1	2	28.49	210.77	34.47	1.23	67.62	46.15	1.68	30.65
		C2	4	62.31	529.55	38.87	0.63	76.53	58.33	0.96	38.65
		C3	6	90.55	811.06	40.85	0.45	80.55	64.54	0.72	42.85
		C4	8	112.25	1038.71	41.93	0.37	82.77	68.66	0.62	45.64
		F					2.69			3.98	
		T									
		T2									
		T3									
		Cc+Tt				50.52			150.25		
		Mass Balance				104.05			110.52		
	2	C1	2	27.18	166.15	33.98			47.29		
		C2	4	60.17	461.54	38.59			59.50		
		C3	6	90.09	763.00	40.69			66.08		
		C4	8	113.29	1013.94	41.85			70.49		
		F									
		T									
		T2									
		T3									
		Cc+Tt				50.70			154.63		
		Mass Balance				101.51			110.56		

Reagents	Run no.	Sample	Time (min)	Cum Solids (g)	Cum Water (g)	Cum Copper Mass (g)	Ave Copper Grade (%)	Ave Copper Recovery (%)	Cum Nickel Mass (g)	Ave Nickel Grade (%)	Ave Nickel Recovery (%)
3 SPW 50 g/t SIBX	1	C1	2	23.95	226.78	31.42	1.17	67.66	43.67	1.65	30.06
		C2	4	74.35	962.56	37.13	0.48	79.97	60.38	0.78	41.07
		C3	6	112.26	1664.96	39.56	0.34	85.10	68.81	0.59	46.68
		C4	8	140.11	2242.18	40.88	0.28	87.69	73.93	0.52	49.94
		F					2.27			3.54	
		T									
		T2									
		T3									
		Cc+Tt				46.95			148.30		
		Mass Balance				122.96			106.25		
	2	C1	2	30.06	249.18	31.08			44.67		
		C2	4	80.43	1008.00	36.74			60.34		
		C3	6	119.80	1732.33	39.05			68.40		
		C4	8	144.95	2303.20	40.13			72.87		
		F									
		T									
		T2									
		T3									
		Cc+Tt				45.43			145.64		
		Mass Balance				107.00			98.33		

Reagents	Run no.	Sample	Time (min)	Cum Solids (g)	Cum Water (g)	Cum Copper Mass (g)	Ave Copper Grade (%)	Ave Copper Recovery (%)	Cum Nickel Mass (g)	Ave Nickel Grade (%)	Ave Nickel Recovery (%)
3 SPW 100 g/t SIBX	1	C1	2	26.85	336.20	33.28	1.14	68.55	43.53	1.53	29.70
		C2	4	68.72	945.32	39.39	0.54	80.75	61.03	0.85	40.85
		C3	6	107.03	1610.41	42.18	0.37	86.24	70.43	0.63	46.97
		C4	8	137.69	2090.44	43.80	0.31	89.17	76.39	0.54	50.46
		F					2.37			3.56	
		T									
		T2									
		T3									
		Cc+Tt				47.79			149.98		
		Mass Balance				99.32			95.48		
	2	C1	2	31.32	324.57	32.77			45.23		
		C2	4	75.94	970.27	38.40			61.06		
		C3	6	115.31	1695.42	40.89			69.95		
		C4	8	139.20	2186.09	42.10			74.42		
		F									
		T									
		T2									
		T3									
		Cc+Tt				48.56			148.88		
		Mass Balance				119.34			102.30		

Reagents	Run no.	Sample	Time (min)	Cum Solids (g)	Cum Water (g)	Cum Copper Mass (g)	Ave Copper Grade (%)	Ave Copper Recovery (%)	Cum Nickel Mass (g)	Ave Nickel Grade (%)	Ave Nickel Recovery (%)
3 SPW 150 g/t SIBX	1	C1	2	25.33	230.73	31.22	1.13	67.74	42.03	1.55	29.29
		C2	4	69.85	834.17	37.07	0.52	79.77	58.99	0.83	40.03
		C3	6	109.64	1517.48	39.77	0.36	85.18	67.51	0.62	45.57
		C4	8	133.90	2015.59	41.02	0.31	87.68	72.12	0.54	48.51
		F					2.33			3.54	
		T									
		T2									
		T3									
		Cc+Tt				46.59			150.50		
		Mass Balance				118.15			103.08		
	2	C1	2	31.42	311.78	32.42			45.07		
		C2	4	73.08	894.62	37.87			60.08		
		C3	6	110.64	1596.07	40.26			68.04		
		C4	8	132.38	2070.04	41.35			72.16		
		F									
		T									
		T2									
		T3									
		Cc+Tt				47.36			146.99		
		Mass Balance				107.93			102.48		

