INVESTIGATION OF THE EFFECT OF THE REAGENT SUITE IN FROTH FLOTATION OF A MERENSKY ORE

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Declaration

I hereby declare that the work presented in this thesis, submitted to the University of Cape Town in fulfilment of the requirements for the degree of Master of Science in Engineering has never been submitted prior to this at this University, or any other institution.

I know the meaning of plagiarism and declare that all the work presented in this thesis, save for that which is duly acknowledged, is my own.

Signed: Signed by candidate Signature Removed

Tiisetso Makheane Moimane

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Synopsis

The mining industry is faced with a challenge to develop efficient and economically feasible processing routes owing to the depletion of high-grade ores, and the ever increasing demand for precious metals for a wide range of applications. The valuable minerals, PGMs (Platinum Group Minerals) and BMS (Base Metal Sulphides) in the ores are extracted through the aid of chemical reagents (activators, **collectors**, **depressants**, **frothers**, modifiers) which are added to the flotation circuits to facilitate the separation between these minerals and the undesired gangue minerals present in the ore. The process is made complex by many surface reactions taking place, the existence of secondary and interactive effects among the flotation reagents, as well as the surface liberation of the minerals. Owing to the stringent regulations around water usage, concentrator plants are left with no option but to recycle water within their operations. This practice leads to accumulation of pollutants, such as organics, flotation reagents residues, **dissolved ions**, etc., which will likely have an influence on the chemical environment of the process, and subsequently will bear an impact on the overall metallurgical performance of the concentrator. This makes the process even more intricate, making it difficult to account for the behaviour of the chemical reagents, as well as making it virtually impossible to precisely assess their individual contribution to the overall flotation performance. Hence it is of crucial importance to adopt a holistic approach when investigating the effects of the chemical parameters in a flotation process.

This is a flotation chemistry study that adopted a two-level-four-factor (2^4) factorial experimental design to evaluate the simultaneous effects of the chemical parameters, with particular reference to **collector**, **depressant**, **frother**, and **ionic strength of the synthetic plant water**, as well as determining the possible interactive effects between the chosen parameters.

This investigation was made possible by conducting batch flotation tests on a PGM-bearing ore from the Merensky reef of the Bushveld Igneous Complex. Sodium isobutyl xanthate (SIBX), a polysaccharide, namely guar gum, and a polyglycol ether, namely Dowfroth 250 were used as the collector, depressant and frother, respectively. These are the typical chemical reagents the dosages of which tailored in the PGM industry for the processing of the ores. The metallurgical performance

indicators used were solids, water, copper and nickel recoveries as well as copper and nickel grades. The copper and nickel assays were carried out using X-ray Fluorescence spectrometry.

This study has shown that it is of crucial importance to know the exact collector dosage that yields maximum recoveries owing to the effect of elevated collector dosage on the froth. Moreover, this would also aid in reducing reagent wastage. It was revealed that there exist interactive effects between the depressant and frother, as well as between the frother and ionic strength of the plant water on solids recovery. No interactions among the parameters in question were observed on copper and water recoveries. Nickel recovery was shown to be affected by interactive effects between depressant and frother, as well as between collector and depressant. The depressant was observed to be the most influential parameter on the flotation behaviour of pentlandite, overriding the effects of collector and frother. Interactive effects are of crucial importance to consider when selecting reagent suites because different metallurgical performances can be obtained from different levels of the parameters in question. Therefore a factorial experimental design can be a useful tool in evaluating the simultaneous effects of such parameters in such a complex process. This will in turn allow for optimisation of such variables, and hence improved recoveries of the valuable minerals. Moreover, coupling this approach with full mineralogical analysis of the feed will enhance the understanding of the behaviour of the flotation reagents in the process. The practice of water recycle should not impose any adverse effects during the beneficiation of PGM bearing ores from the Merensky reef in which the base metal sulphide minerals, chalcopyrite and pentlandite, serve as a good diagnostic for the flotation behaviour of the PGMs.

Abbreviations

BIC	Bushveld Igneous Complex
BMS	Base metal sulphide
Ca^{2+}	Calcium cation
$Ca(NO_3)_2.4H_2O$	Calcium nitrate 4-hydrate
$CaCl_2$	Calcium chloride
C1	First concentrate
C2	Second concentrate
C3	Third concentrate
C4	Fourth concentrate
CMC	Carboxymethyl cellulose
CMR	Centre for Minerals Research
DS	Degree of substitution
DTP	Dithiophosphate
DTC	Dithiocarbamate
g/t	grams per ton
g/mol	grams per mole
Guar	guar gum
IS	Ionic strength
L/min	Litres per minute
Mg^{2+}	Magnesium cation
$MgSO_4.7H_2O$	Magnesium sulphate heptahydrate
$Mg(NO_3).6H_2O$	Magnesium nitrate
mm	Millimetres
m/v	Mass volume
NaCl	Sodium chloride
Na_2CO_3	Sodium carbonate
NFG	Naturally floatable gangue
PAX	Potassium amyl xanthate
PGM	Platinum Group Mineral

QEMSCAN	Quantitative Evaluation of Minerals using Scanning Electron Microscopy
rpm	Revolutions per minute
SEX	Sodium ethyl xanthate
SIBX	Sodium isobutyl xanthate
SNPX	Sodium normal propyl xanthate
TDS	Total Dissolved Solids
ToF-SIMS	Time of flight secondary ion mass spectrometry
UCT	University of Cape Town
µm	Micron
XRF	X-ray Fluorescence

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1. Introduction

1.1 Background

It is well known that South Africa ranks first on a global scale in the production of platinum, hosting about 75% of the world's platinum reserves within the Bushveld Igneous Complex (BIC), which consists of three main ore bodies, namely the Merensky reef, the UG2 reef and the Platreef (Cawthorn 1999). The platinum group minerals (PGM) are extracted and refined to produce scarce and expensive metals such as platinum, ruthenium, rhodium, palladium, osmium and iridium. In addition to these PGMs, there are also base metal sulphides (BMS) in the form of chalcopyrite, pentlandite, pyrrhotite and pyrite. With the ever increasing demand for these minerals (PGMs and BMS) in order to produce metals for specialised applications ranging from catalysis, medicine, fuel cells, to other industrial uses (Gupta et al. 2014), it is imperative that processing and metallurgical operations develop economically favourable and optimum methods for the beneficiation of the ores.

The conventional method for valuable mineral extraction is froth flotation, one of the most widely used industrial separation technologies, and has been practised for over 100 years since its commercialisation in the early 20th century (Ata 2012). However, it is not fully understood and still remains fairly inefficient (Shean & Cilliers 2011) especially as ore compositions change and high-grade ores are being depleted. Laboratory scale flotation is a valuable tool in studying industrial scale flotation (Mishra et al. 2013) in a quest to understand the governing mechanisms and process optimisation. This process utilizes the differences in surface properties between the valuable minerals and gangue in order to separate them. A combination of reagents; collectors, depressants, activators, modifiers and frothers are added to flotation pulps to manipulate the pulp chemistry. This has the collective effect of enhancing the differences in the surface properties of the valuable minerals and gangue (Bradshaw et al. 2005). Of particular interest to the present study is the collector, depressant and frother as well as water quality.

Collectors are added to impart hydrophobicity to the valuable mineral particles for transportation into the froth phase after successful attachment to the air bubbles, and ultimately in the concentrate launder from where they can be sent for further refinement. Efforts are made to inhibit the recovery of gangue minerals, which dilute the concentrate, by adding depressants which render the gangue mineral surface hydrophilic and hence they remain submerged in the pulp and are subsequently disposed into the tailing stream. To ensure an adequate separation between the valuables and the gangue, the 'heart' of the flotation process – the froth phase, has to be 'ideally' stable, and frothers are responsible for this stability as well as bubble formation and dispersion.

It has been reported that in addition to the primary role of a chemical reagent, there exist various reagent interactions and secondary effects (Bradshaw et al. 2005). Moreover, studies have demonstrated that a change in one reagent in the overall reagent suite usually has an influence on the overall performance of the process. It is thus challenging to precisely assess the individual contributions of a reagent due to the above-mentioned effects in addition to its primary role. This makes it difficult to precisely predict whether the intentions have been achieved directly or indirectly, thus a holistic approach is sought. Therefore a factorial design approach can be adopted as it has been reported to be a powerful tool in simultaneously evaluating the effects of several process parameters (Nanthakumar & Kelebek 2007). In addition, the traditional approach (i.e. one variable at a time) of assessing effects of process variables can potentially mask important aspects, such as interactions among the variables in question, contributing to the overall performance of the process.

Due to the stringent environmental regulations around water usage, concentrator plants are forced to find other sources of water supply such as borehole water, sea water or recycled plant water. The concentration of inorganic ions in such water is generally high (Bournival et al. 2012), and the presence of those ions modifies the chemical environment in the flotation circuits, and ultimately affects the overall performance of a metallurgical plant. Efforts were made to mimic typical concentrator plant water when conducting bench scale experiments by the development of synthetic plant water (SPW), which contains inorganic ions only, with TDS (total dissolved solids) of 1023 mg/ L (Wiese et al. 2005). As many mining operations

recycle and reuse water within their metallurgical circuits, the concentration of those ions, as well as other pollutants such as organics, flotation reagent residues, etc., increase with time (Corin & Wiese 2014; Manono et al. 2012; Kurniawan et al. 2011; Bıçak et al. 2012; Levay et al. 2001; Rao & Finch 1989), and will likely alter the plant output performance. It is therefore of importance to understand the effect that the build-up of such ions can have in the flotation process.

In light of this, the present study adopts a four-variable-two-level (2^4) Factorial design experimental approach in efforts to understand the interactive effects of the collector, frother, depressant and ions present in the plant water on the flotation performance of a Merensky ore. This will illustrate the overall changes that should be taken into account when there is a change in one of these process variables, and to allow for the prediction of an optimum set of conditions in process control. Furthermore, this will provide some insights into the impact water recycling can have on the metallurgical performance of a typical concentrator plant.

1.2 Scope of the project

The present work evaluates the metallurgical performance of a Merensky ore by chemically analysing for the recovery and grade of the elements copper and nickel, which simulate the flotation behaviour of the sulphide minerals chalcopyrite and pentlandite, respectively. Furthermore, solids and water recoveries will also be used as indicators for the metallurgical performance of this ore, subject to varying the concentration of the collector, frother, depressant and ions in the synthetic plant water in batch flotation experiments. This work is exclusively laboratory based and will not include any plant trials. Shown in Figure 1.1 is a more detailed summary of the scope of this research project.

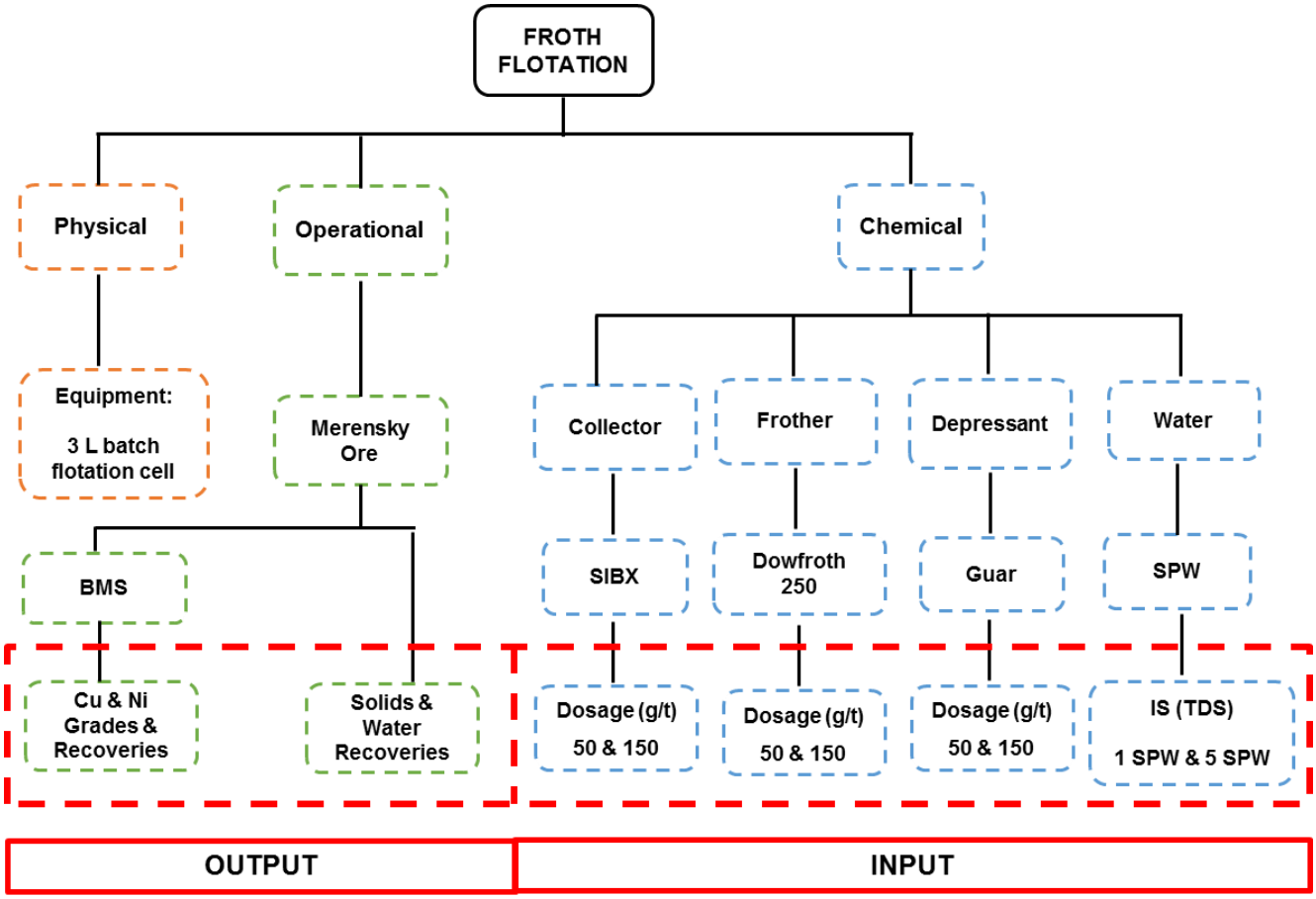


***Figure 1.1**: Schematic representation of the scope of this thesis (Adapted from Wiese 2009)*

2. Literature review

2.1 Merensky Ore

The world's largest Platinum Group Mineral (PGM) reserves are hosted by the Bushveld Igneous Complex (BIC), which has a total surface area of about 65 000 km^2, in South Africa. This complex consists of three main ore bodies, *viz* the Merensky reef, the UG2 reef and the Platreef. Shown in Figure 2.1 is a geological map of the BIC. The present study focuses on the flotation behaviour of an ore from the Merensky reef which was discovered in 1924 by Dr Hans Merensky (Cawthorn 1999). The Base Metal Sulphide (BMS) content in this reef is in the region of 1 %, and the PGM are associated with these BMS (Schouwstra et al. 2000; Liddell et al. 1986). The main PGMs present in this reef are cooperite (PtS), braggite {(Pt,Pd)NiS}, sperrylite ($PtAs_2$) and PGE alloys, and their compositions vary according to the region where they are found across the reef (Schouwstra et al. 2000). The BMS are in the form of pyrrhotite (~40 %), pentlandite (~30 %), chalcopyrite (~15 %), and trace amounts of millerite, troilite, pyrite, and cubanite. The predominantly occurring silicate minerals in the Merensky reef comprise orthopyroxene (~60 %), plagioclase feldspar (~20 %), pyroxene (~15%), phlogopite (~5 %), and sometimes olivine. Other silicate minerals present are talc, serpentine, chlorite and magnetite, and their compositions also vary (Schouwstra et al. 2000). Among the gangue minerals, talc is the only one known to be naturally floatable and hence can report to the concentrate by 'true flotation'. It is present in trace amounts in the Merensky reef, however, the volume of naturally floatable gangue (NFG) recovered in the concentrate during the flotation of this ore is usually significant (Wiese et al. 2005). It was postulated that additional mineralogical components were contributing to the NFG (Becker et al. 2009). This was confirmed (Becker et al. 2009), using Quantitative Evaluation of Minerals by Scanning Electron Microscopy (QEMSCAN) for liberation analysis, which revealed that there was preferential association of talc with pyroxene. This was further attested to, using Time of Flight Secondary Ion Mass Spectrometry (ToF-SIMS) (Jasieniak & Smart 2009).

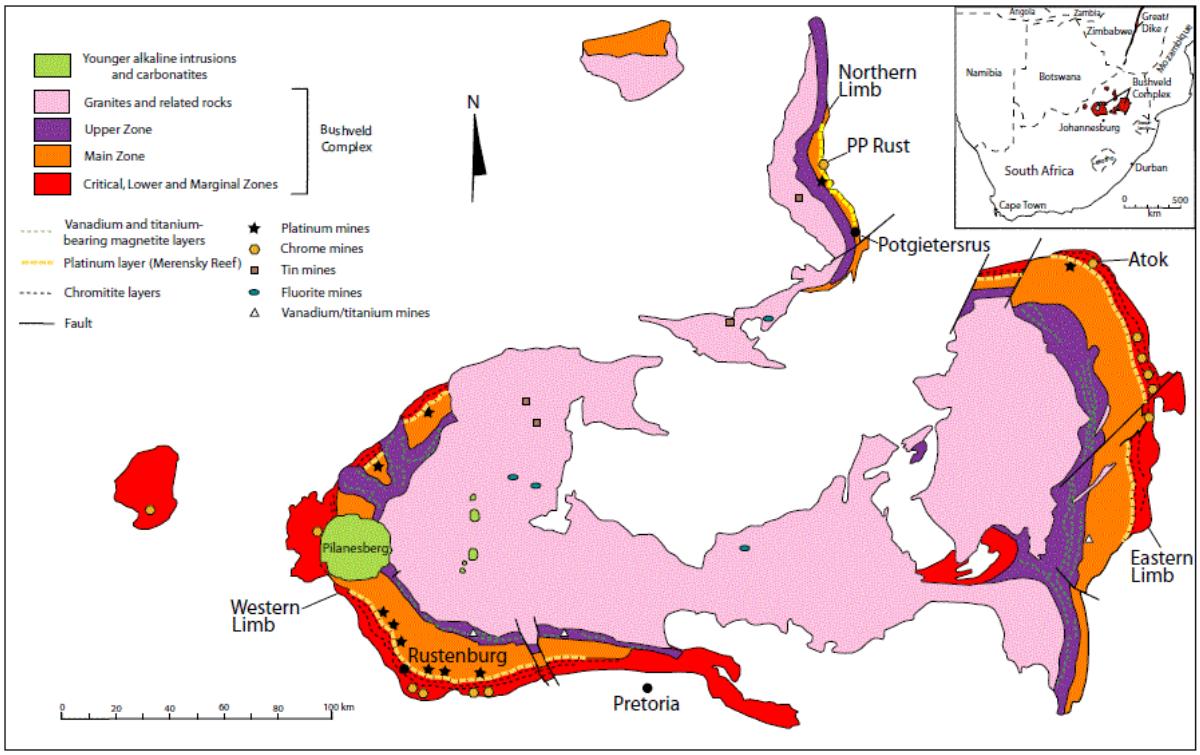


***Figure 2.1**: Simplified schematic of a geological map of the Bushveld Igneous Complex (http://home.hiroshima-u.ac.jp/er/Rmin_EG_KS_01_A&ME.html)*

2.2 Fundamentals of flotation

The valuable minerals in the reef are extracted by froth flotation, a separation technique which relies on exploiting the surface property of the minerals known as wettability. By means of chemical treatment, the mineral surface properties can be selectively altered to achieve necessary properties eligible for separation (Rankin, 2011). The basis of the flotation process is that air is introduced into the pulp in a flotation cell to generate bubbles to which hydrophobic particles (valuable minerals) are attached. The laden bubbles rise to the surface from where the particles are collected, and the hydrophilic particles (gangue) remain in the flotation cell and are consequently disposed into the tailing stream (Figure 2.2). The success of the flotation process is defined by both grade and recovery of the minerals of interest. Grade is the fraction of the mineral of interest in the concentrate, and recovery is the fraction of the mineral of interest in the concentrate relative to that in the feed.

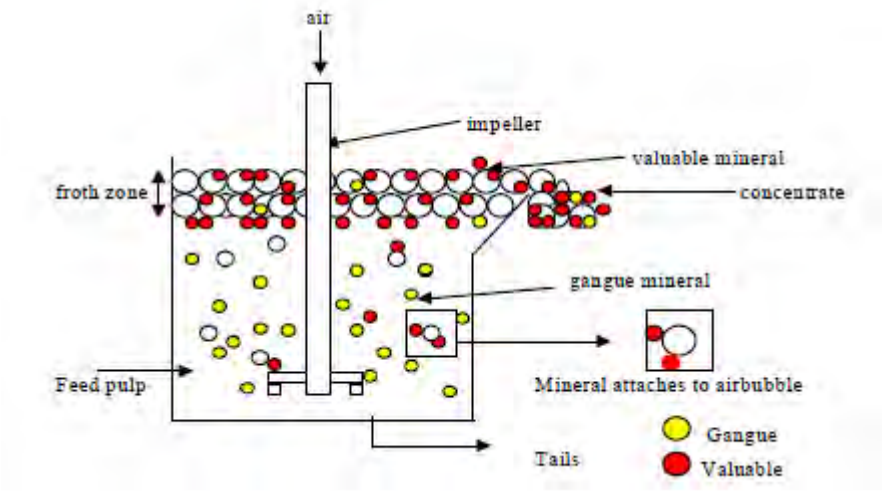


***Figure 2.2**: Schematic representation of the froth flotation process (Martinovic 2004)*

Shown in Figure 2.3 is an idealized schematic illustration of the tensile forces when a mineral particle is attached to an air bubble. At equilibrium, the three tensile forces are related by Young's equation as;

$$\gamma_{mineral-air} - \gamma_{mineral-water} = \gamma_{water-air} \cos\theta$$

Where: $\gamma_{mineral-air}$,$\gamma_{mineral-water}$ and $\gamma_{water-air}$ are the energies of the mineral-air, mineral-water and water-air boundaries respectively, and θ is the contact angle between the mineral surface and the air bubble.

For flotation to occur, i.e., for the mineral particles to successfully attach to the air bubbles and ultimately be transported into the froth, the following condition should hold;

$$\gamma_{mineral-air} - \gamma_{mineral-water} < \gamma_{water-air}$$

This infers that $\theta > 0$, and therefore the water is not evenly spread over the particle surface, as a result the particle surface is said to be water-repellent. Hence the particle is amenable to be recovered by ''true flotation''.

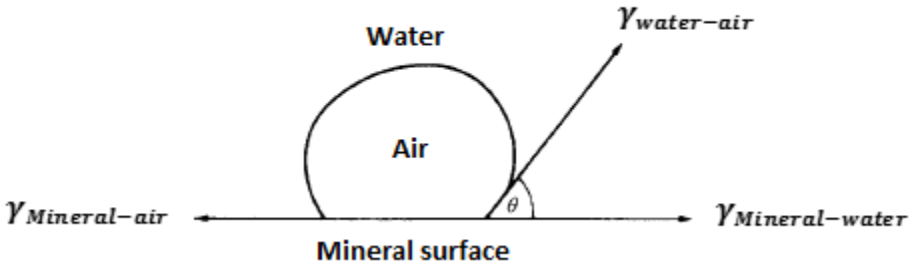


***Figure 2.3**: Illustration of the surface tension forces between air, water and mineral surface (Adapted from* (Chau et al. 2009)

2.2.1 Pulp phase and froth phase

The flotation system consists of two major phases, *viz*. the pulp phase and the froth phase. An environment suitable for successful bubble-particle collision and valuable mineral particle attachment to air bubbles is crucial in the pulp phase. The valuable mineral particles ought to be rendered hydrophobic in order to attach to the air bubbles and ultimately transport to the surface. At the same time, attachment of the gangue particles should be inhibited by rendering their surface hydrophilic, and hence ineligible to recovery by ‘’true flotation’’ (Bradshaw et al. 2005).

As the final separation phase in a flotation system, the froth phase plays a crucial role in determining the overall metallurgical performance of a flotation process. The predominant role of this phase is to facilitate the upgrading of the valuable mineral particles reporting to the concentrate, at the same time ensuring that there is no loss in recovery. It is clear that the stability of the froth phase plays a central role and it is therefore imperative to have an optimum stability of the froth. This is primarily governed by factors such as frother type and concentration, the presence of particles of varying hydrophobicity (Bradshaw et al. 2005) as well as water quality (Wiese et al. 2011). A ‘too stable’ froth phase, though no loss is experienced in the recovery of the valuables, results in considerable recovery of gangue minerals by entrainment. This makes upgrading of valuable minerals unlikely to be adequate. A ‘too unstable’

froth phase may give rise to a good grade of the valuable minerals but is often accompanied by a loss in recovery (Bradshaw et al. 2005). So the relationship between recovery and grade of the minerals is a trade-off that can be well described by the classical grade-recovery curve shown in Figure 2.4. Depending on operational constraints and priorities of a concentrator plant in question, the recovery of the minerals can be higher however at a lower grade, and vice-versa.

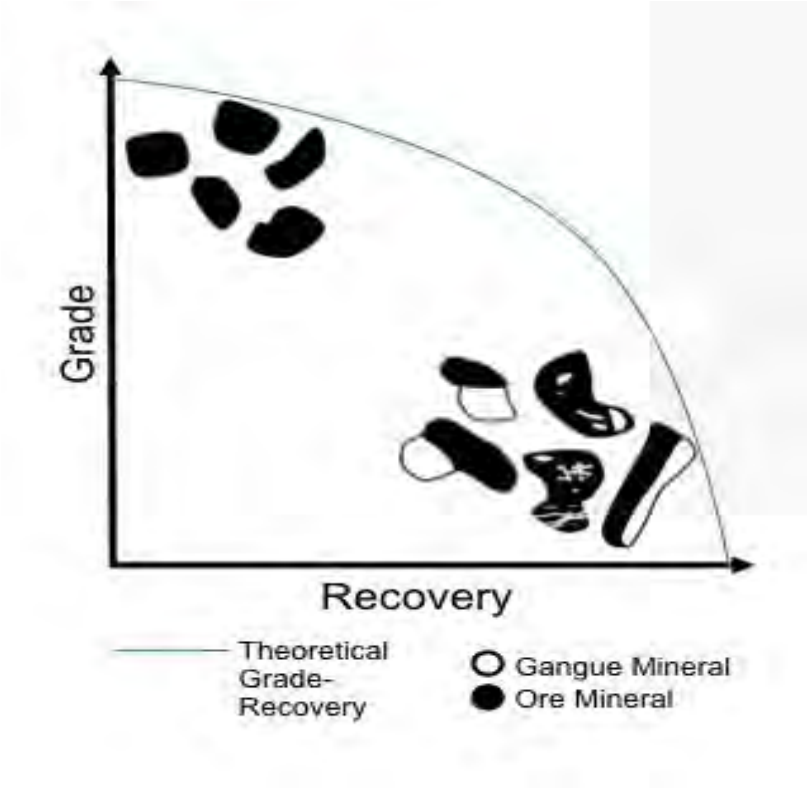


***Figure 2.4**: A typical classical concentrate grade-recovery curve (www.minassist.com.au/blog)*

2.2.2 True flotation and entrainment

There is always some gangue material recovered to the concentrate, and this is due to the fact that in a flotation system there are two primary mechanisms by which a gangue particle can report to the froth phase. It can be transported into the froth by attachment to an air bubble (true flotation), or it can be suspended in the water trapped between the air bubbles and transported to the froth (entrainment). While the former mechanism is selective between hydrophobic and hydrophilic particles, the latter is nonselective and not directly affected by changes in mineral surface properties but is rather affected by particle properties such as density and size (Bradshaw et al. 2005). Therefore entrained particles are just as likely to be gangue

minerals as they are to be the valuable minerals. However, there are some naturally floatable gangue (NFG) minerals such as talc that can report to the concentrate by both mechanisms. It has also been reported that there is an association of talc with orthopyroxene (Becker et al. 2009), thereby rendering the orthopyroxene particles hydrophobic and hence also eligible to report to the concentrate via both mechanisms.

2.3 Parameters affecting flotation

Froth flotation is a complex process which is affected by many parameters. Klimpel (1984) divided the major parameters into three categories, *viz*. chemistry components, equipment components and operation components. The focus of the present study is restricted to the first category, with particular attention to those highlighted in red (Figure 2.5).

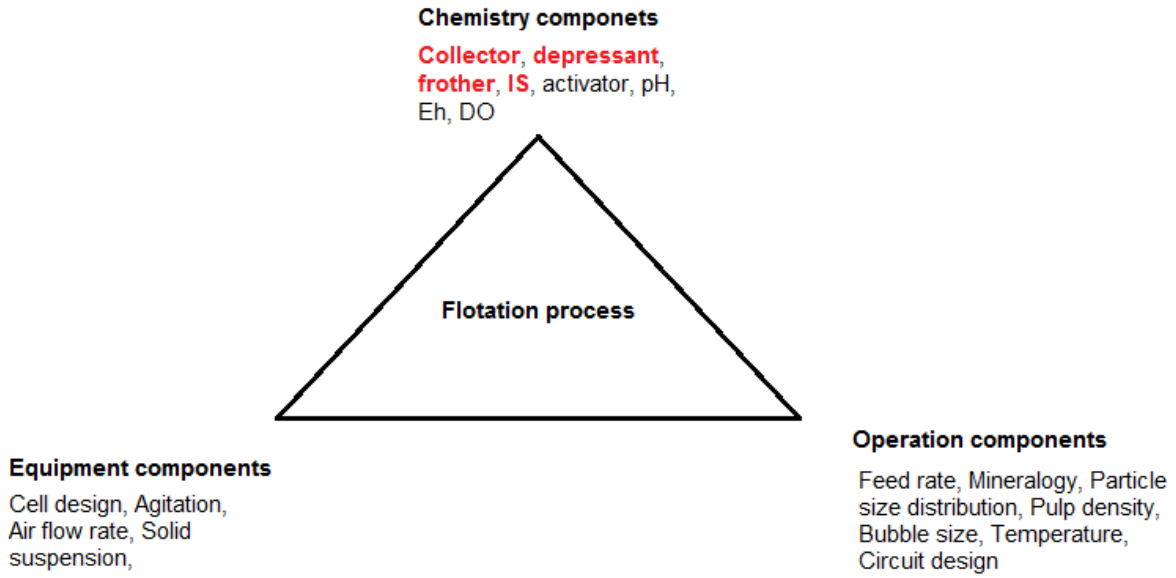


***Figure 2.5**: Summary of parameters affecting the flotation process (Adapted from Klimpel 1984)*

2.4 Flotation reagents

In order for the valuable minerals to be eligible for transportation into the froth phase and the gangue to remain submerged in the pulp, their surface properties should be selectively altered by the addition of surfactants; termed flotation reagents. A typical reagent suite comprises; collector, frother and depressant, and in some cases, an

activator. This study focuses on the first three, and these are discussed in the following sections.

2.4.1 Collectors

Collectors are polar compounds consisting of a non-polar hydrocarbon chain, which is hydrophobic in nature, and a polar head group which interacts with the mineral surface, forming either a chemical or physical bond depending on the type of adsorption mechanism at play. Their primary role is to selectively impart hydrophobicity to the valuable mineral particle surface (Lotter & Bradshaw 2010). Shown in Figure 2.6 is an idealized schematic representation of a valuable mineral particle coated with collector molecules, with the hydrocarbon group orienting perpendicular to the mineral surface and protruding into the pulp.

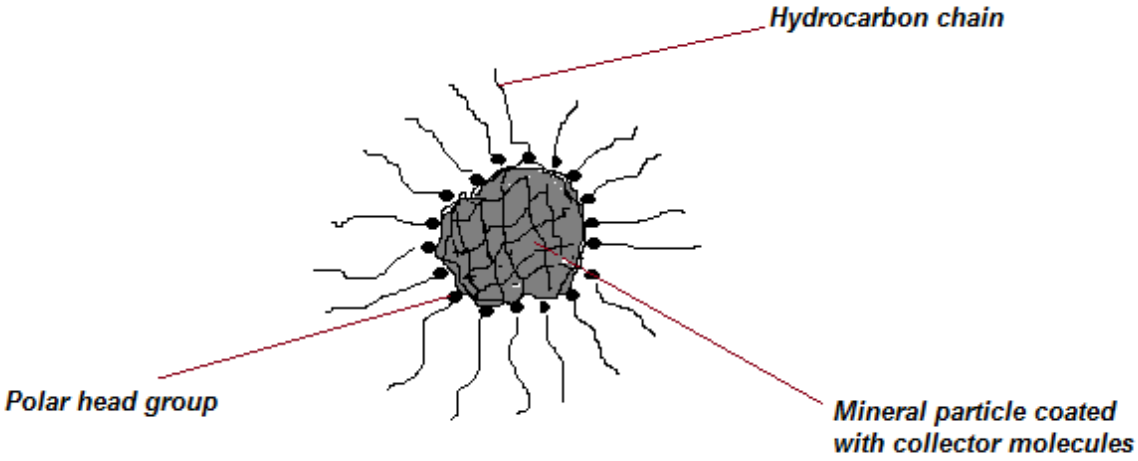


***Figure 2.6**: Illustration of collector molecules adsorbing on mineral particle surface*

The predominantly used class of collectors for the flotation of sulphide minerals is the thiol collector class, which consists of xanthates, dithiophosphates and dithiocarbamates. Within this class, xanthates have been "*the workhorse"* of sulphide mineral flotation since their introduction in the early 1920s (Breytenbach et al. 2003). This is due to their low cost, intermediate selectivity and strong collecting power, collectively resulting in a reasonably higher recovery at an acceptable grade of the valuable minerals (Adkins & Pearse 1992). The generic structures of the sub-classes of the thiol collectors are shown in Figure 2.7.

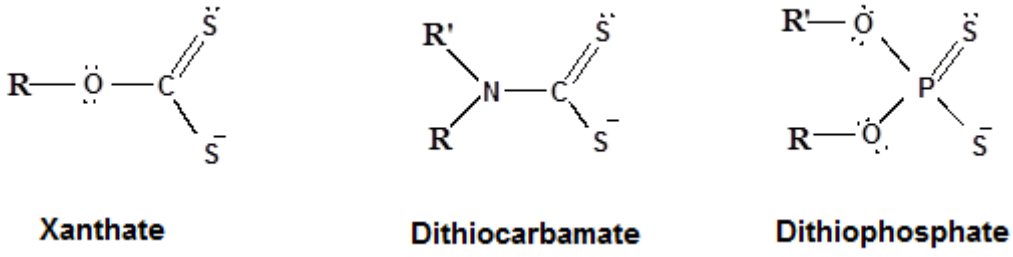


***Figure 2.7**: Generic structures of thiol collectors. The R group represents a hydrocarbon chain (Adapted from* Lotter & Bradshaw 2010)

Dithiophosphates are the second most commonly used thiol collectors and their use in froth flotation dates back to 1920, followed by dithiocarbamates which were discovered in 1850 (Lotter & Bradshaw 2010). The strength and selectivity of these collectors in the froth flotation of sulphide minerals is as follows:

Collector strength: dithiocarbamate > xanthate > dithiophosphate

Selectivity: dithiophosphate > xanthate > dithiocarbamate

(Lotter & Bradshaw 2010)

Contrary to expectations based on this sequence of strength and selectivity of the thiol collectors, a study conducted by Hangone et al. (2005) revealed that dithiocarbamate (di-C2-DTC) was the weakest and least selective collector in the flotation of a copper sulphide ore (Figure 2.8).

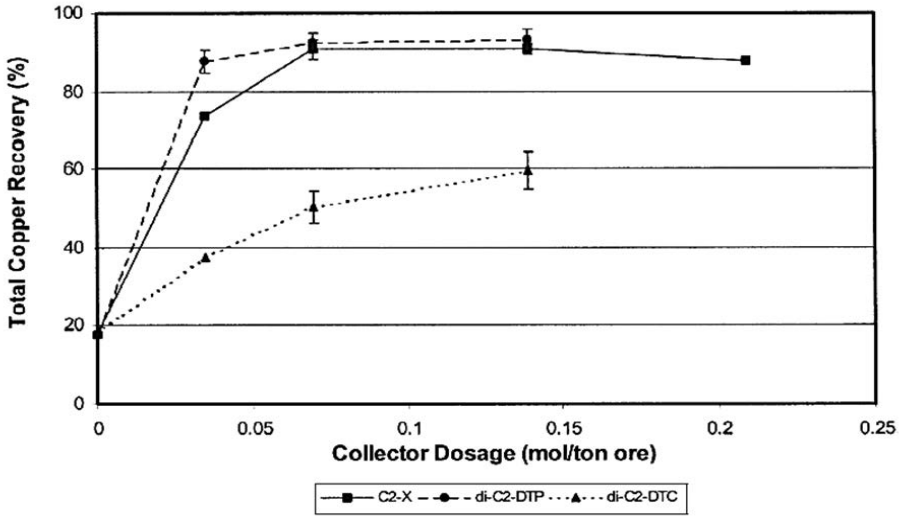
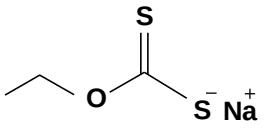


***Figure 2.8**: Final cumulative copper recovery versus collector dosage obtained with ethyl xanthate (C2-X), di-ethyl-dithiophosphate (di-DTP) and di-ethyl-dithiocarbamate (di-C2-DTC) (Reproduced from* Hangone et al. 2005)

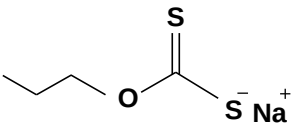
This study also supported the theory that the effectiveness of a collector also depends on the hydrocarbon chain (Mbonambi 2009; Ackerman et al. 1987) with di-ethyl-dithiophosphate (di-C2-DTP) resulting in higher copper recoveries than ethyl xanthate (C2-X). This is by virtue of the di-C2-DTP having two hydrocarbon chains and consequently enhanced hydrophobicity of the mineral surface which results in improved recoveries. The results also depict that there is an optimum collector dosage, and therefore it is of importance for concentrators to be aware of the exact dosage that yields maximum recovery of the valuables for the particular ore being processed. This conserves reagents and optimises the costs.

The present study utilises a xanthate collector which is commonly used by many of the South African mining operations concentrating sulphide ores. The most commonly used xanthate collectors are shown in Figure 2.9. The raw materials for the synthesis of xanthate collectors are alcohol (R-OH), potassium or sodium hydroxide, and carbon disulphide (CS_2). Reaction 1 shows this synthesis for potassium xanthates (Lotter & Bradshaw 2010; Dimou 1986; Wiese 2009).

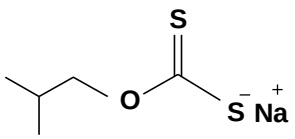
$$ROH + KOH + CS_2 \rightarrow ROCS_2K + H_2O \qquad (1)$$



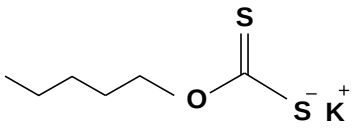
Sodium ethyl xanthate (SEX)



Sodium normal propyl xanthate (SNPX)



Sodium isobutyl xanthate (SIBX)



Potassium amyl xanthate (PAX)

Figure 2.9*: Schematics of the molecular structures of the most commonly used xanthate collectors in flotation of sulphide ores*

Dimou (1986) investigated the flotation behaviour of pyrite using xanthate collectors of varying hydrocarbon chain length. It was found that increasing the concentration and hydrocarbon chain length of the collector increased the final concentrate grade. The author attributed this to the increased hydrophobicity of the resulting collector-coated pyrite particles, and hence improved recovery of pyrite. To further attest to these findings Bradshaw et al. (2004) used Potassium amyl xanthate (PAX) and Sodium ethyl xanthate (SEX) in the flotation of galena, in a frothless microflotation system. It was determined that the use of PAX yielded higher recoveries relative to the use of SEX. This indicated that the particles coated with PAX were more hydrophobic than those coated with SEX, and hence improved recovery was obtained. In a later study, this investigation was carried out in a batch flotation system – in order to ascertain whether or not froth had an impact. This study was carried out in the absence of talc, which has been reported to possess froth-stabilizing properties (Wiese 2009; Wiese et al. 2007), and the situation was reversed – higher recoveries were obtained with SEX. This agrees well with the observation that highly hydrophobic particles have a destabilising effect on the froth phase (Schwarz & Grano 2005; Johansson & Pugh 1992). Using SIBX and SEX Bradshaw et al. (2005) confirmed this finding (highly hydrophobic particles can destabilise the froth) in batch flotation tests using a Merensky ore. SIBX led to a reduction in mineral recovery, inferring a reduction in the stability of the froth phase, compared to when SEX was used. This effect of the degree of particle hydrophobicity on the nature of the froth phase can be well explained using the diagram in Figure 2.10, which was reproduced from Aveyard et al. (1994). The half-life ratio on the y-axis denotes the ratio of the difference in time for half-life of the foam in the presence and absence of particles, and the contact angles on the x-axis represents the hydrophobicity of the particles. The half-life of the foam is the burst rate of the bubbles. It follows that stabilisation of foams by particles leads to a half-life ratio in the positive direction, similarly, destabilisation of foams by particles leads to a half-life in the negative direction.