Reagents	Run no.	Sample	Time (min)	Cum Solids (g)	Cum Water (g)	Cum Copper Mass (g)	Ave Copper Grade (%)	Ave Copper Recovery (%)	Cum Nickel Mass (g)	Ave Nickel Grade (%)	Ave Nickel Recovery (%)
3 SPW 50 g/t SEX	1	C1	2	25.61	247.12	33.64	1.41	71.61	46.33	1.90	30.50
		C2	4	68.25	852.68	38.76	0.58	82.80	60.39	0.91	40.84
		C3	6	104.01	1455.26	40.94	0.40	87.56	67.91	0.66	46.18
		C4	8	130.16	1924.40	42.10	0.32	90.04	72.68	0.56	49.47
		F					2.70			4.03	
		T									
		T2									
		T3									
		Cc+Tt				46.86			150.42		
		Mass Balance				97.97			95.37		
	2	C1	2	22.73	206.55	34.04			45.22		
		C2	4	67.05	745.12	39.50			62.21		
		C3	6	105.36	1354.15	41.81			70.71		
		C4	8	133.20	1872.65	42.99			75.80		
		F									
		T									
		T2									
		T3									
		Cc+Tt				47.65			149.75		
		Mass Balance				99.47			94.80		

Reagents	Run no.	Sample	Time (min)	Cum Solids (g)	Cum Water (g)	Cum Copper Mass (g)	Ave Copper Grade (%)	Ave Copper Recovery (%)	Cum Nickel Mass (g)	Ave Nickel Grade (%)	Ave Nickel Recovery (%)
3 SPW 100 g/t SEX	1	C1	2	26.17	255.18	34.12	1.44	70.08	47.34	1.94	30.96
		C2	4	62.67	778.12	38.31	0.62	79.78	59.54	0.97	40.27
		C3	6	98.82	1413.29	40.43	0.41	84.60	67.82	0.68	46.04
		C4	8	126.32	1944.60	41.62	0.32	87.15	72.88	0.57	49.68
		F					2.79			4.15	
		T									
		T2									
		T3									
		Cc+Tt				47.11			146.61		
		Mass Balance				115.84			101.49		
	2	C1	2	21.73	175.49	34.14			45.18		
		C2	4	62.09	667.82	39.42			60.92		
		C3	6	104.27	1326.24	42.01			69.90		
		C4	8	136.16	1900.68	43.31			75.73		
		F									
		T									
		T2									
		T3									
		Cc+Tt				50.39			152.54		
		Mass Balance				118.15			100.02		

Reagents	Run no.	Sample	Time (min)	Cum Solids (g)	Cum Water (g)	Cum Copper Mass (g)	Ave Copper Grade (%)	Ave Copper Recovery (%)	Cum Nickel Mass (g)	Ave Nickel Grade (%)	Ave Nickel Recovery (%)
3 SPW 150 g/t SEX	1	C1	2	21.09	194.75	33.24	1.48	68.86	45.00	2.01	31.04
		C2	4	59.82	724.66	38.68	0.61	79.47	58.79	0.94	40.65
		C3	6	98.44	1404.10	41.07	0.40	84.26	67.46	0.66	46.42
		C4	8	126.84	1949.48	42.37	0.32	86.89	72.78	0.56	50.07
		F					2.82			4.16	
		T									
		T2									
		T3									
		Cc+Tt				48.35			145.70		
		Mass Balance				104.30			96.29		
	2	C1	2	25.76	220.85	35.88			48.44		
		C2	4	71.07	825.39	41.07			63.60		
		C3	6	113.84	1506.79	43.48			72.27		
		C4	8	144.73	2047.65	44.82			77.94		
		F									
		T									
		T2									
		T3									
		Cc+Tt				52.03			155.29		
		Mass Balance				92.00			97.05		