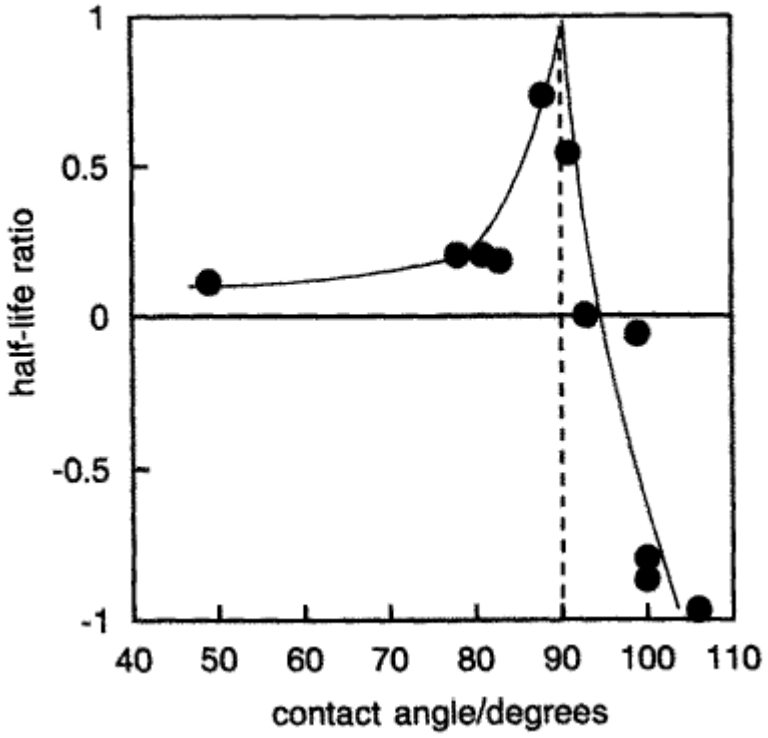


***Figure 2.10**: Half-life ratios as a function of contact angle* (Aveyard et al. 1994)

Figure 2.10 depicts that increasing the particle hydrophobicity (contact angle), up to a certain point, increases the stability of the froth thereby reaching maximum, and beyond that hydrophobicity, particles were observed to lead to film rupture – froth destabilisation. This in turn decreases the recovery of the solid particles into the concentrate launder, and hence a loss in recovery is experienced.

Ngobeni & Hangone (2013) showed that PAX yielded lower recoveries than SEX in the froth flotation of a pentlandite-containing ore from Nkomati mine. However, the use of PAX gave rise to higher concentrate grades due to lower water recoveries and lower entrainment, as a result of reduced froth stability.

This destabilising effect of highly hydrophobic collector-coated particles on the froth phase has further been confirmed in a recent study (Wiese et al. 2011), by replacing SEX with SIBX. It thus follows that there exists an optimum particle hydrophobicity or contact angle (by increasing either the chain length or dosage of a collector), above which the collector-coated particles start destabilising the froth phase consequently reducing valuable mineral recovery.

Several researchers explored the effect of using collector mixtures with the general thought that since collectors adsorb on mineral surfaces via different mechanisms,

their mixtures would ideally result in improved adsorption characteristics, leading to improved surface coverage on the mineral. The benefits associated with this compared to use of pure collectors are higher recoveries and grades, lower dosage requirements, improved kinetics and selectivity. Such benefits have been observed in a number of studies (Nyambayo 2014; McFadzean et al. 2012; Makanza et al. 2008; Hangone et al. 2005; Bradshaw 1997). However, the concept of collector mixtures is not part of the scope of the present study.

2.4.2 Depressants

The role of a depressant contrasts that of a collector, and inhibits certain minerals from floating, specifically the intrinsically floatable gangue minerals (mainly talc in the PGM ores from the BIC) that dilute the concentrate, subsequently reducing the grade of the valuable minerals. Talc is a hydrous magnesium silicate mineral [$Mg_3(Si_2O_5)_2(OH)_2$] consisting of two layers of silica tetrahedra sandwiched between brucite, $Mg(OH)_2$ (Figure 2.11). It consists of two kinds of surface area, *viz.* the neutral planes made of Si-O, which are believed to be hydrophobic in nature, and charged edges (Mg^{2+} and OH^-) which exhibit hydrophilic properties. The proportion of the planes to the edges is said to depend on the mineralogical properties of the talc (Khraisheh et al. 2005).

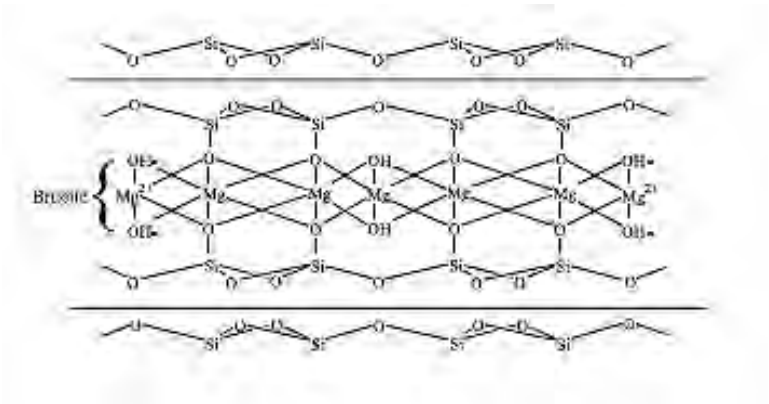


Figure 2.11*: Schematic of the molecular structure of talc (Reproduced from* Khraisheh et al. 2005)

Polymers have been used for a number of years in the mining industry to inhibit the recovery of such hydrophobic gangue minerals, and the adsorption characteristics of the polymer depressants on talc have been reported to be influenced by many factors. These include polymer type and concentration, molecular weight, degree of substitution (DS), pH, and ionic strength (Parolis et al. 2008; Khraisheh et al. 2005; Wang et al. 2005; Morris et al. 2002; Rath et al. 1997).

Many of the South African mining operations concentrating PGM bearing ores commonly use either carboxymethyl cellulose (CMC), or modified guar gum (guar) as depressants to reduce the amount of naturally floatable gangue (NFG) present in these ores (Wiese et al. 2007; Bradshaw et al. 2005). Schematics of these depressants are shown in Figure 2.12 and Figure 2.13, respectively.

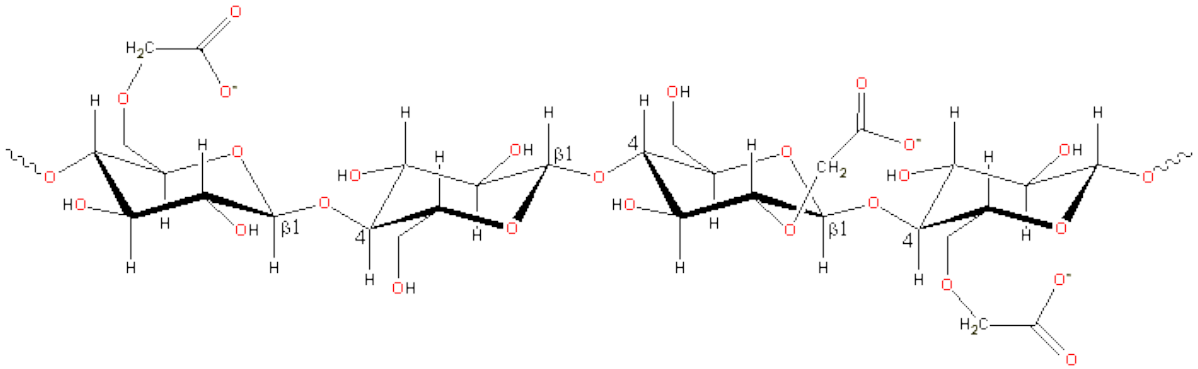


***Figure 2.12**: A schematic representation of the molecular structure of CMC (www.lsbu.ac.uk/water/carboxymethylcellulose.html)*

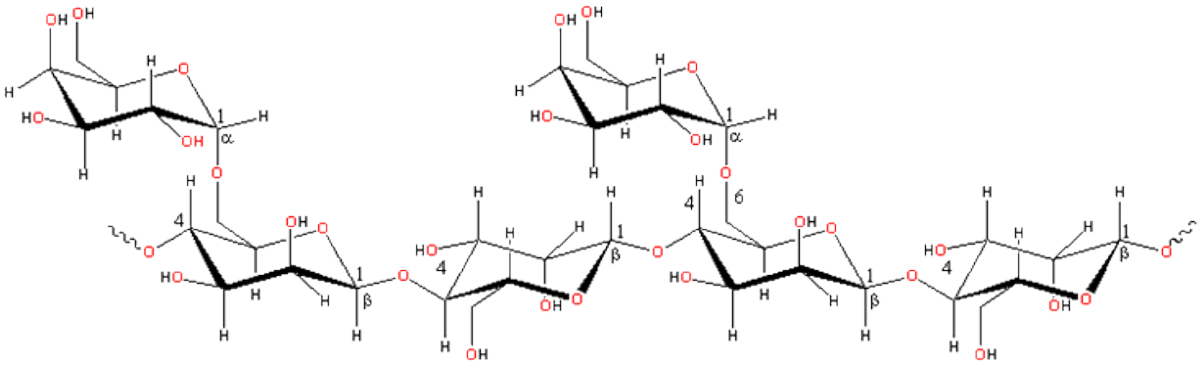


***Figure 2.13**: A schematic of the molecular structure of guar gum monomer (http://www.lsbu.ac.uk/water/guar_gum.html)*

Wiese et al. (2007) conducted a study on two ores from different parts of the Merensky reef using the two depressants; CMC and guar, and a fixed collector suite comprising of xanthate and dithiophosphate. This study investigated the effect of increasing depressant dosages on the amount of NFG reporting to the concentrate, while also observing the response of the sulphide minerals to higher depressant dosages. Solids and water recoveries decreased in conjunction with an increase in depressant dosage. This signifies reduction of the NFG in the concentrate and a decrease in froth stability (as shown by water recovery). This supports the finding that the naturally floatable talc mineral possesses froth stabilising properties, and

hence inhibiting it completely from reporting to the froth can have adverse consequences on the stability of this phase. Furthermore, it infers that recovery by entrainment will decrease, and hence concentrate grade will increase.

The study showed that copper recoveries were not affected by higher depressant dosages, however, nickel recoveries were shown to be slightly affected by high dosages. The authors ascribed this to the fact that it has been observed over the years that there is very little that affects the floatability of chalcopyrite due to its fast floating properties, while the slower floating pentlandite is mostly affected at high depressant dosages. This is in agreement with a study by Bradshaw et al. (2005) which demonstrated that pentlandite is more prone to the effects of high depressant dosages. This phenomenon is also ascribed to the oxidation on the surface of the minerals being different (Mishra 2011).

Guar was shown to be more dominant than CMC particularly at lower dosages (100 and 200 g/t), however, their depressive strengths were similar at higher dosages. This was also confirmed in a later study (Wiese 2009), the author attributed this to different adsorption mechanisms of these depressants. Guar is believed to adsorb to talc surfaces mainly via hydrogen bonding (Wang et al. 2005; Rath et al. 1997). However, other researchers have previously proposed that guar adsorbs to talc mainly at the basal planes via hydrophobic bonding (Jenkins & Ralston 1998; Steenberg & Harris 1984). CMC is believed to adsorb via acid / base interactions (Wiese 2009). Other proposed mechanisms of polymer adsorption on talc surfaces include chemical, electrostatic and hydrophobic interactions (Rath et al. 1997; Pugh 1989).

Apart from improving the selectivity of flotation by rendering gangue minerals hydrophilic, and improving concentrate grade, there is also a drawback associated with elevated depressant dosage as it affects the stability of the froth. Additionally, if the valuable minerals are not fully liberated from the gangue minerals during the grinding stage, having too high a concentration of the polymer in solution can depress the gangue-valuable mineral composite particles. It was also hypothesised that if the collector adsorption on the mineral surface is weaker, there is a possibility that the depressant molecules could co-adsorb since they are assumed to do so by physical bonding forces (Wiese et al. 2007). It then follows that bubble-particle

interaction will be hindered since the depressant molecules are bulky, and therefore a loss in recovery is bound to occur.

The present study uses a guar depressant, the adsorption of which is unlikely to be affected by solution conditions such as pH and ionic strength, just like any other non-ionic polymer depressant (Parolis et al. 2008; Khraisheh et al. 2005; Wang et al. 2005; Morris et al. 2002).

2.4.3 Frothers

Unlike collectors and depressants, frothing agents adsorb at the air-water interface of the bubbles, thereby controlling the frothing behaviour of the system (Manev & Pugh 1993), which subsequently define the nature of the froth phase. Therefore their role is to ensure that the overall metallurgical performance determinant – the froth phase, is 'ideally' stable to allow for adequate recovery of the minerals at an acceptable grade. However, the secondary effect associated with charging the frothing agents at elevated concentrations can be a reduction in the concentrate grade, owing to a more stable froth that allows for high water recovery, and hence unselective recovery of particles. Frothers are not associated with particular categories of minerals since they do not adsorb on the mineral surface. These are surface active, and usually non-ionic, heteropolar molecules with frothing abilities attributed to the hydroxyl (-OH), ester (-COOR) and carbonyl (-CO) groups. Commercially available frothers can be categorised into three main groups; alcohols, alkoxyparaffins, and polyglycols or polyglycol ethers (Bradshaw et al. 1998). The use of different frothing agents is well documented in literature (Gupta et al. 2007; Laskowski et al. 2003; Cho & Laskowski 2002; Aldrich & Feng 2000; Hosten & Tezcan 1990), as well as the use of frother blends, which have been reported to result in improved frothing properties (Dey et al. 2014; Ngoroma et al. 2013; Elmahdy & Finch 2013). The present study will utilise a polyglycol ether frother, which is normally used in the flotation of sulphide minerals.

2.5 Water quality in flotation

The wastewater produced in mineral processing operations comprises suspended solid particles, flotation reagents residuals, organics, heavy metal ions and other pollutants and this has a negative impact on water as a vital resource and on the

environment (Chen et al. 2009; Levay et al. 2001). As one of the measures taken in efforts to circumvent the challenge of water scarcity, mining, just like other industries, is forced to recycle and reuse water within their operations. However, this has implications on the performance of concentrators as water recycling results in an accumulation of these pollutants, which alter the chemical environment of the processing circuits and ultimately affect the overall plant output (Rao & Finch 1989). There has been ongoing research over the years on the impact that water recycling and reuse can have on metallurgical performance of various ore types. This practice also adds to the complexity of a flotation system, making it even more difficult to understand due to the many reactions taking place in the process. Therefore it is imperative to understand the behaviour of flotation reagents subject to the changes in the composition of the process water.

In the context of ores from the Merensky reef, UCT has conducted extensive research on this subject, mimicking typical concentrator process water by considering only inorganic ions. The implications of this practice are well documented. Manono et al. (2012) investigated the effect of ionic strength, depressant dosage and depressant type on the metallurgical performance of a PGM bearing ore from the Merensky reef. The predominant role played by the ions was to stabilise the froth, as evidenced by an increase in solids and water recoveries as the ionic strength of the plant water was increased (Figure 2.14). Moreover, copper and nickel recoveries were observed to increase with an increase in ionic strength. However, this occurred at the expense of the concentrate grade as a result of high gangue recovery by entrainment. This study has also further confirmed the susceptibility of pentlandite to high depressant dosages. A previous study (Corin et al. 2011) conducted on an ore from the same reef showed the same trends. A more recent study by (Corin & Wiese 2014) has also demonstrated the powerful frothing properties of the ions at high concentrations by yielding better flotation responses under high ionic strength conditions (measured by TDS) compared to high frother concentrations.

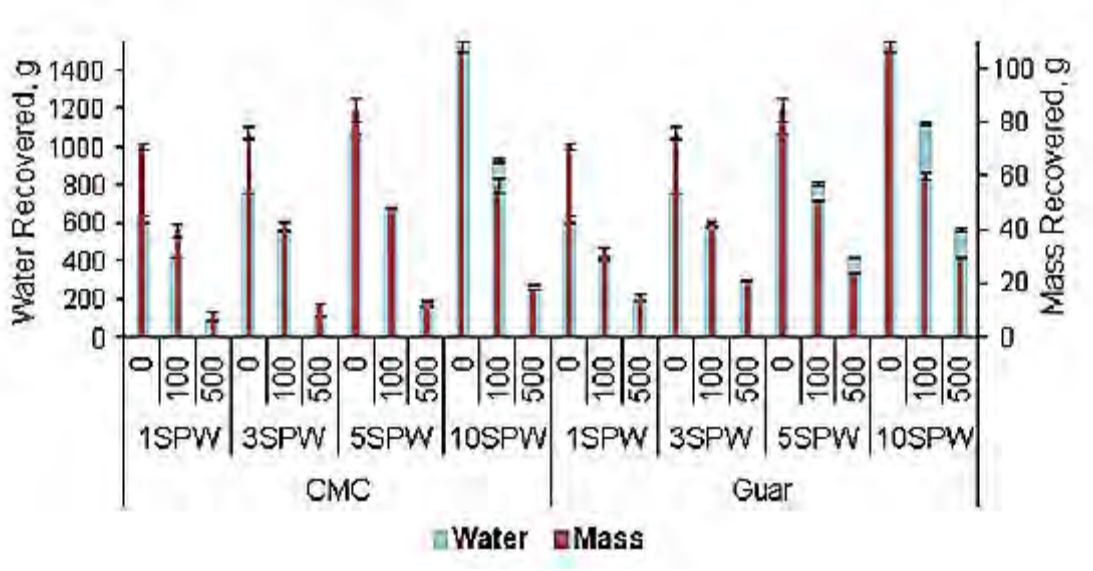


***Figure 2.14**: Final mass and water recoveries for all synthetic plant water types and depressant dosages* (Manono et al. 2012).

Other researchers have also investigated the effect of dissolved ions in process water on the flotation performance of various ore types. Chen et al. (2009) investigated flotation behaviour of galena and pyrite minerals in three different water types, *viz*. distilled, lead-concentrate and sulphur-concentrate. They showed that galena floatability could be improved by using lead-concentrate water compared to distilled water, while sulphur-concentrate water had a detrimental effect (pyrite flotation was found to be contrary to the flotation of galena). pH has also been shown to play a role in the flotation of both galena and pyrite, with a decrease in recovery as the pH increases. This could be ascribed to the formation of hydroxide species and precipitation of such on the mineral surfaces, rendering the minerals hydrophilic, as well as hindering their reaction with the collector. It was shown that copper and nickel recoveries can be improved in the flotation of a nickel sulphide ore by addition of calcium and thiosulfate ions after grinding in a steel mill (Kirjavainen et al. 2002). However, both (galena and pyrite) their floatabilities were supressed when grinding in a ceramic mill. Liu et al. (1993) reported that pyrite was depressed in the presence of calcium ions and thiosalts, thereby improving copper floatability in a Cu-Zn ore. Bıçak et al. (2012) showed that sphalerite and chalcopyrite flotation kinetics and recovery were enhanced by the presence of metal ions such as Cu^{2+} and Pb^{2+} in a Cu-Zn complex sulphide ore. However, at high concentration of the sulphide ions (thiosulphate and sulphate) in the process water, a depressive effect on sphalerite

and pyrite was observed, thereby counteracting the activation action of the metal ions. Moreover, froth stability was shown to increase in conjunction with the dissolved ions (mainly the sulphides). Kurniawan et al. (2011) reported that coal flotation can be improved by the addition of salt solutions, however, this depended on the type and concentration of the salts considered. Coal recovery increased with increasing concentrations of $MgCl_2$ and $NaClO_3$, with the former yielding higher recoveries. Furthermore, a reduction in bubble size was also observed, which infers an increased froth stability and hence increased flotation recovery.