Reagents	Run no.	Sample	Time (min)	Cum Solids (g)	Cum Water (g)	Cum Copper Mass (g)	Ave Copper Grade (%)	Ave Copper Recovery (%)	Cum Nickel Mass (g)	Ave Nickel Grade (%)	Ave Nickel Recovery (%)
5 SPW 50 g/t SIBX	1	C1	2	34.91	364.45	32.82	1.14	65.73	47.13	1.59	31.11
		C2	4	80.17	1058.36	37.79	0.51	76.21	61.16	0.81	41.27
		C3	6	120.80	1863.52	40.23	0.36	80.80	69.69	0.61	46.69
		C4	8	149.91	2556.67	41.69	0.30	83.61	74.93	0.53	50.19
		F					2.30			3.54	
		T									
		T2									
		T3									
		Cc+Tt				49.98			149.52		
		Mass Balance				102.13			95.49		
	2	C1	2	25.48	244.21	33.89			46.37		
		C2	4	72.62	943.89	39.55			62.87		
		C3	6	109.54	1624.05	41.76			70.63		
		C4	8	137.40	2207.76	43.15			75.92		
		F									
		T									
		T2									
		T3									
		Cc+Tt				51.50			151.02		
		Mass Balance				115.95			103.60		

Reagents	Run no.	Sample	Time (min)	Cum Solids (g)	Cum Water (g)	Cum Copper Mass (g)	Ave Copper Grade (%)	Ave Copper Recovery (%)	Cum Nickel Mass (g)	Ave Nickel Grade (%)	Ave Nickel Recovery (%)
5 SPW 100 g/t SIBX	1	C1	2	24.21	202.98	33.93	1.43	67.63	45.36	1.88	29.72
		C2	4	69.78	790.77	39.97	0.56	79.41	63.26	0.87	41.50
		C3	6	111.41	1475.29	42.88	0.38	84.79	72.36	0.63	47.38
		C4	8	144.34	2128.82	44.48	0.31	87.66	78.40	0.53	51.08
		F					2.68			3.91	
		T									
		T2									
		T3									
		Cc+Tt				51.07			156.26		
		Mass Balance				109.60			104.74		
	2	C1	2	24.81	210.34	36.39			46.68		
		C2	4	77.97	917.88	42.59			65.23		
		C3	6	121.75	1691.25	45.26			74.34		
		C4	8	151.82	2339.73	46.64			79.75		
		F									
		T									
		T2									
		T3									
		Cc+Tt				52.87			153.43		
		Mass Balance				104.15			100.10		

Reagents	Run no.	Sample	Time (min)	Cum Solids (g)	Cum Water (g)	Cum Copper Mass (g)	Ave Copper Grade (%)	Ave Copper Recovery (%)	Cum Nickel Mass (g)	Ave Nickel Grade (%)	Ave Nickel Recovery (%)
5 SPW 150 g/t SIBX	1	C1	2	20.69	164.31	31.78	1.37	65.95	42.01	1.83	27.98
		C2	4	67.00	773.61	38.87	0.55	79.92	61.54	0.89	40.56
		C3	6	109.74	1535.94	41.87	0.37	85.80	71.29	0.64	46.81
		C4	8	141.39	2209.42	43.53	0.30	89.03	77.25	0.54	50.55
		F					2.59			3.89	
		T									
		T2									
		T3									
		Cc+Tt				48.21			153.94		
		Mass Balance				100.24			102.24		
	2	C1	2	26.71	241.52	32.04			43.31		
		C2	4	72.79	860.25	38.46			62.17		
		C3	6	114.57	1588.26	41.14			71.49		
		C4	8	144.65	2200.01	42.62			76.93		
		F									
		T									
		T2									
		T3									
		Cc+Tt				48.56			151.11		
		Mass Balance				99.13			108.83		