It then follows that depending on the type and concentration of dissolved ions in solution, pulp conditions such as pH, and grinding media used, floatability of certain minerals can be improved, while for other minerals it can be inhibited. Furthermore, the dissolved ions in process water have also been shown to impose dynamic forces on the nature and the stability of the froth.

2.6 Factorial design

The traditional research methods generally study the effect of one independent variable on a dependent variable at a time. This approach can potentially miss out some important aspects in the interpretation of the effect of a given variable on a given response especially when considering complex processes like flotation. It is thus crucial to establish how a certain independent variable can affect a given response in the presence of other independent variables subject to changes in the other variables. This can be achieved by adopting a factorial experimental design, which is simply an experiment whose design consists of at least two factors, each with discrete possible values or levels. Through such designs it is possible to evaluate the effect of several factors simultaneously. A design is notated a^k factorial, where a is the number of levels and k is the number of factors. For example, a 2^3 factorial refers to a design with 3 factors and 2 levels, and 8 experimental conditions ($2^3 = 8$). This kind of an experimental design can also aid in determining optimum conditions, over a given range of operating conditions, of a process in question. Different researchers have used various factorial designs to understand the multivariable and interactive effects with particular reference to reagents in flotation

of various ore types (Nanthakumar & Kelebek, 2007; Sheridan et al., 2002; Smar, Klimpel & Aplan, 1994).

2.7 Summary

As highlighted in the previous sections, flotation is a very complex process consisting of many sub-processes and interactions among the reagents. Studies have shown that in addition to the predominant role of a flotation reagent there exist secondary effects which can override the desired effect for effective separation. More specifically, enhancing the sulphide mineral particles' hydrophobicity for amenability to true flotation may result in bubble rupture and consequently reduction in recovery. On the other hand, in reducing the hydrophobicity of the gangue minerals such as talc – which also possess froth stabilising properties and hence allowing for high recovery of other non-naturally floating gangue minerals by entrainment, charging the depressant at high dosages has drawbacks on the recovery. Moreover, the action of these reagents can also be limited by liberation of the particles. Furthermore, the presence of dissolved ions as a result of accumulation due to water recycle and reuse also influence the chemical environment of the flotation process. It is thus a challenging task to precisely predict whether the intentions have been achieved directly or indirectly, and hence it is crucial to take a holistic approach in assessing the influence of the reagent suite in flotation. Additionally the traditional way (i.e., one variable at a time) of assessing the effects of variables can mask the possibility of interactions between variables for a better performance. A factorial experimental design has been reported to be a powerful tool in simultaneously assessing the effects of parameters in a flotation system (Nanthakumar & Kelebek, 2007; Sheridan et al., 2002; Smar, Klimpel & Aplan, 1994).

In light of this, the present study adopts a four-variable-two-level (2^4) factorial design experimental approach in efforts to understand the interactive effects of the reagents; collector, frother, and depressant and ions present in the plant water on the flotation performance of a Merensky ore. This will illustrate the overall changes that should be taken into account when there is a change in one of these process variables, and to allow for the prediction of an optimum set of conditions in process control. Furthermore, this will provide some insights into the impact water recycling can have on the metallurgical performance of a typical concentrator plant.

2.8 Key questions and hypotheses

On the basis of the literature survey presented in this Chapter, the following key questions and hypotheses are formulated;

Q1: Is a factorial experimental design an appropriate tool to use in holistically evaluating the effects of reagents, and understanding the nature of the possible interactive effects among the process variables in question, in a quest to predict and determine optimum operating conditions?

Q2: How does the change in water quality (ionic strength), owing to the practice of water recycle and reuse, affect the metallurgical performance as well as the role of the flotation reagents with particular reference to the collector, depressant and frother, on the metallurgical performance of the ore in question? With particular emphasis on the following;

- ✓ What is the effect of increasing the concentrations of the ions, present in the plant water, in the pulp on the adsorption behaviour of the ionic type collector, SIBX, and non-ionic depressant, guar, used in this study?
- ✓ What is the effect of increasing the concentrations of the ions, in the plant water, on the frothing properties of the polyglycol ether, which is non-ionic in nature?

H1: The factorial experimental design is an appropriate tool for a holistic evaluation of the effects of the flotation reagents since it allows for simultaneous evaluation of the effects of more than one variables. This will also reveal any possible interactions between the variables in question, and subsequently allow for prediction of optimum operating conditions within the range of the chosen variables.

H2: An increase in the concentration of the ions present in the synthetic plant water will increase recoveries, however, this may occur at the expense of the concentrate

grade because the presence of the ions at high concentration have been reported to exhibit strong frothing properties. This is not expected to influence the behaviour of the non-ionic depressing and frothing agents. However, this may impose some dynamics on the behaviour of the ionic collector, owing to possible electrostatic interactions between the collector ions and the ions present in the plant water.

3. Experimental details and materials

This chapter presents the materials and detailed experimental procedures used in this study, and is divided into five sections. Section 3.1 gives a brief summary about the type and composition of the ore, Section 3.2 gives a summary of the flotation reagents and how they were prepared, Section 3.3 provides a summary of the preparation of the synthetic plant water, Sections 3.4 and 3.5 provide the detailed milling and batch flotation procedures adopted in this study, and Section 3.6 provides summary of the experimental design.

3.1 Ore

A sample of a typical Impala Merensky ore was obtained from an operation in the western limb of the Bushveld Igneous Complex in the North West province of South Africa. The bulk ore sample was crushed, blended, riffled and split using a rotary splitter into 1 kg sample portions. This Merensky ore comprises of PGMs, BMS and gangue minerals. However, Table 3.1 shows only the percentage compositions of the BMS and gangue minerals in the feed ore since the scope of this work does not include analysis of PGMs. The BMS are used as a proxy for the flotation behaviour of the PGMs since they are strongly associated in the ore (Schouwstra et al. 2000; Liddell et al. 1986).

Table 3.1**: **Quantitative mineralogical data of the Merensky feed 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	**1.09**
Plagioclase	43.38
Orthopyroxene	32.6
Olivine	0.59
Clinopyroxene	7.48
Talc	3.51
Serpentine	0.8
Chlorite	0.83
Phlogopite	0.46
Quartz	0.67
Calcite	0.18
Oxides	8.1
Other	0.32
TOTAL	**100**

3.2 Flotation reagents

The reagent suite used in this study, together with the tested dosages, is shown in Table 3.2. Molecular weights and purity of these reagents are also shown. It is worth highlighting that both the collector and depressant were not corrected for active content.

***Table 3.2**: Reagent suite used in this work and the tested dosages.*

Reagent	Type	Molecular weight (g/mol)	Purity (%)	Dosage* (g/t)
Collector	SIBX	171	90	50 and 150
Depressant	Sendep 348	239 000	92	100 and 300
Frother	Dowfroth 250	264	100	50 and 70

*Three centre point tests: 100 g/ t SIBX, 200 g/ t Sendep 348, and 60 g/ t Dowfroth 250 were conducted for reproducibility

3.2.1 Collector

A xanthate collector, sodium isobutyl xanthate (SIBX), which was supplied by Senmin in powder form was used in this test work. A solution of 1% (w/v) SIBX was freshly prepared each day using distilled water. The collector dosage was varied over two levels 50 and 150 g/t, as shown in Table 3.2. The midpoint dosage was 100 g/t.

3.2.2 Depressant

A polysaccharide depressant, namely guar gum (Sendep 348), was used in this study. This depressant was supplied by Senmin in powder form. A solution of 1% (w/v) Sendep 348 was freshly prepared every 5th day by hydrating the required amount of dry depressant in distilled water for two hours using a magnetic stirrer to allow for complete dissolution. This depressant was varied over two dosage levels of 100 and 300 g/t, as shown in Table 3.2. The midpoint dosage was 200 g/t.

3.2.3 Frother

A polyglycol ether frother, Dowfroth 250, which was supplied by Betachem in concentrated form was used in all the batch flotation experiments. The frother was varied over two dosage levels of 50 and 70 g/t as shown in Table 3.2. The midpoint dosage was 60 g/t.

3.3 Plant water

All batch flotation experiments were conducted in synthetic plant water (SPW), which was developed to mimic typical process water at operations processing Merensky ores (Wiese et al. 2005). Standard synthetic plant water (which is herein referred to as 1 SPW) was prepared by dissolving various chemical salts in the order given in distilled water to achieve a total dissolved solids (TDS) concentration of 1023 mg/ L. Shown in Table 3.3 is the recipe for 1 SPW.

***Table 3.3**: Recipe for preparation of the standard synthetic plant water (1 SPW)*

Chemical salt	Formula	Mass (in g) per L of water
Magnesium Sulphate	$MgSO_4.7H_2O$	0.615
Magnesium Nitrate	$Mg(NO_3)_2.6H_2O$	0.107
Calcium Nitrate	$Ca(NO_3)_2.4H_2O$	0.236
Calcium Chloride	$CaCl_2.2H_2O$	0.147
Sodium Chloride	NaCl	0.356
Sodium Carbonate	Na_2CO_3	0.030

Some tests were conducted in synthetic plant water with increased ionic strength (by a factor of 5, herein referred to as 5 SPW), which was prepared by exactly following the preceding procedure, except that the masses of the chemical salts were increased by a factor of 5, to achieve a TDS concentration of 5115 mg/L. Table 3.4 shows these two water types with the concentrations of the ions after dissociation of the chemical salts.

***Table 3.4**: The concentration of the ions present in the synthetic plant water* (Wiese et al. 2005)

Water type	Ca^{2+} **(ppm)**	Mg^{2+} **(ppm)**	Na^{+} **(ppm)**	Cl^{-} **(ppm)**	SO_4^{2-} **(ppm)**	NO_3^{-} **(ppm)**	NO_2^{-} **(ppm)**	CO_3^{2-} **(ppm)**	**TDS (ppm)**
1 SPW	80	70	153	287	240	176	-	17	1023
5 SPW	400	350	765	1435	1200	880	-	85	5115

3.4 Milling procedure

An Eriez laboratory scale stainless steel rod mill with a diameter of 200 mm, charged with twenty stainless steel rods of varying diameter in the following ratio: 6 x 25 mm, 8 x 20 mm and 6 x 16 mm, was used to mill the ore. Samples of the Merensky ore (in 1 kg portions), with the collector added at the required dosage, were milled in synthetic plant water (at the required ionic strength) at 66% solids to achieve a grind of 60% passing 75 µm. The basis for choosing this grind was to match the primary rougher grind at operations processing this kind of ore (Wiese 2009). The milling curve for this ore is shown in Figure 3.1. It is also shown on the figure, the dashed lines, the time required to achieve the 60% passing 75 µm grind.

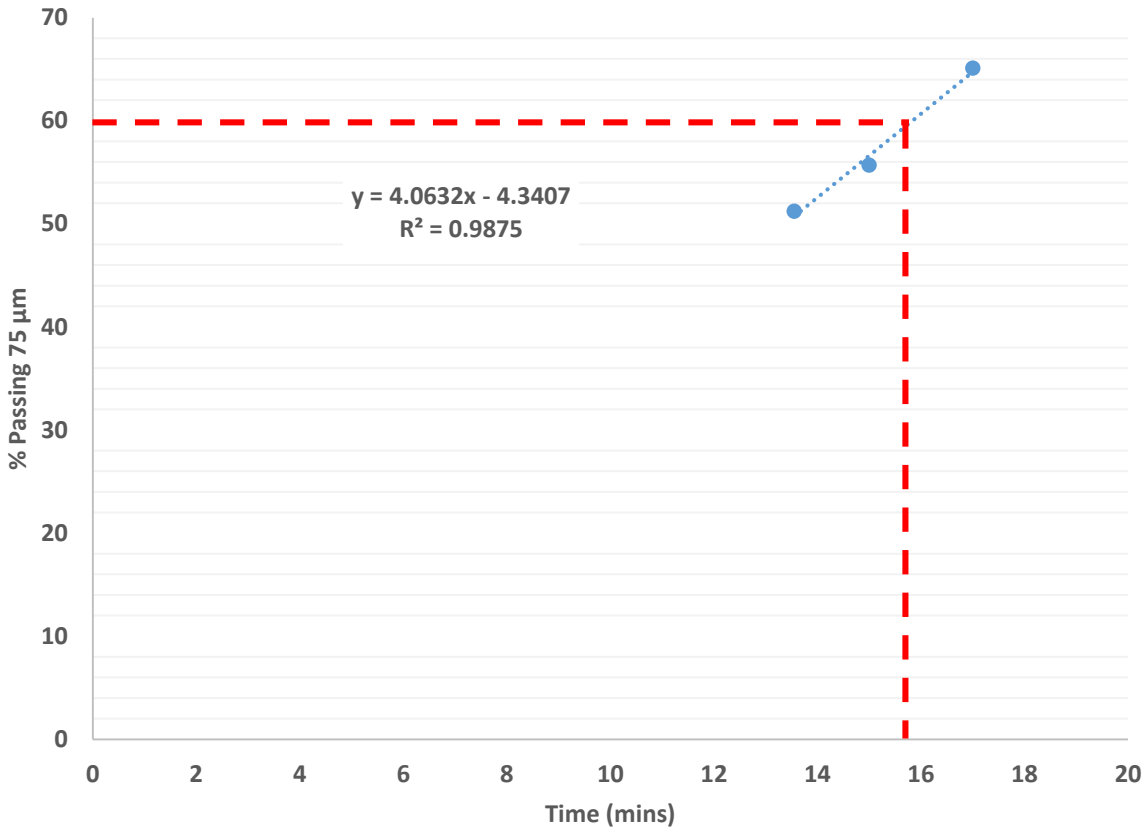


***Figure 3.1**: Milling curve for the Merensky ore used in this study.*

3.5 Batch flotation procedure

The milled slurry was transferred to a UCT Barker 3 L batch flotation cell (shown in Figure 3.2), and synthetic plant water (at ionic strength required for that particular test) was added to achieve a pulp density of 35 % solids. The cell was fitted with a variable speed drive and the pulp level was controlled manually by addition of synthetic plant water. The impeller speed of the flotation cell was set to 1200 rpm. A feed sample was drawn using a syringe at the beginning of each test. The depressant at the required dosage was added and conditioned for 2 min. The frother at the required dosage was added and conditioned for 1 min. Air was then introduced into the cell, at a flow rate of 7 L/min, which was maintained throughout the test. A constant froth height of 2 cm was sustained throughout the test, and the froth height was constantly corrected to 2 cm by addition of synthetic plant water. Four concentrates (C1-C4) were collected into a pan by scraping off the froth at intervals of 15 s for collection times of 2, 4, 6 and 8 min, respectively. After 20 min

flotation time the air was switched off, and a tails sample was drawn using a syringe. The water usage was monitored throughout the flotation tests. The feeds, concentrates, and tails were filtered, dried and weighed before analysis. Copper and total nickel analysis of all samples was carried out using a Bruker S4 Explorer X-ray Fluorescence (XRF) Spectrometer. Sulphur analysis was carried out using a LECO DR423 sulphur analyser.

***Figure 3.2**: The UCT Barker 3 litre flotation cell used in this study*

Table 3.5 shows a summarised version of the batch flotation procedure followed in this study.

***Table 3.5**: Summary of the batch flotation procedure followed in this study.*

Action	Time (minutes)
Grinding	As determined by grinding curve
Collector	Added to mill before grinding
Feed sample drawn	0
Depressant	0
Frother	2
Air introduced and froth allowed to develop	3
C1	5
C2	9
C3	15
C4	23
Tails sample drawn	23

3.6 Experimental design

A factorial design was used to investigate the main and interactive effects of the chemical parameters (summarised in Table 3.6) on the flotation performance. The responses used were water, solids, copper and nickel recoveries as well as copper and nickel grades. Design Expert 8.0 software (Anderson and Whitcomb, 2000) was used to carry out analysis of variance (ANOVA) on the data, where the main and interactive effects are tested for statistical significance by the *F*-test. This software uses the method of least squares to fit a linear model to the data. Three centre point tests were conducted to check for curvature and reproducibility, and no curvature was found in any of the models.

***Table 3.6**: Parameters and levels for Factorial design*

	Collector (SIBX) (g/t)	Depressant (guar) (g/t)	Frother (Dow 250) (g/t)	Water quality (SPW) (IS)
Min	50	100	50	1
Max	150	300	70	5

4. Results

This chapter presents the results of all batch flotation experiments conducted. The aim of this study was to investigate the interactive effects of flotation chemical factors, with particular reference to the flotation reagents; collector, depressant, and frother, as well as the ionic strength (IS) of the synthetic plant water on the flotation performance of a sulphide ore from the Merensky reef. The flotation performance of the ore was represented in terms of solids, water, copper and nickel recoveries, as well as copper and nickel grades. The copper and nickel recoveries represent the flotation behaviour of the base metal sulphide (BMS) minerals chalcopyrite and pentlandite, respectively, and this is expected to simulate the flotation behaviour of the Platinum Group Minerals (PGMs) due to the strong association in the Merensky reef between the BMS and the PGMs (Schouwstra et al. 2000; Liddell et al. 1986).

This chapter is divided in to five sections; Section 4.1 examines the reproducibility of the work, Section 4.2 presents all the batch flotation results, as well as further elucidating the effect of each of the investigated variables on the flotation performance of the ore, Section 4.3 presents the flotation kinetics parameters for all the tests, Section 4.4 presents the statistical analysis carried out on the data and the results obtained, and Section 4.5 summarises the key findings of this work. The reagent conditions in the graphs are abbreviated for ease of reference. For example, 50 D250 refers to 50 g/t of the frother Dowfroth 250, 100 Guar refers to 100 g/t of the guar gum depressant and 50 SIBX refers to 50 g/t of the collector sodium isobutyl xanthate.

Table 4.1 shows the entities for the experimental conditions for the data presented in the graphs in Section 4.2 for ease of reference in the text. It should be noted that this numbering system for the conditions only applies in this Section 4.2, and does not apply in the subsequent sub-sections in the bar graphs.

***Table 4.1**: The experimental conditions for the data presented in the graphs in Section 4.2.*

1	50 SIBX, 100 Guar, 50 D250, 1 SPW	9	50 SIBX, 100 Guar, 50 D250, 5 SPW
2	50 SIBX, 300 Guar, 50 D250, 1 SPW	10	50 SIBX, 300 Guar, 50 D250, 5 SPW
3	150 SIBX, 100 Guar, 50 D250, 1SPW	11	150 SIBX, 100 Guar, 50 D250, 5 SPW
4	150 SIBX, 300 Guar, 50 D250, 1 SPW	12	150 SIBX, 300 Guar, 50 D250, 5 SPW
5	50 SIBX, 100 Guar, 70 D250, 1 SPW	13	50 SIBX, 100 Guar, 70 D250, 5 SPW
6	50 SIBX, 300 Guar, 70 D250, 1 SPW	14	50 SIBX, 300 Guar, 70 D250, 5 SPW
7	150 SIBX, 100 Guar, 70 D250, 1 SPW	15	150 SIBX, 100 Guar, 70 D250, 5 SPW
8	150 SIBX, 300 Guar, 70 D250, 1 SPW	16	150 SIBX, 300 Guar, 70 D250, 5 SPW

4.1 Reproducibility

All batch flotation tests were conducted in duplicate in order to determine and minimise the experimental errors associated with the tests. The variables that were used to determine the reproducibility of the tests were solids and water recoveries, and concentrate assays (copper and nickel analysis). The values presented for each experimental condition are the average value obtained from the duplicate tests, and the standard deviations associated with those values are represented by the error bars in the graphs. The UCT standard batch flotation procedure requires the standard deviation to be at most 5 and 10 % of the total recovered solids and water, respectively (Manono 2012). The standard deviation for all batch flotation experimental data presented in this thesis was found to be within the limits required by the UCT standard batch flotation procedure.

4.2 Solids, water, copper and nickel recoveries, as well as copper and nickel grades for all tested conditions.

This section presents results for all the tests that were conducted in this work. Figure 4.1 shows cumulative solids recovery as a function of flotation time for all the reagent conditions and the two synthetic plant water types. The highest and lowest recoveries were obtained under conditions 15 [150 g/t SIBX, 100 g/t guar, 70 g/t D250, and 5 SPW] and 4 [150 g/t SIBX, 300 g/t guar, 50 g/t D250, and 1 SPW], respectively. This is an indication of a more stable froth phase for the former condition, and a less stable froth for the latter.