Reagents	Run no.	Sample	Time (min)	Cum Solids (g)	Cum Water (g)	Cum Copper Mass (g)	Ave Copper Grade (%)	Ave Copper Recovery (%)	Cum Nickel Mass (g)	Ave Nickel Grade (%)	Ave Nickel Recovery (%)
5 SPW 50 g/t SEX	1	C1	2	27.98	299.71	34.98	1.37	67.39	48.41	1.82	30.76
		C2	4	76.72	1071.74	39.85	0.57	77.32	63.03	0.88	40.82
		C3	6	119.16	1958.99	41.97	0.38	81.57	71.94	0.64	46.53
		C4	8	144.56	2579.45	42.99	0.31	83.77	76.51	0.54	50.03
		F					2.63			3.87	
		T									
		T2									
		T3									
		Cc+Tt				51.33			151.57		
		Mass Balance				104.90			103.26		
	2	C1	2	23.26	224.39	34.42			44.19		
		C2	4	64.46	994.63	39.78			59.85		
		C3	6	102.10	1879.91	42.04			68.13		
		C4	8	133.33	2511.93	43.29			74.06		
		F									
		T									
		T2									
		T3									
		Cc+Tt				51.66			149.40		
		Mass Balance				106.47			102.64		

Reagents	Run no.	Sample	Time (min)	Cum Solids (g)	Cum Water (g)	Cum Copper Mass (g)	Ave Copper Grade (%)	Ave Copper Recovery (%)	Cum Nickel Mass (g)	Ave Nickel Grade (%)	Ave Nickel Recovery (%)
5 SPW 100 g/t SEX	1	C1	2	26.22	236.55	36.87	1.70	69.56	47.80	2.20	31.15
		C2	4	71.06	753.94	42.82	0.71	80.21	64.58	1.06	41.52
		C3	6	110.30	1177.16	45.36	0.46	85.06	73.97	0.74	47.47
		C4	8	143.75	1778.58	46.90	0.35	88.07	80.46	0.60	51.79
		F					3.22			4.60	
		T									
		T2									
		T3									
		Cc+Tt				52.77			157.46		
		Mass Balance				105.84			101.96		
	2	C1	2	19.39	117.98	38.72			50.10		
		C2	4	54.73	539.39	44.33			65.93		
		C3	6	93.02	997.71	47.05			75.24		
		C4	8	128.46	1470.86	48.80			82.34		
		F									
		T									
		T2									
		T3									
		Cc+Tt				55.91			156.89		
		Mass Balance				119.15			100.81		

Reagents	Run no.	Sample	Time (min)	Cum Solids (g)	Cum Water (g)	Cum Copper Mass (g)	Ave Copper Grade (%)	Ave Copper Recovery (%)	Cum Nickel Mass (g)	Ave Nickel Grade (%)	Ave Nickel Recovery (%)
5 SPW 150 g/t SEX	1	C1	2	19.97	189.45	33.25	1.67	71.32	43.53	2.15	29.83
		C2	4	55.86	699.78	38.07	0.71	81.20	57.14	1.04	38.89
		C3	6	92.60	1336.87	40.44	0.45	86.10	65.53	0.72	44.56
		C4	8	124.07	1986.62	41.81	0.35	88.83	71.45	0.58	48.60
		F					3.18			4.50	
		T									
		T2									
		T3									
		Cc+Tt				46.92			147.50		
		Mass Balance				102.67			99.06		
	2	C1	2	21.59	184.47	36.20			45.88		
		C2	4	55.74	613.73	40.97			59.40		
		C3	6	93.64	1186.46	43.37			68.03		
		C4	8	125.43	1730.73	44.65			74.21		
		F									
		T									
		T2									
		T3									
		Cc+Tt				50.43			152.19		
		Mass Balance				108.14			109.55		

Entrainment factor raw data for Section 5.5

Condition	**Sample**	**Solids rec**		**Water rec**		**Copper**			**Nickel**			**Total Gangue (g)**
		mass (g)	**cum mass (g)**	**mass (g)**	**cum mass (g)**	**% Copper**	**mass (g)**	**cum mass (g)**	**% Nickel**	**mass (g)**	**cum mass (g)**	
3SPW-SIBX	C1	13.76	13.76	195.33	195.33	2.25	0.31	0.31	2.86	0.39	0.39	13.06
	C2	20.91	34.67	388.29	583.62	0.27	0.06	0.37	0.67	0.14	0.53	33.77
	C3	23.06	57.73	456.59	1040.21	0.12	0.03	0.39	0.30	0.07	0.60	56.73
	C4	15.62	73.35	371.50	1411.71	0.09	0.01	0.41	0.25	0.04	0.64	72.30
5SPW-SIBX	C1	10.58	10.58	327.71	327.71	2.87	0.30	0.30	3.39	0.36	0.36	9.92
	C2	24.84	35.42	568.02	895.73	0.30	0.08	0.38	0.75	0.19	0.54	34.50
	C3	30.84	66.26	704.28	1600.01	0.11	0.03	0.41	0.30	0.09	0.64	65.21
	C4	29.93	96.19	728.20	2328.21	0.07	0.02	0.43	0.22	0.07	0.70	95.05
3SPW-SEX	C1	7.89	7.89	73.84	73.84	4.65	0.37	0.37	5.67	0.45	0.45	7.08
	C2	10.52	18.41	164.36	238.20	0.58	0.06	0.43	1.21	0.13	0.57	17.41
	C3	15.90	34.31	256.83	495.03	0.19	0.03	0.46	0.42	0.07	0.64	33.21
	C4	20.24	54.55	365.77	860.80	0.09	0.02	0.48	0.28	0.06	0.70	53.38
5SPW-SEX	C1	7.84	7.84	81.92	81.92	4.16	0.33	0.33	4.78	0.37	0.37	7.14
	C2	18.78	26.62	318.51	400.43	0.40	0.08	0.40	0.88	0.16	0.54	25.68
	C3	25.47	52.09	480.88	881.31	0.14	0.04	0.44	0.32	0.08	0.62	51.03
	C4	25.91	78.00	530.65	1411.96	0.09	0.02	0.46	0.24	0.06	0.68	76.85

Table 8.19: Residual xanthate concentration raw data

Condition	**Absorbance T1**	**Absorbance T2**	**Ave. Absorbance**	**Concentration (ppm)**
0-SEX-50	0.51	0.16	0.33	1.17
0-SEX-100	0.84	0.67	0.75	2.64
0-SEX-150	1.20	2.39	1.79	6.29
0-SIBX-50	3.12	3.36	3.24	19.16
0-SIBX-100	1.74	3.45	2.60	15.38
0-SIBX-150	0.58	0.49	0.53	3.15
3-SEX-50	0.46	0.49	0.47	1.65
3-SEX-100	1.14	1.13	1.13	3.96
3-SEX-150	1.76	1.71	1.73	6.06
3-SIBX-50	0.13	0.05	0.09	0.40
3-SIBX-100	0.11	0.15	0.13	0.58
3-SIBX-150	0.33	0.40	0.36	1.65
5-SEX-50	0.51	0.25	0.38	1.30
5-SEX-100	0.63	0.77	0.70	2.40
5-SEX-150	1.26	1.41	1.33	4.59
5-SIBX-50	0.10	0.14	0.12	0.44
5-SIBX-100	0.18	0.37	0.27	0.99
5-SIBX-150	0.29	0.32	0.30	1.11

Appendix B: Zeta potential measurements raw data

Table 8.20: Zeta potential raw data for no collector and SEX in 0 SPW

Reagent	*No collector*	**Run**	**Zeta potential (mV)**
Dosage (g/t)		*Run 1*	-20.00
SPW	0 SPW		-21.90
			-20.70
		Run 2	-20.50
			-22.20
			-21.30
		Average	**-21.10**
		Standard deviation	**0.85**
Reagent	*SEX*	**Run**	**Zeta potential (mV)**
Dosage (g/t)	50.00	*Run 1*	-15.33
SPW	0 SPW		-16.22
			-22.54
		Run 2	-16.30
			-17.80
			-17.10
		Average	**-17.55**
		Standard deviation	**2.62**
Reagent	*SEX*	**Run**	**Zeta potential (mV)**
Dosage (g/t)	150.00	*Run 1*	-21.40
SPW	0 SPW		-20.40
			-19.00
		Run 2	-19.30
			-20.50
			-19.60
		Average	**-20.03**
		Standard deviation	**0.90**