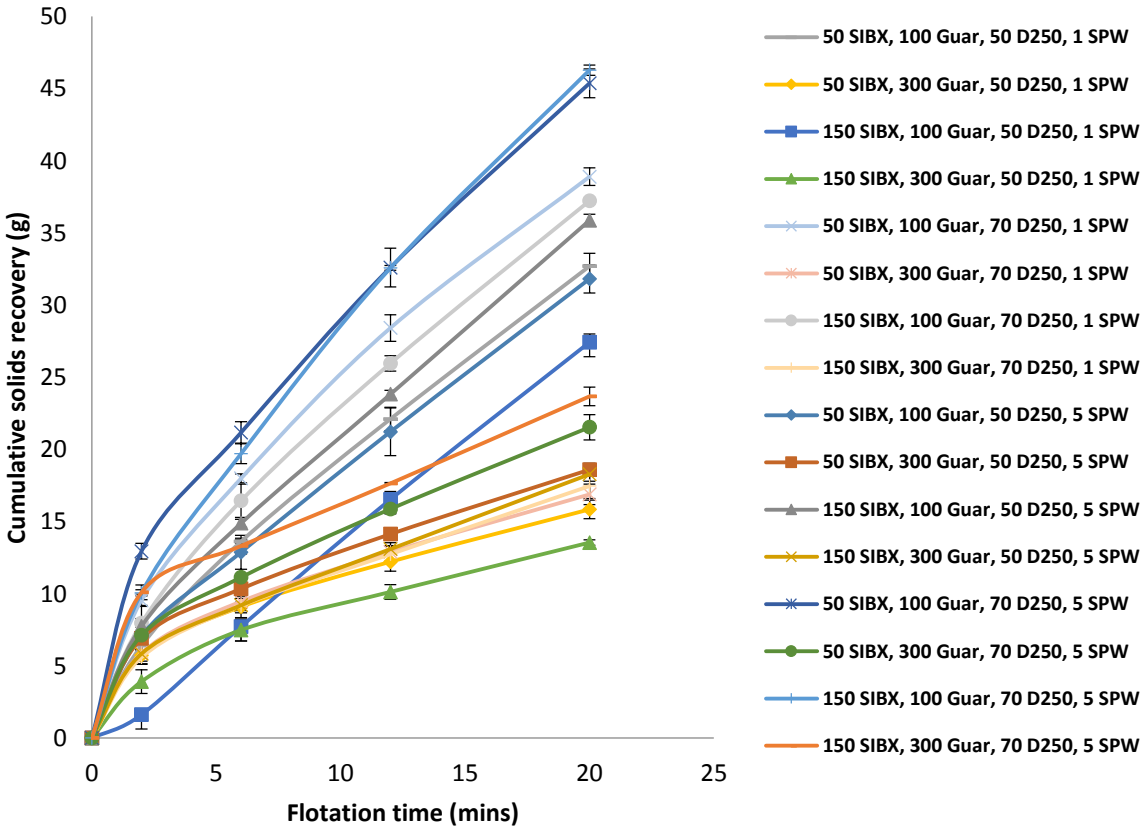


***Figure 4.1**: Cumulative solids recovery as a function of flotation time for all test conditions. Error bars represent the standard deviation between duplicate tests.*

Cumulative water recovery as a function of flotation time for all the batch flotation tests are shown in Figure 4.2, illustrating that the highest final recoveries were obtained under condition 13 [50 g/t SIBX, 100 g/t guar, 70 g/t D250, and 5 SPW], whereas the lowest recoveries were obtained with condition 4 [150 g/t SIBX, 300 g/t guar, 50 g/t D250, and 1 SPW].

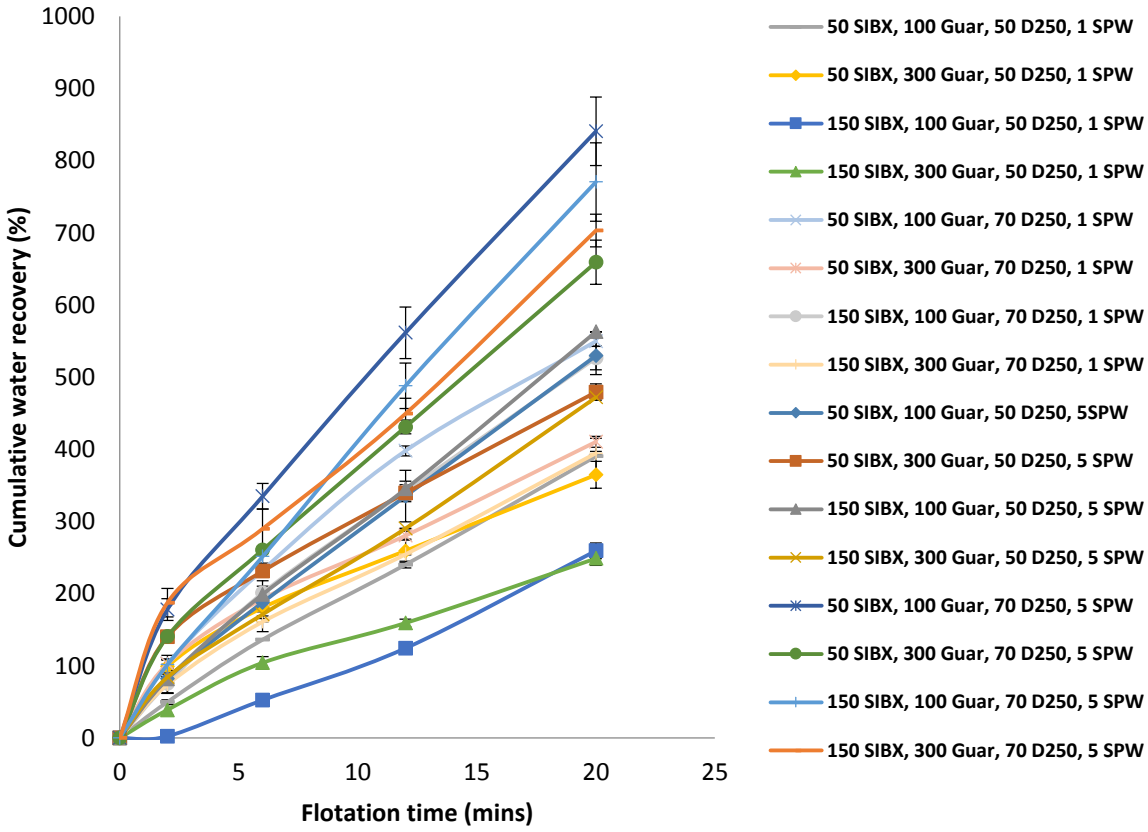


***Figure 4.2**: Cumulative water recovery as a function of flotation time for all test conditions. Error bars represent standard deviation between duplicate tests.*

Figure 4.3 shows the cumulative solids recovery as a function of cumulative water recovery for all tested conditions. It is clear from this figure that high and low recoveries for both solids and water were obtained under the same conditions as those illustrated in the previous figures.

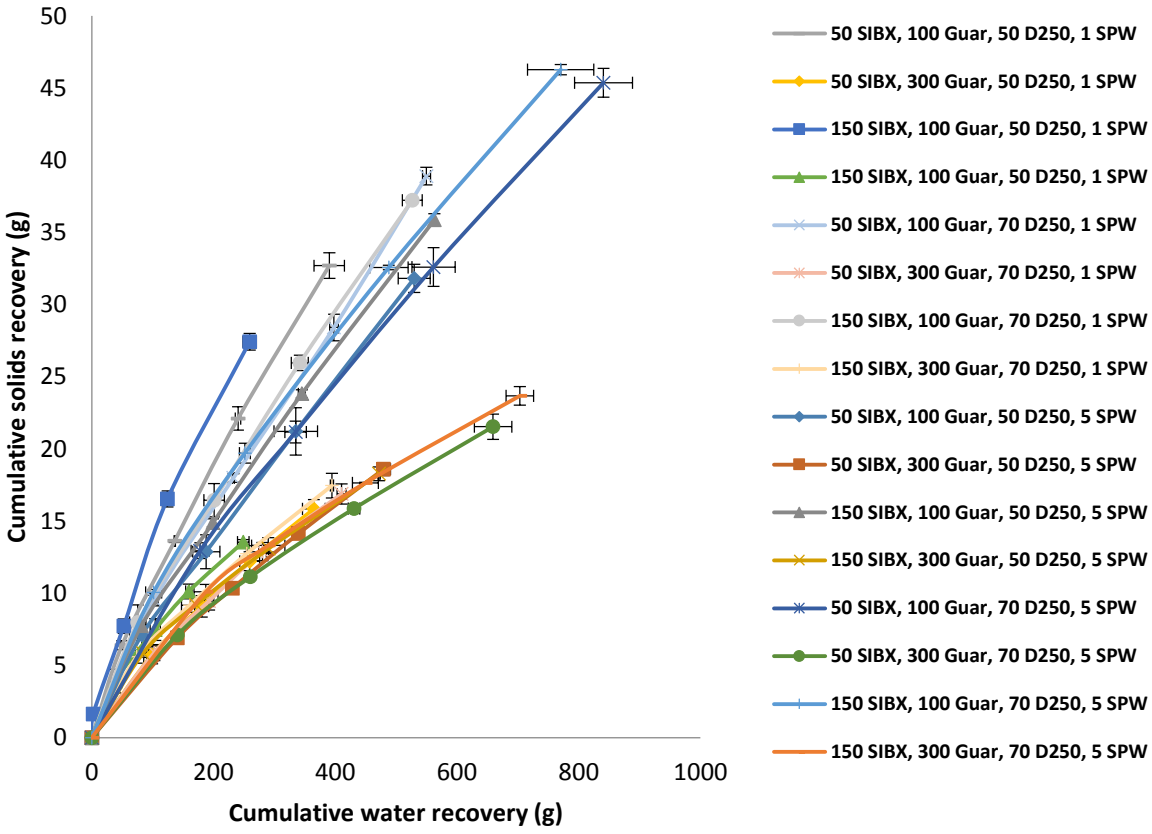


***Figure 4.3**: Cumulative solids recovery as a function of water recovery for all test conditions. Error bars represent standard deviation between duplicate tests.*

Figure 4.4 shows copper recovery as a function of water recovery for all the tests, illustrating that the highest copper and water recoveries were obtained under condition 13. This is an indication that this condition gave rise to the most stable froth, which allows for high recoveries, as also seen with the solids and water recoveries in the preceding figures. This figure also illustrates that the maximum copper recovery was 74.2 %, which was obtained at a water recovery of 840.7 g.

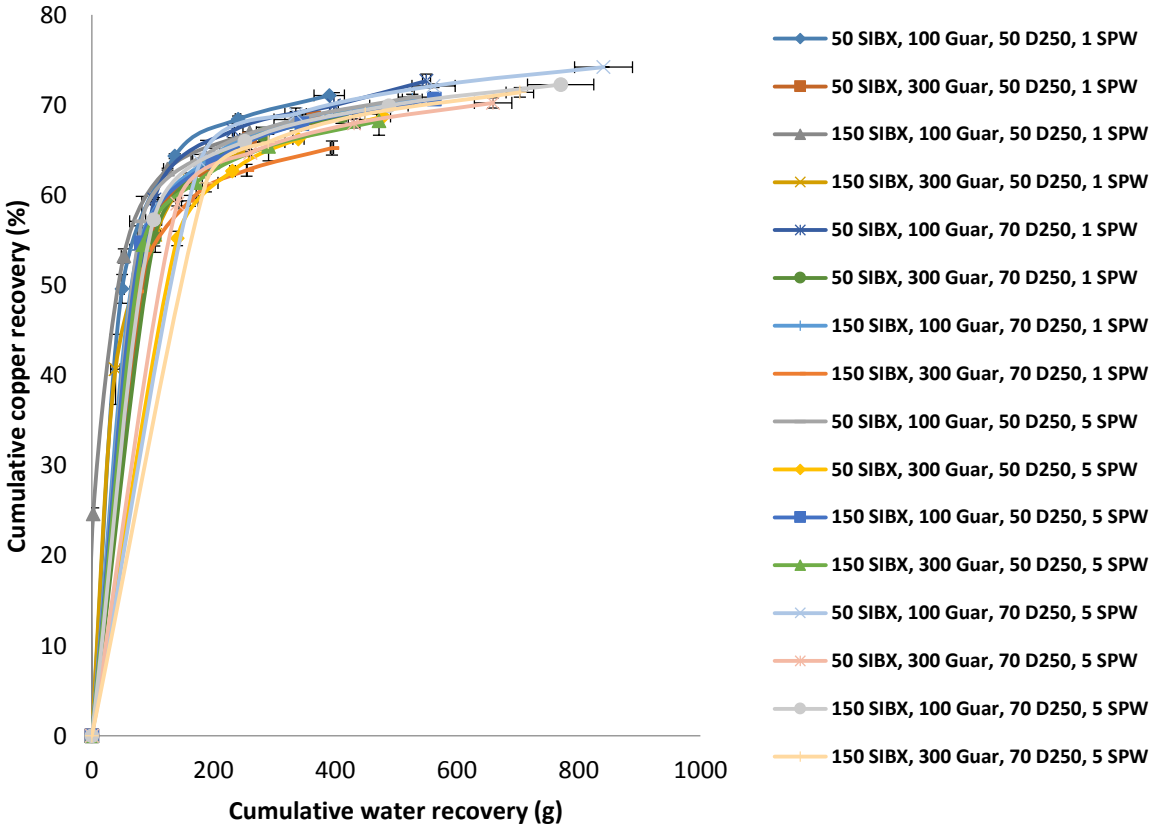


***Figure 4.4**: Cumulative copper recovery as a function of water recovery for all test conditions. Error bars represent standard deviation between duplicate tests.*

Copper recovery as a function of flotation time is shown in Figure 4.5. The copper recoveries are similar to those presented in the previous figure. This figure shows that the minimum copper recovery (about 65.2 %) was obtained under condition 4. It further shows that, under the conditions that yielded higher final copper recovery, about 63.7 % of the total copper present in feed was already recovered within the first two minutes of the flotation test.

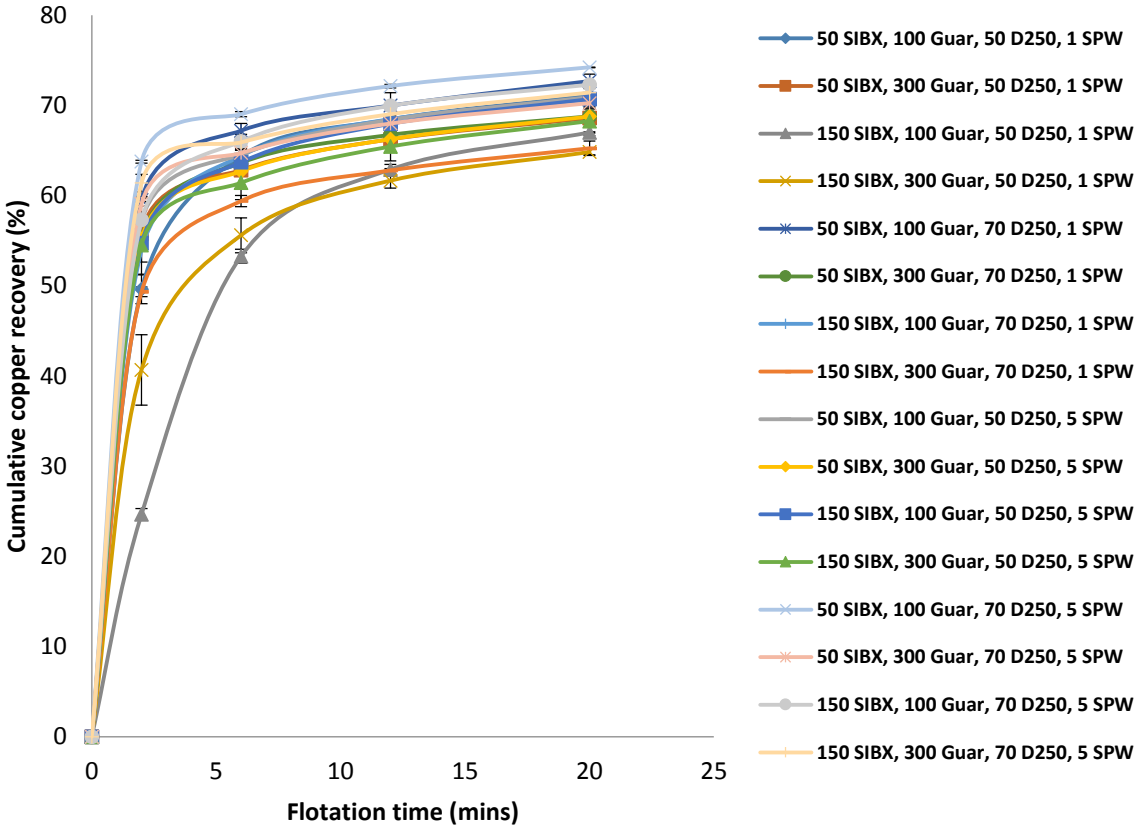


***Figure 4.5**: Cumulative copper recovery as a function of flotation time for all test conditions. Error bars represent standard deviation between duplicate tests.*

Figure 4.6 shows the cumulative copper grade as a function of cumulative copper recovery for all the tests and illustrates that the final copper grade was approximately the same for most of the tests. The minimum final copper grade obtained was below 2 %, and this was expected to be low since the laboratory scale batch tests are an equivalent of a rougher stage at an industrial plant, where purity of the valuables is still low, and hence the need for improvement in the subsequent stages.

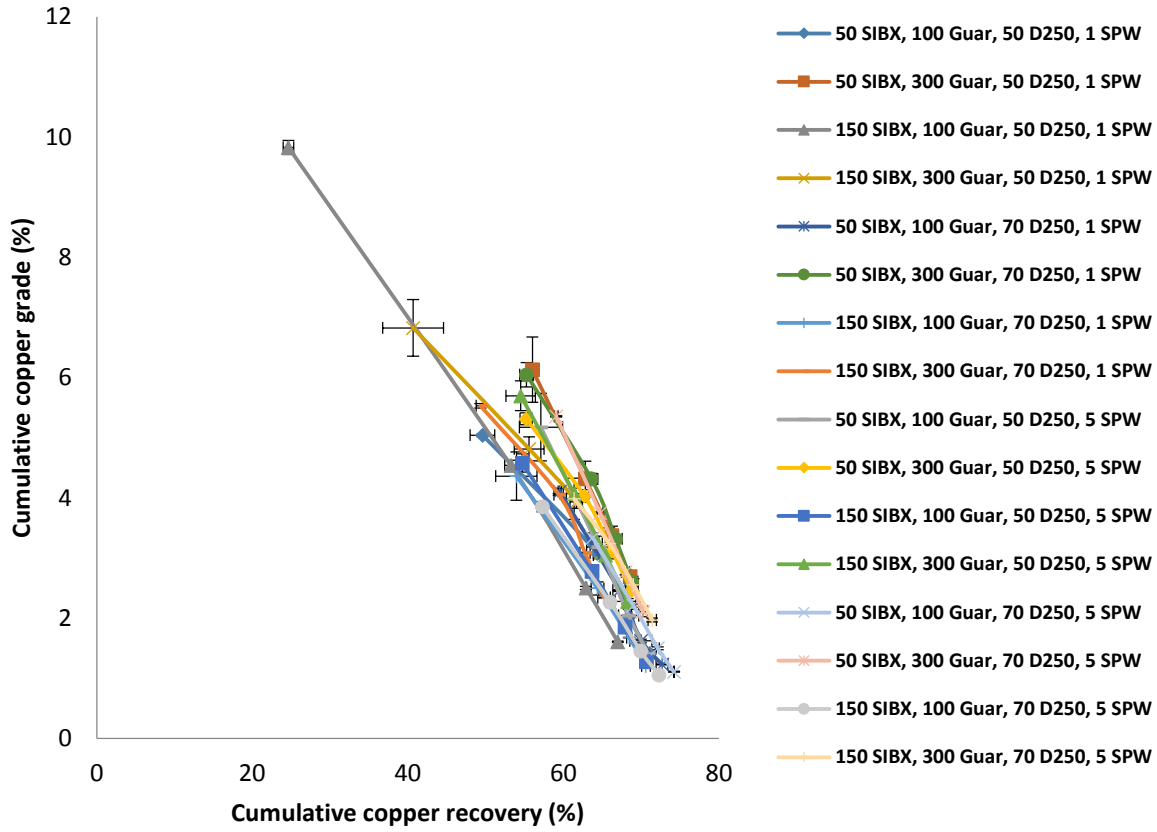


***Figure 4.6**: Cumulative copper grade as a function of recovery for all test conditions. Error bars represent standard deviation between duplicate tests.*

Nickel recovery as a function of water recovery is shown in Figure 4.7 for all experimental conditions conducted in this test work. The maximum nickel recovery was attained under the same condition (13) that yielded maximum copper recovery.

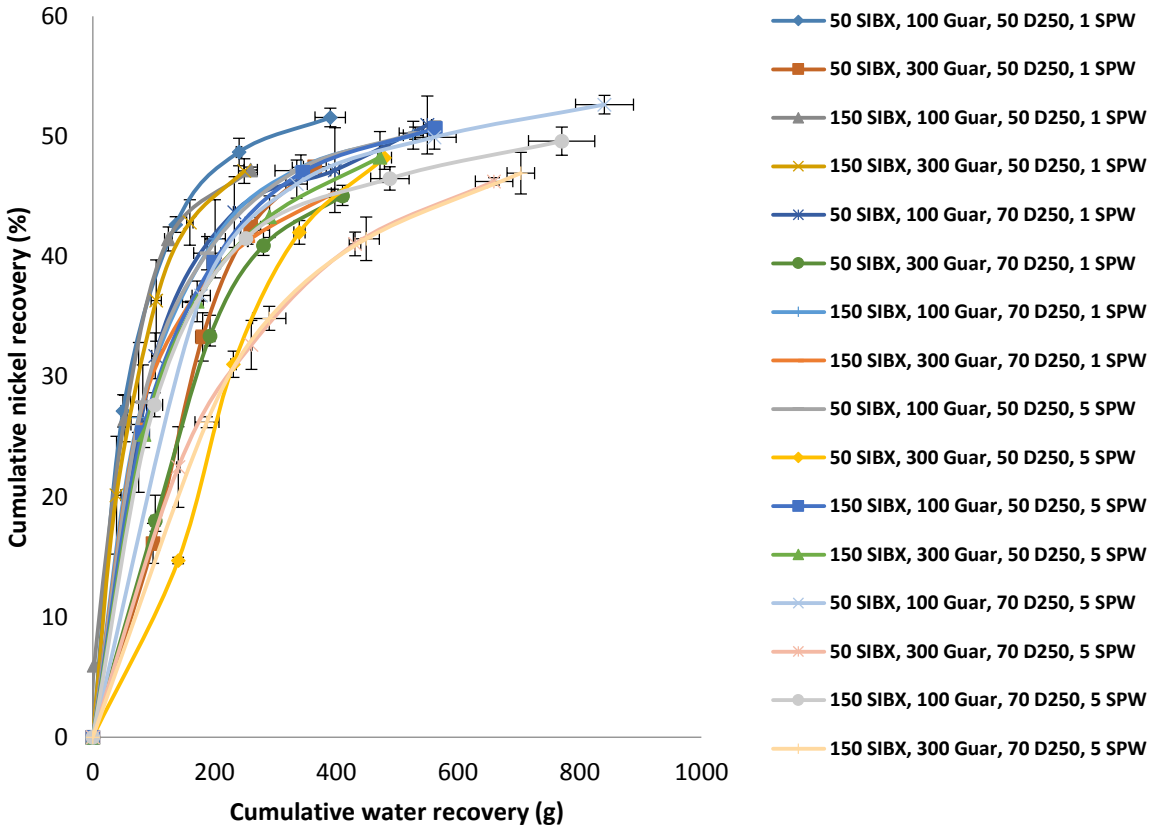


***Figure 4.7**: Cumulative nickel recovery as a function of water recovery for all test conditions. Error bars represent standard deviation between duplicate tests.*

Figure 4.8 presents cumulative nickel recovery as a function of flotation time This figure shows that the highest final nickel recovery was 52.6 % . Nickel grade as a function of nickel recovery is presented in Figure 4.9, illustrating that the highest final nickel grade of 6.04% was attained under condition 4. This is an indication that this condition gave rise to a more selective separation of particles in the froth phase.

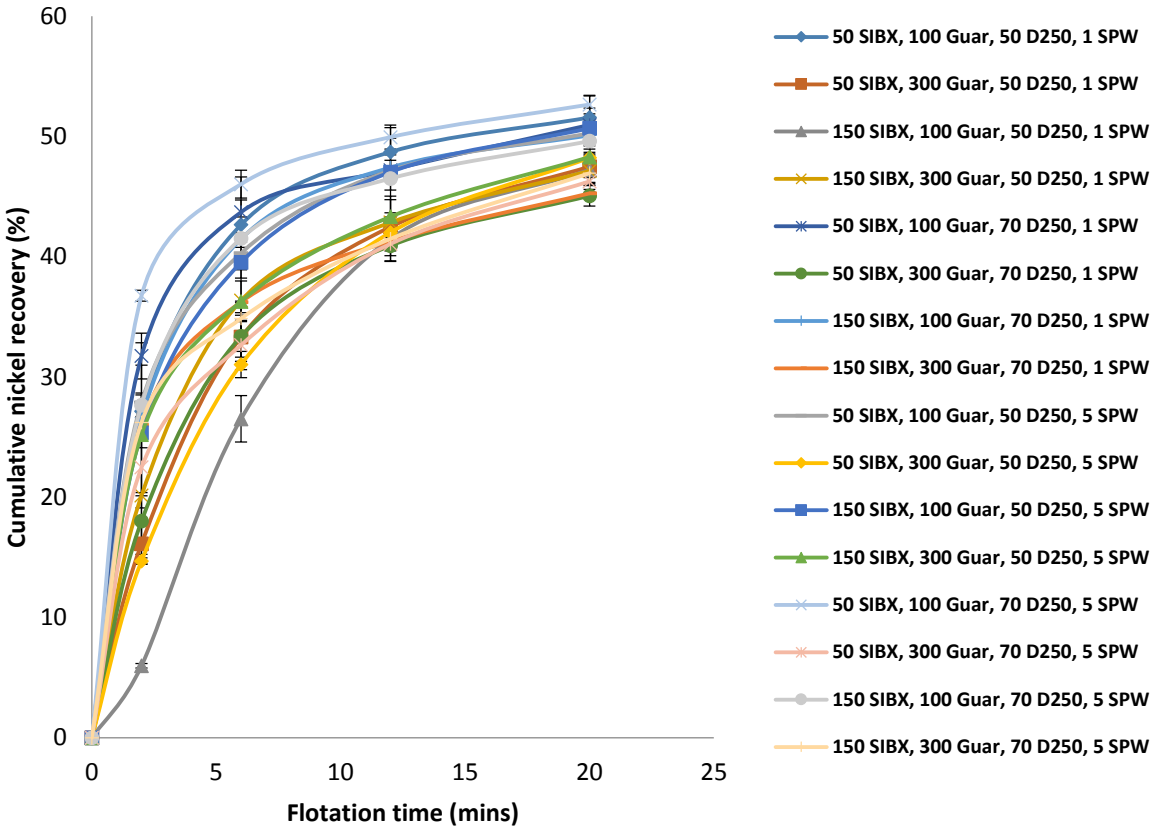


***Figure 4.8**: Cumulative nickel recovery as a function of flotation time for all tests. Error bars represent standard deviation between duplicate tests.*

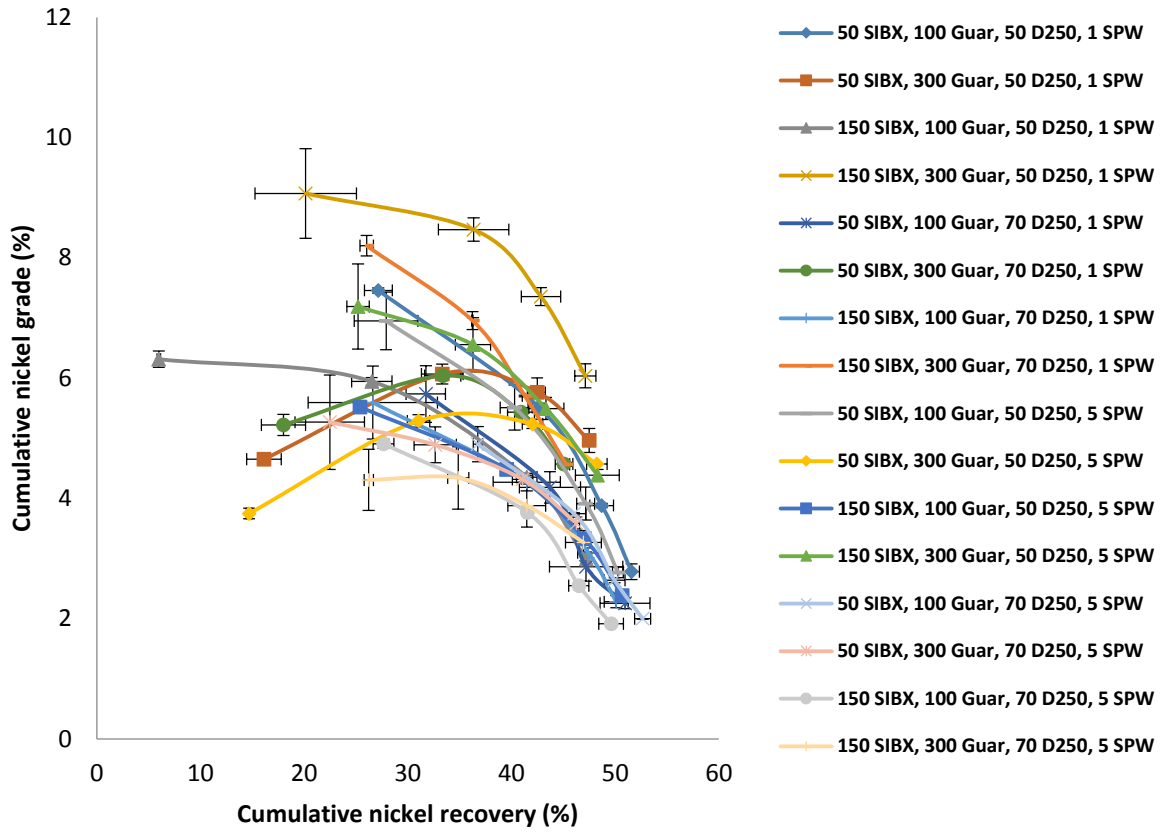


***Figure 4.9**: Cumulative nickel grade as a function of recovery for all test conditions. Error bars represent standard deviation between duplicate tests.*

4.2.1 The effect of collector dosage on solids, water, copper and nickel recoveries, as well as copper and nickel grades.

This section presents results showing the effect of varying the collector dosage, under different conditions of the other reagents as well as the plant water types, on the flotation performance of the ore.

Figure 4.10 shows the final solids and water recoveries for tests conducted under different reagent conditions, evaluating the effect of varying collector dosage over the two levels of 50 and 150 g/t, as well as under the two synthetic plant water types; 1 SPW and 5 SPW. Increasing the collector dosage from 50 to 150 g/t decreased solids and water recoveries for the conditions tested under 1 SPW, the solids recovery under high depressant shows little change, tests 7 and 8, and was found to be within experimental error. Thus the general trend observed was that both solids and water recoveries decreased in conjunction with an increase in collector dosage (from 50 to 150 g/t) using the standard synthetic plant water, 1SPW.

Contrarily, under 5 SPW, it is shown that increasing the collector dosage gave rise to a prominent increase in both solids and water recoveries at low and high dosages of both the depressant and frother (tests 9 and 10 as well as for tests 15 and 16, respectively). However, at high depressant and low frother dosages (tests 11 and 12), an increase of about 7 g for water recovery was noted, with a negligible increase in solids recovery. Similarly, at low depressant and high frother dosages (tests 13 and 14), a decrease in water recovery, about 70 grams, as well as a slight increase in solids recovery, approximately 1 g, was observed.

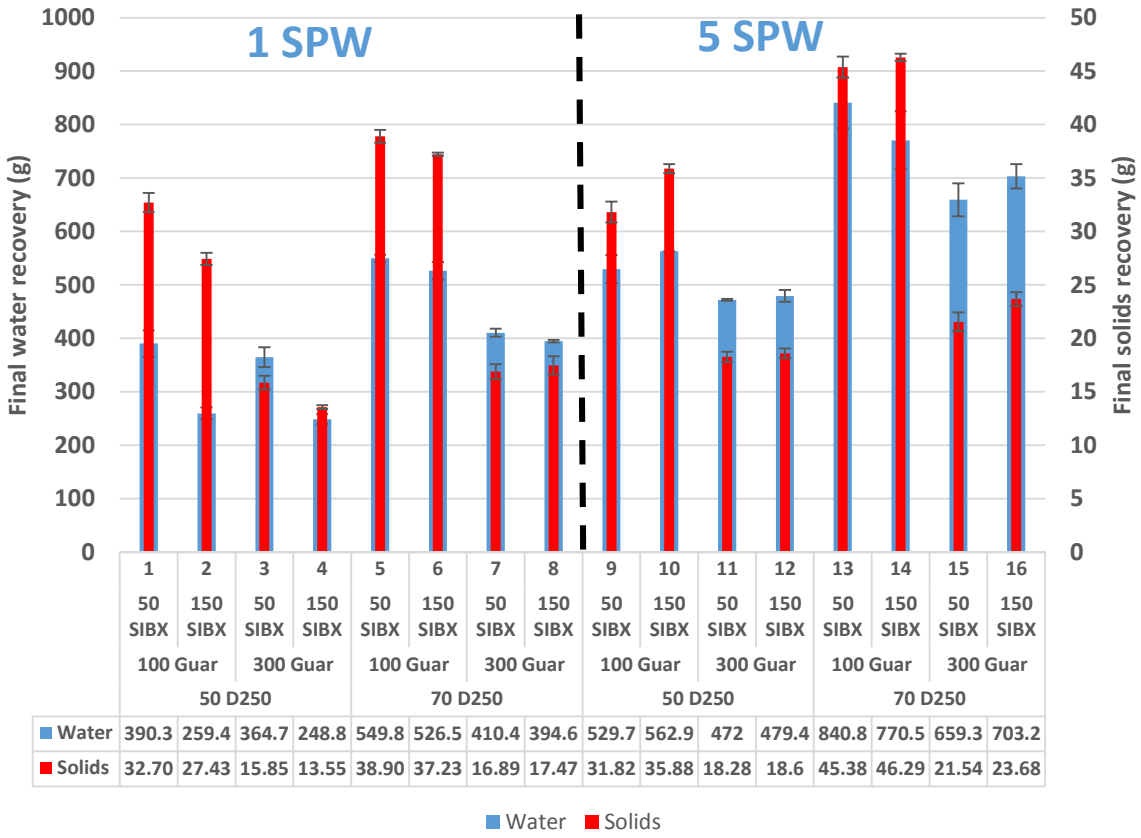


***Figure 4.10**: Final solids and water recoveries for the two collector dosages under 1 SPW and 5 SPW. Error bars represent standard deviation between duplicate tests.*

The effect of collector dosage on final copper grade and recovery under 1 SPW and 5 SPW are shown in Figure 4.11. It is apparent from the figure that the final copper recoveries decreased, in the range of about 2 – 4 %, as a result of increasing collector dosage under 1 SPW. There was a negligible change in the final copper grade due to an increase in collector dosage. For the tests under the high ionic strength of the plant water (5 SPW), the effect of increasing the collector dosage on decreasing copper recoveries was minimal particularly for tests 9 and 10, and 11 and 12), compared to the tests under 1 SPW. However, for tests 13 and 14, and 15 and 16) the decrease was noticeable, about 1.93 and 1.17 %, respectively. The change in copper grade was insignificant.

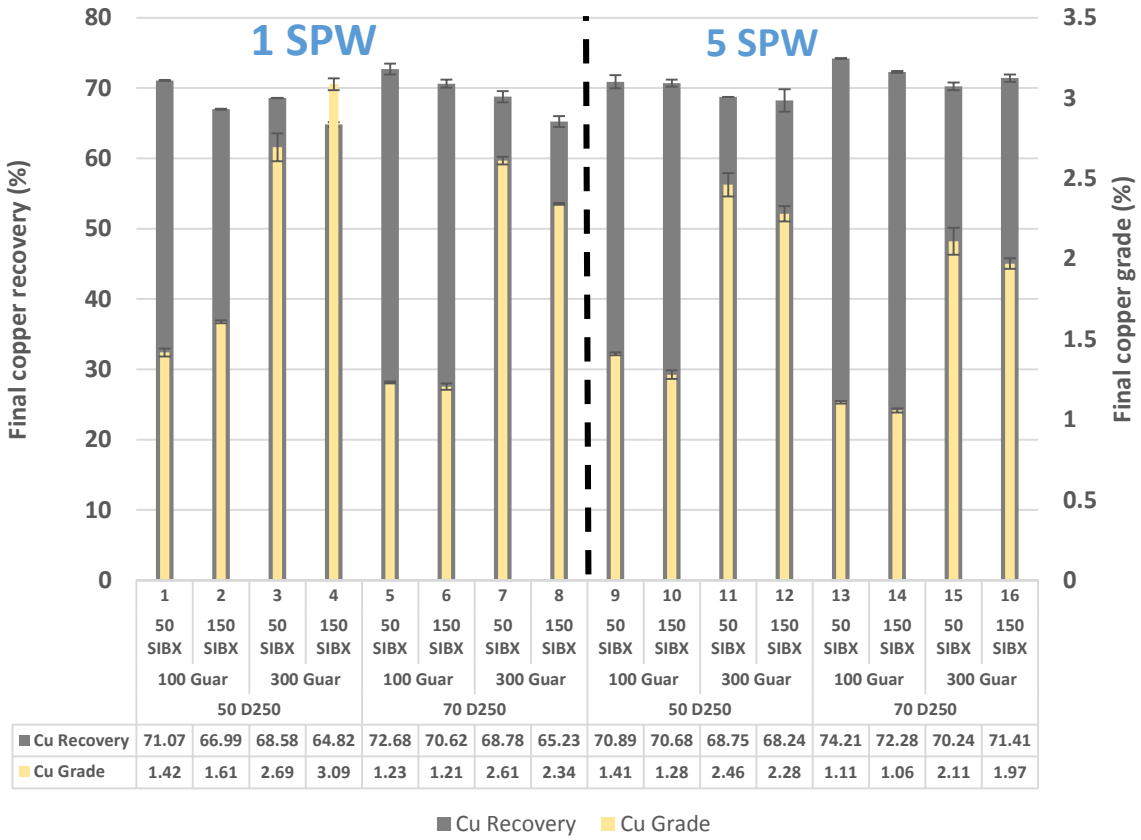


***Figure 4.11**: Final copper grades and recoveries for the two collector dosages under 1 SPW and 5 SPW. Error bars represent standard deviation between duplicate tests.*

Figure 4.12 shows the nickel grades and recoveries as a result of varying the collector dosage under 1 SPW and 5 SPW. There was an approximately 4 % reduction in nickel recovery as a result of increasing the collector dosage under low depressant and frother dosages, tests 1 and 2, for 1 SPW. However, there was a negligible change when the collector dosage was varied, particularly for the tests that were conducted under high depressant dosage of 300 g/ t, tests 3 and 4 and 7 and 8, and an almost 1 % decrease under low depressant and high frother dosages, tests 5 and 6. The nickel grade increased negligibly in conjunction with an increase in collector dosage. On the other hand, for tests conducted under 5 SPW, the effect of changing collector dosage was only evident at low depressant and high frother dosage, tests 13 and 14, with a reduction of about 3.04 %. A reduction in nickel grade under these conditions was observed although this was negligible.