Table 8.21: Zeta potential raw data for SIBX in 0 SPW

Reagent	*SIBX*	**Run**	**Zeta potential (mV)**
Dosage (g/t)	50	*Run 1*	-21.30
SPW	0 SPW		-22.40
			-21.90
		Run 2	-20.60
			-20.40
			-19.80
		Average	**-21.07**
		Standard deviation	**0.98**
Reagent	*SIBX*	**Run**	**Zeta potential (mV)**
Dosage (g/t)	150	*Run 1*	-19.00
SPW	0 SPW		-18.00
			-18.00
		Run 2	-20.20
			-21.80
			-21.60
		Average	**-19.77**
		Standard deviation	**1.70**

Table 8.22: Zeta potential raw data for no collector and SEX in 3 SPW

Reagent	*No collector*	**Run**	**Zeta potential (mV)**
Dosage (g/t)		*Run 1*	-10.20
SPW	3 SPW		-11.40
			-9.75
		Run 2	-8.91
			-11.10
			-7.40
		Average	**-9.79**
		Standard deviation	**1.48**
Reagent	*SEX*	**Run**	**Zeta potential (mV)**
Dosage (g/t)	50	*Run 1*	-9.97
SPW	3 SPW		-9.63
			-11.50
		Run 2	-10.11
			-10.68
			-10.80
		Average	**-10.45**
		Standard deviation	**0.71**
Reagent	*SEX*	**Run**	**Zeta potential (mV)**
Dosage (g/t)	150	*Run 1*	-7.59
SPW	3 SPW		-8.82
			-8.85
		Run 2	-8.00
			-8.47
			-9.24
		Average	**-8.50**
		Standard deviation	**0.61**

Table 8.23: Zeta potential raw data for no collector and SIBX in 3 SPW

Reagent	*SIBX*	**Run**	**Zeta potential (mV)**
Dosage (g/t)	50	*Run 1*	-7.23
SPW	3 SPW		-8.57
			-9.17
		Run 2	-9.05
			-7.70
			-7.70
		Average	**-8.24**
		Standard deviation	**0.80**
Reagent	*SIBX*	**Run**	**Zeta potential (mV)**
Dosage (g/t)	150	*Run 1*	-5.41
SPW	3 SPW		-7.15
			-7.70
		Run 2	-6.00
			-6.99
			-7.30
		Average	**-6.76**
		Standard deviation	**0.87**

Table 8.24: Zeta potential raw data for no collector and SEX in 5 SPW

Reagent	*No collector*	**Run**	**Zeta potential (mV)**
Dosage (g/t)		*Run 1*	-1.31
SPW	5 SPW		-0.90
			-1.65
		Run 2	-1.47
			-1.99
			-2.88
		Average	**-1.70**
		Standard deviation	**0.68**
Reagent	*SEX*	**Run**	**Zeta potential (mV)**
Dosage (g/t)	50	*Run 1*	-0.52
SPW	5 SPW		-0.39
			-0.16
		Run 2	-0.67
			-0.23
			-0.19
		Average	**-0.36**
		Standard deviation	**0.21**
Reagent	*SEX*	**Run**	**Zeta potential (mV)**
Dosage (g/t)	150	*Run 1*	-3.25
SPW	5 SPW		-4.38
			-3.81
		Run 2	-2.39
			-3.34
			-3.14
		Average	**-3.39**
		Standard deviation	**0.67**

Table 8.25: Zeta potential raw data for SIBX in 5 SPW

Reagent	*SIBX*	**Run**	**Zeta potential (mV)**
Dosage (g/t)	50	*Run 1*	-0.24
SPW	5 SPW		-1.30
			-1.88
		Run 2	-0.77
			-1.60
			-1.05
		Average	**-1.14**
		Standard deviation	**0.59**
Reagent	*SIBX*	**Run**	**Zeta potential (mV)**
Dosage (g/t)	150	*Run 1*	-5.41
SPW	5 SPW		-7.15
			-7.70
		Run 2	-6.00
			-6.99
			-7.30
		Average	**-6.76**
		Standard deviation	**0.87**