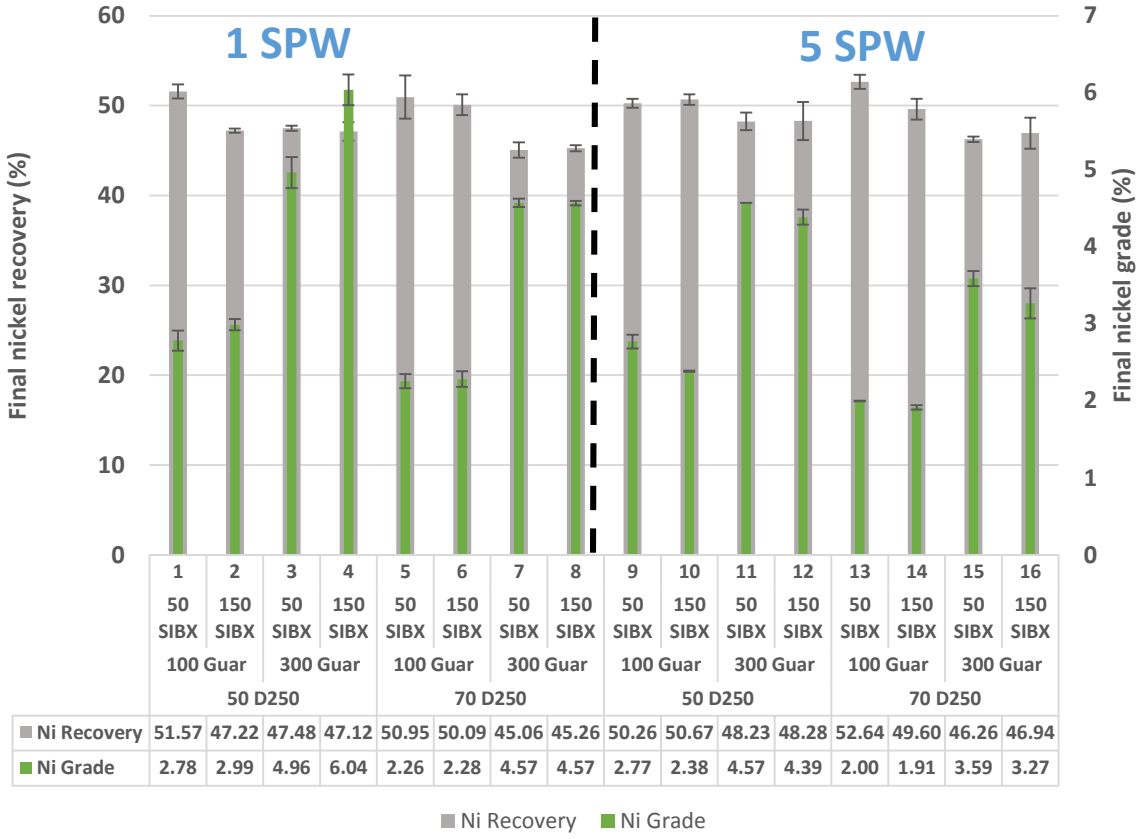


***Figure 4.12**: Final nickel grades and recoveries for the two collector dosages under 1 SPW and 5 SPW. Error bars represent standard deviation between duplicate tests.*

4.2.2 The effect of depressant dosage on solids, water, copper and nickel recoveries, as well as copper and nickel grades.

This section presents results that illustrate the effect of varying the depressant dosage under the two synthetic plant waters; 1 SPW and 5 SPW. It is expected that increasing the depressant dosage should decrease the amount of solid particles, particularly the naturally floating gangue, that report to the concentrate. It is illustrated in Figure 4.13 that solids recoveries decreased with an increase in depressant dosage for both 1 SPW and 5 SPW. In addition, water recoveries also decreased in conjunction with an increase in depressant dosage.

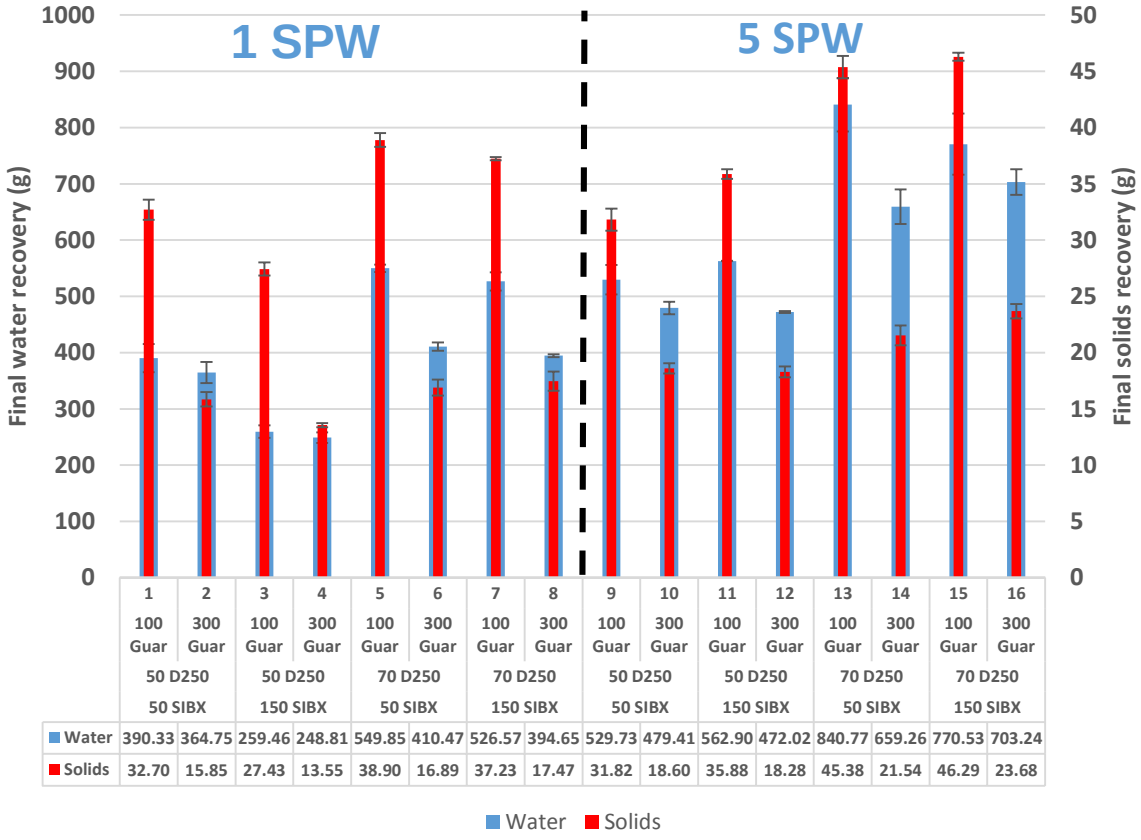
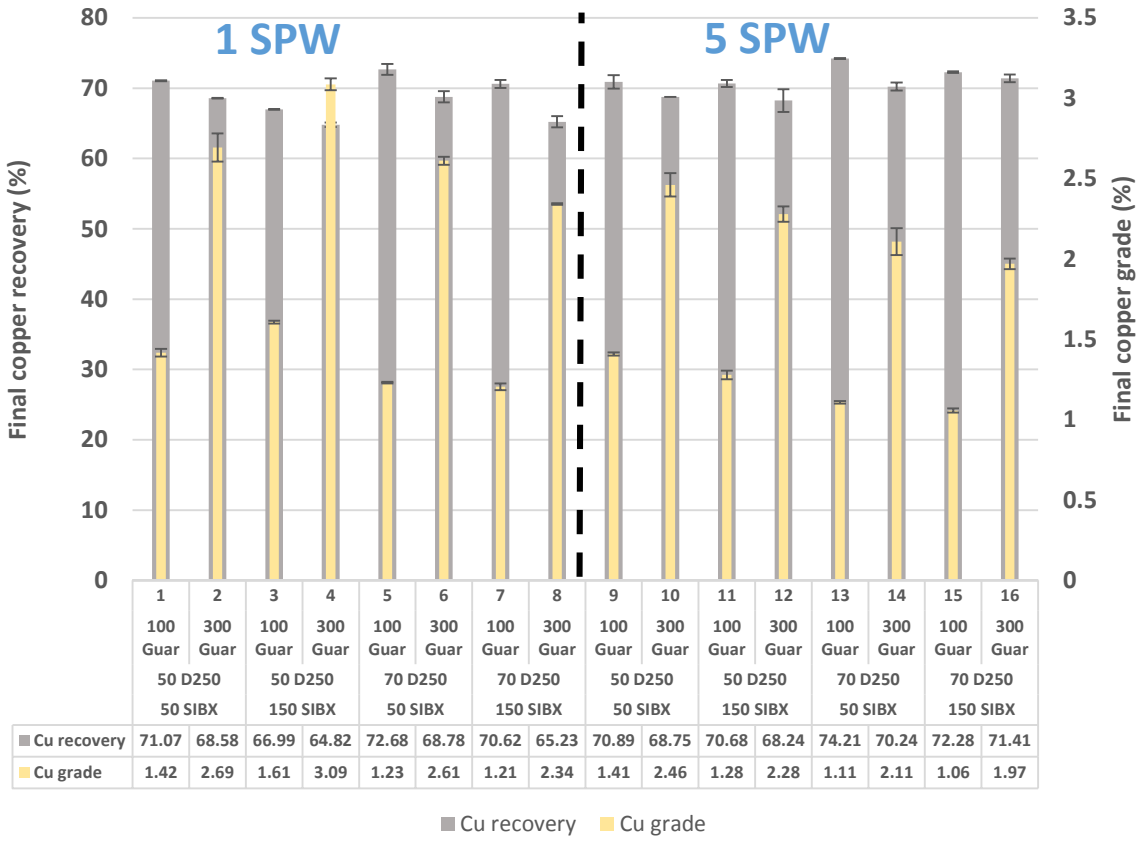


***Figure 4.13**: Final solids and water recoveries for the two depressant dosages under 1 SPW and 5 SPW. Error bars represent standard deviation between duplicate tests.*

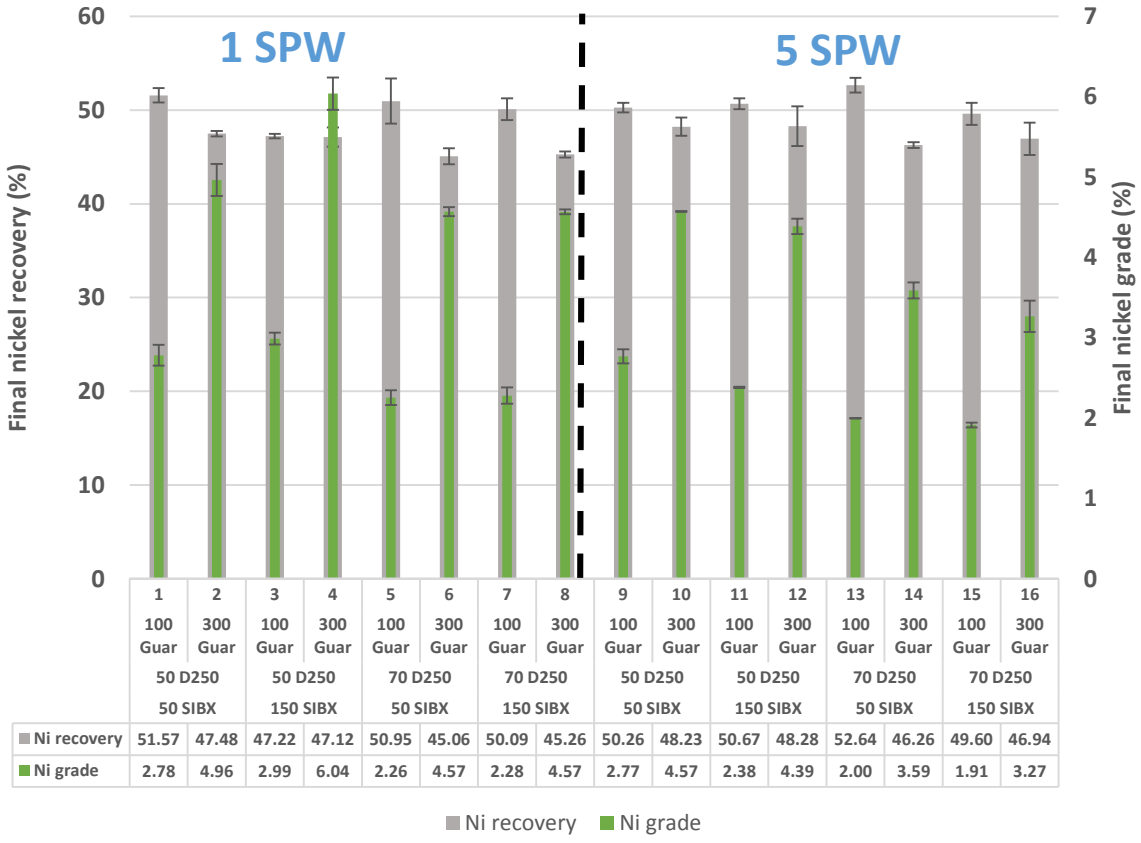
The results for copper grade and recovery are shown in Figure 4.14. Copper recoveries decreased when the depressant dosage was increased under all the different conditions and synthetic plant water types. On the other hand, copper grade increased as the depressant dosage was increased for all conditions.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	100 Guar 50 D250 50 SIBX	300 Guar 50 D250 50 SIBX	100 Guar 50 D250 150 SIBX	300 Guar 50 D250 150 SIBX	100 Guar 70 D250 50 SIBX	300 Guar 70 D250 50 SIBX	100 Guar 70 D250 150 SIBX	300 Guar 70 D250 150 SIBX	100 Guar 50 D250 50 SIBX	300 Guar 50 D250 50 SIBX	100 Guar 50 D250 150 SIBX	300 Guar 50 D250 150 SIBX	100 Guar 70 D250 50 SIBX	300 Guar 70 D250 50 SIBX	100 Guar 70 D250 150 SIBX	300 Guar 70 D250 150 SIBX
Cu recovery	71.07	68.58	66.99	64.82	72.68	68.78	70.62	65.23	70.89	68.75	70.68	68.24	74.21	70.24	72.28	71.41
Cu grade	1.42	2.69	1.61	3.09	1.23	2.61	1.21	2.34	1.41	2.46	1.28	2.28	1.11	2.11	1.06	1.97

***Figure 4.14**: Final copper grades and recoveries for the two depressant dosages under 1 SPW and 5 SPW. Error bars represent standard deviation between duplicate tests.*

The results for nickel grade and recovery are presented in Figure 4.15, and the same trends as seen for copper are observed. However, there was a negligible decrease, about 0.1 %, in nickel recovery when the depressant dosage was varied at 50 g/t frother and 150 g/t collector, tests 3 and 4.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	100 Guar	300 Guar	100 Guar	300 Guar	100 Guar	300 Guar	100 Guar	300 Guar	100 Guar	300 Guar	100 Guar	300 Guar	100 Guar	300 Guar	100 Guar	300 Guar
	50 D250		50 D250		70 D250		70 D250		50 D250		50 D250		70 D250		70 D250	
	50 SIBX		150 SIBX		50 SIBX		150 SIBX		50 SIBX		150 SIBX		50 SIBX		150 SIBX	
Ni recovery	51.57	47.48	47.22	47.12	50.95	45.06	50.09	45.26	50.26	48.23	50.67	48.28	52.64	46.26	49.60	46.94
Ni grade	2.78	4.96	2.99	6.04	2.26	4.57	2.28	4.57	2.77	4.57	2.38	4.39	2.00	3.59	1.91	3.27

***Figure 4.15**: Final nickel grades and recoveries for the two depressant dosages under 1 SPW and 5 SPW. Error bars represent standard deviation between duplicate tests.*

4.2.3 The effect of frother dosage on solids, water, copper and nickel recoveries, as well as copper and nickel grades.

This section presents results illustrating the effect of varying the frother dosage, under different conditions of the other reagents as well as the plant water types, on the flotation performance of the ore.

Figure 4.16 shows the effect of varying frother dosage on solids and water recoveries under 1 SPW and 5 SPW. Both solids and water recoveries increased in conjunction with an increase in frother dosage for all conditions as well as the two synthetic plant waters. However, this effect was minimal under high depressant dosage and 1 SPW, tests 3 and 4.

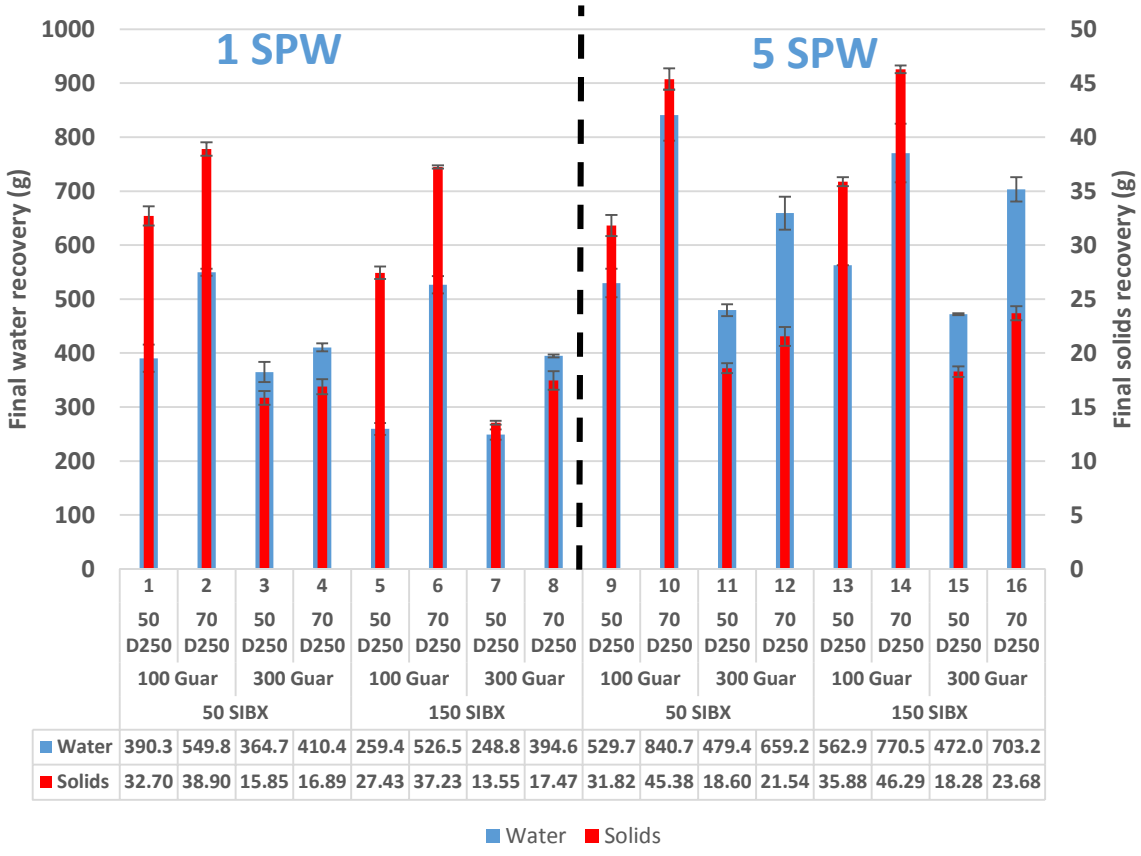


***Figure 4.16**: Final solids and water recoveries for the two frother dosages under 1 SPW and 5 SPW. Error bars represent standard deviation between duplicate tests.*

Copper and nickel grade - recovery results are shown in Figure 4.17 and Figure 4.18 respectively. The former shows that copper recoveries increased with an increase in frother dosage under both 1 SPW and 5 SPW. Moreover, the increase was slightly more pronounced under 5 SPW, showing the role played by the ions in the process particularly at high concentrations. The expected benefit of increasing frother dosage on increasing recoveries was not achieved for nickel, particularly under high depressant dosage, indicating the susceptibility of the sulphide mineral pentlandite to high depressant dosages. A reduction in grade for both copper and nickel was observed when frother dosage was increased, however, it was not considerable.

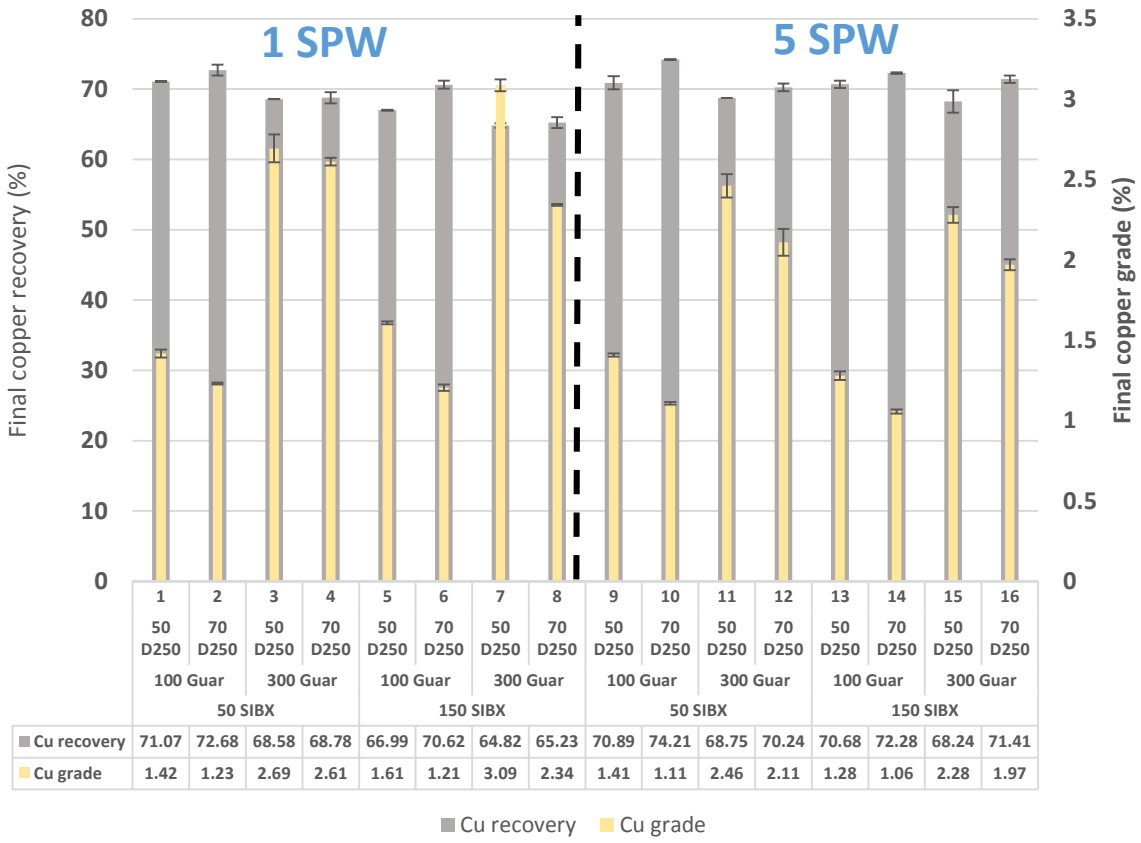
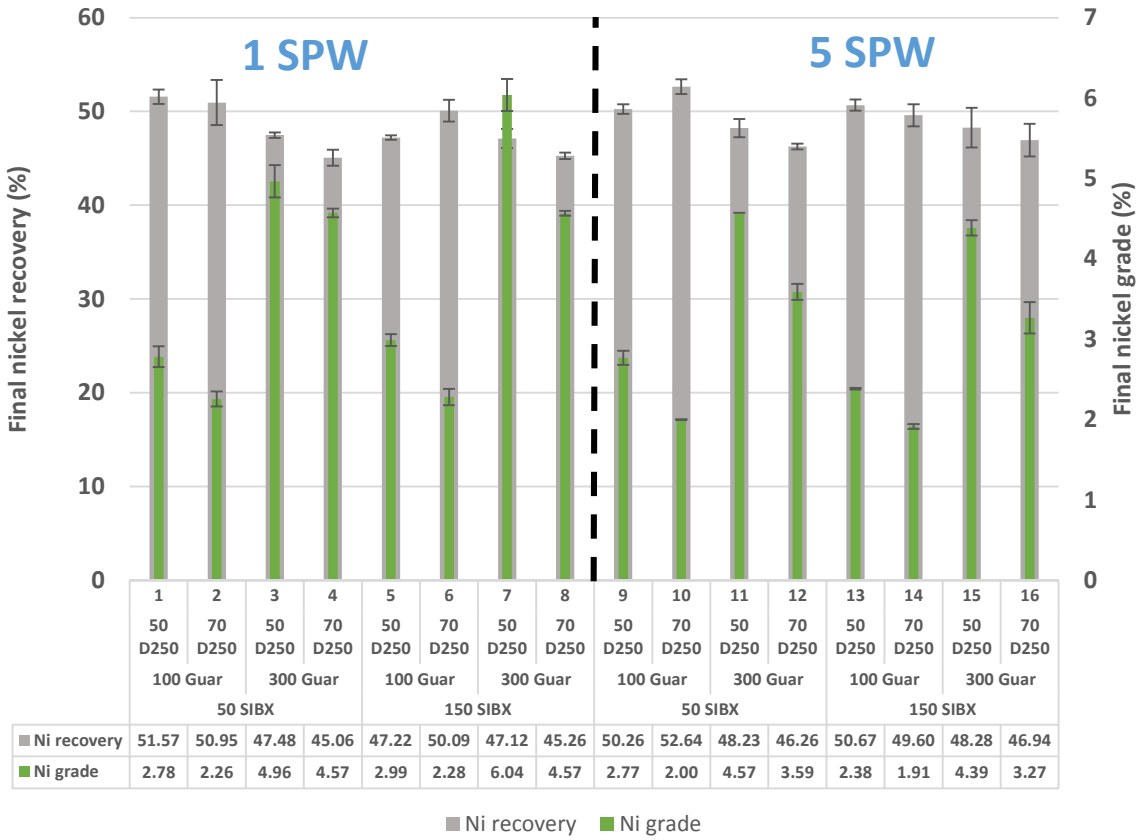


***Figure 4.17**: Final copper grades and recoveries for the two frother dosages under 1 SPW and 5 SPW. Error bars represent standard deviation between duplicate tests.*



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	50 D250	70 D250	50 D250	70 D250	50 D250	70 D250	50 D250	70 D250	50 D250	70 D250	50 D250	70 D250	50 D250	70 D250	50 D250	70 D250
	100 Guar		300 Guar		100 Guar		300 Guar		100 Guar		300 Guar		100 Guar		300 Guar	
	50 SIBX				150 SIBX				50 SIBX				150 SIBX			
Ni recovery	51.57	50.95	47.48	45.06	47.22	50.09	47.12	45.26	50.26	52.64	48.23	46.26	50.67	49.60	48.28	46.94
Ni grade	2.78	2.26	4.96	4.57	2.99	2.28	6.04	4.57	2.77	2.00	4.57	3.59	2.38	1.91	4.39	3.27

***Figure 4.18**: Final nickel grades and recoveries for the two frother dosages under 1 SPW and 5 SPW. Error bars represent standard deviation between duplicate tests.*

4.2.4 The effect of water quality on solids, water, copper and nickel recoveries, as well as copper and nickel grades.

From an examination of the results shown in the previous sections, it is evident that generally higher recoveries were obtained from tests that were conducted under high ionic strength of the synthetic plant water (5 SPW), and these are explicitly presented in tables in this section.

***Table 4.2**: Test conditions for the entries in Table 4.5*

1	2	3	4	5	6	7	8
50 SIBX 100 Guar 50 D250	150 SIBX 100 Guar 50 D250	50 SIBX 300 Guar 50 D250	150 SIBX 300 Guar 50 D250	50 SIBX 100 Guar 70 D250	150 SIBX 100 Guar 70 D250	50 SIBX 300 Guar 70 D250	150 SIBX 300 Guar 70 D250

It is worth highlighting that the effect of increasing the ionic strength of the plant water on increasing recoveries was not observed for tests conducted under condition 1 [50 g/t SIBX, 100 g/t guar, and 50 g/t D250]. These are marked with an asterisk in the tables. It is shown in Table 4.3 that both solids and water recoveries increased in conjunction with an increase in the ionic strength of the synthetic plant water. This is an indication that the presence of the ions at high concentrations in the plant water increases the frothability of the system.

***Table 4.3**: Final solids and water recoveries for tests under 1 SPW and 5 SPW*

	1 SPW		5 SPW	
	Solids Rec (g)	Water Rec (g)	Solids Rec (g)	Water Rec (g)
1*	32.7	390.33	31.82	529.73
2	27.43	259.46	35.88	562.9
3	15.85	364.75	18.28	472.02
4	13.55	248.81	18.6	479.41
5	38.9	549.85	45.38	840.77
6	37.23	526.57	46.29	770.53
7	16.89	410.47	21.54	659.26
8	17.47	394.65	23.68	703.24

The copper grades and recoveries subject to varying the ionic strength of the synthetic plant water are shown in Table 4.4. It is evident that copper recoveries increased with an increase in ionic strength. Of particular importance to highlight is

the negligible increase in recovery observed in test 3 [50 g/t SIBX, 300 g/t guar and 50 g/t D250], an indication of the drastic effect that the depressant has on the froth phase. The effect of increasing the ionic strength on decreasing copper grade was minimal.

***Table 4.4**: Final copper grades and recoveries for tests conducted under 1 SPW and 5 SPW*

	1 SPW		5 SPW	
	Copper Recovery (%)	Copper Grade (%)	Copper Recovery (%)	Copper Grade (%)
1*	71.07	1.42	70.89	1.41
2	66.99	1.61	70.68	1.28
3	68.58	2.69	68.75	2.46
4	64.82	3.09	68.24	2.28
5	72.68	1.12	74.21	1.11
6	70.62	1.21	72.28	1.06
7	68.78	2.61	70.24	2.11
8	65.23	2.34	71.41	1.97

The results for nickel grades and recoveries are shown in Table 4.5. The general trend is the same as that observed for copper. However, for nickel the depressant appears to play a major role as seen by the negligible increase in recoveries, when the ionic strength was increased, at high depressant dosage conditions, tests 3 and 4. Moreover, for test condition 6 [150 g/t SIBX, 100 g/t Guar, 70 g/t D250], although solids recovery as well as copper recovery were increased, this was not achieved for nickel, an indication of nonselective recovery of the particles in the process.

***Table 4.5**: Final nickel grades and recoveries for tests conducted under 1 SPW and 5 SPW*

	1 SPW		5 SPW	
	Nickel Recovery (%)	Nickel Grade (%)	Nickel Recovery (%)	Nickel Grade (%)
1*	51.57	2.78	50.26	2.77
2	47.22	2.99	50.67	2.38
3	47.48	4.96	48.23	4.57
4	47.12	6.04	48.28	4.39
5	50.95	2.26	52.64	2.00
6	50.09	2.28	49.60	1.91
7	45.06	4.57	46.26	3.59
8	45.26	4.57	46.94	3.27

4.3 Determination of batch flotation kinetics using the classical model

This section presents the flotation kinetics parameters of the batch flotation tests, subject to varying the dosages of the reagents; collector, depressant and frother, as well as the ionic strength of the synthetic plant water. This was achieved by using the classical batch flotation kinetics model, shown in the equation (1);

$$\boldsymbol{R = R_{max}\left(1 - e^{-kt}\right)} \qquad (\mathbf{1})$$

Where $\boldsymbol{R}$ is recovery of mineral, $\boldsymbol{R_{max}}$ is maximum possible recovery of mineral, $\boldsymbol{k}$ is the flotation rate constant (1/min) and $\boldsymbol{t}$ is flotation time (mins).

Figure 4.19 and Figure 4.20 illustrate copper and nickel recoveries as a function of flotation time, respectively for all the tested reagent conditions and the two synthetic plant water types. The actual laboratory experimental data is represented by the markers, and the kinetic models are represented by the solid curves.

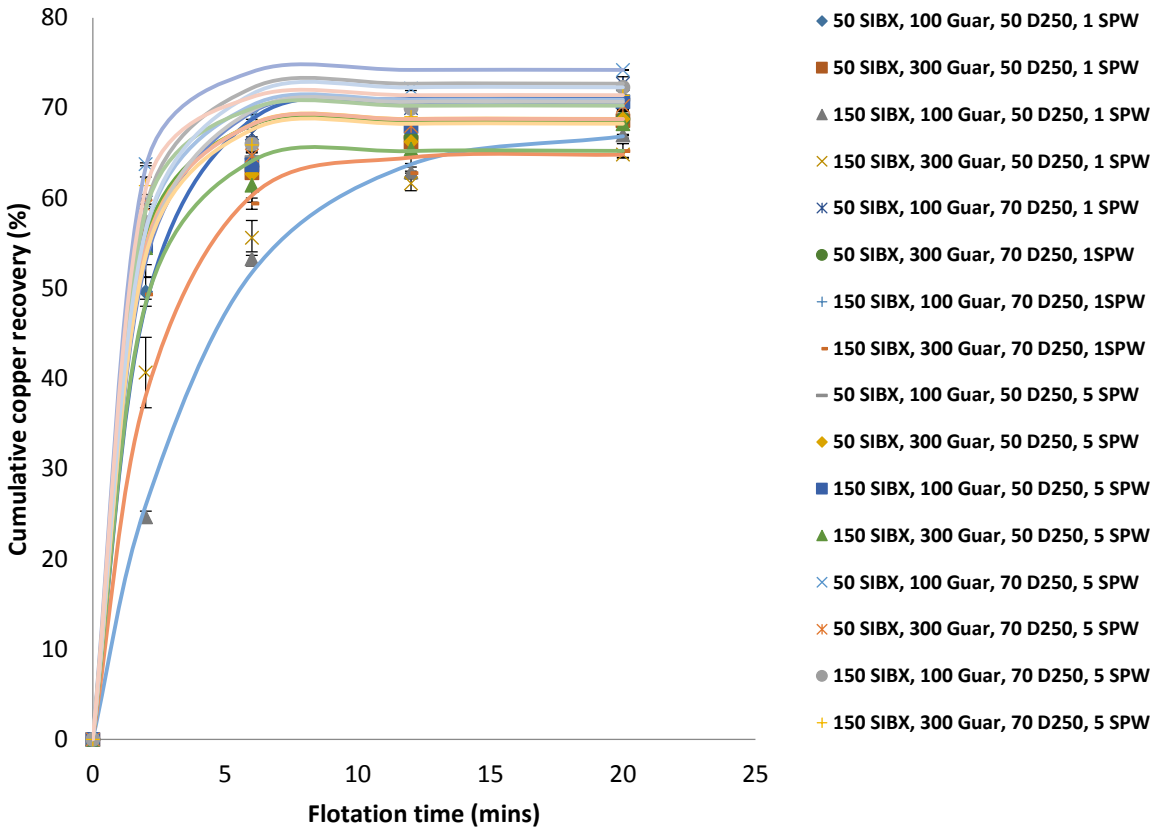


***Figure 4.19**: Cumulative copper recovery as a function of flotation time for both experimental data and model for all tests. Error bars represent standard deviation between duplicate tests.*

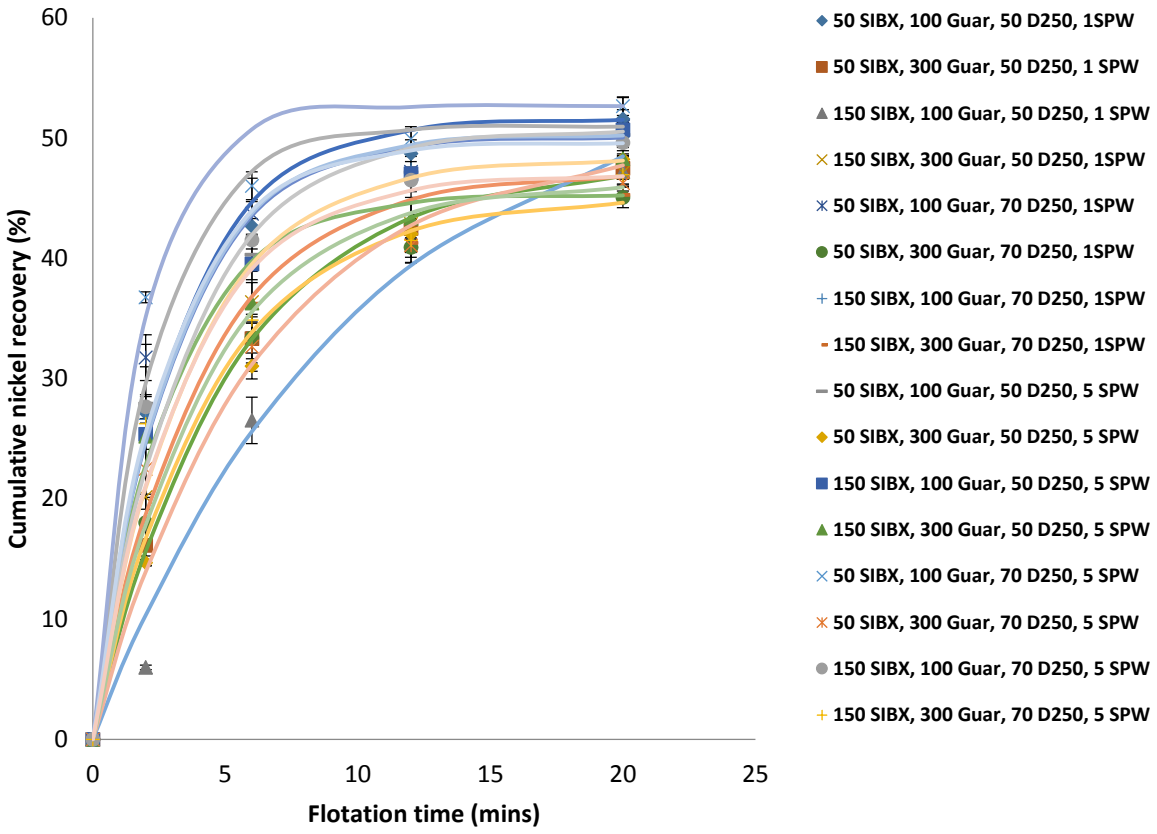


***Figure 4.20**: Cumulative nickel recovery as a function of flotation time for both experimental data and model for all test. Error bars represent standard deviation between duplicate tests.*

The summary of the flotation kinetics parameters (flotation rate constant and the maximum recovery) for both copper and nickel obtained from these curves is presented in Table 4.6. The table shows that the highest rates of flotation; 0.96 and 0.55 min^{-1} for copper and nickel, respectively, were obtained under test condition 5 and 5 SPW for both copper and nickel. This condition also gave rise to the highest maximum copper and nickel recoveries at 74.2 and 52.6 %, respectively. The lowest rate of flotation for both copper and nickel, 0.24 and 0.10 min^{-1}, respectively, was obtained under test condition 2 and 1 SPW. The table also illustrates that the rate constants for copper recovery were higher than those for nickel recovery under all the conditions tested. This further attests to the differences in floatability of the sulphide minerals chalcopyrite and pentlandite, with the former known to be a faster floating mineral than the latter.

***Table 4.6**: Summary of the flotation kinetics rate constant (K) and maximum recovery (R_{max}) for copper and nickel for all tests.*

Test conditions	Copper recovery				Nickel recovery			
	1 SPW		5 SPW		1 SPW		5 SPW	
	K (min^{-1})	R_{max} (%)	*K* (min^{-1})	R_{max} (%)	*K* (min^{-1})	R_{max} (%)	*K* (min^{-1})	R_{max} (%)
1	0.57	71.1	0.79	70.9	0.33	51.6	0.34	50.2
2	0.24	67.4	0.71	70.7	0.10	55.6	0.29	50.7
3	0.83	68.6	0.79	68.8	0.20	47.8	0.17	49.6
4	0.44	64.8	0.77	68.2	0.25	47.1	0.28	48.3
5	0.83	72.7	0.96	74.2	0.44	50.9	0.55	52.6
6	0.69	70.6	0.76	72.3	0.34	50.1	0.36	49.6
7	0.79	68.8	0.90	70.2	0.23	45.1	0.24	46.3
8	0.68	65.2	0.96	71.4	0.35	45.3	0.30	46.9

4.4 Statistical Analysis of Variance

To further corroborate the results presented in the preceding sections, a statistical analysis was carried out on the data using Design Expert software (Anderson & Whitcomb, 2000) incorporating 95 % confidence limit. The responses were solids and water recoveries as well as copper and nickel grades and recoveries, and the variables used were collector, depressant, frother and water quality. Using this tool it is possible to determine the major and interactive effects of the variables in question. There exists an interaction between two independent variables if the effect of one variable, on a given response, depends on the level of the other independent variable. The summary of the statistical analysis is presented in tables as well as models in this section, illustrating the contribution of each factor to the overall response. Values of ‘’Prob > *F*’’ less than 0.0500, in the Table 4.9 (Pages 64 and 65), indicates that the contribution of a given factor is statistically significant, and therefore the term is included in the model. M1, M2, M3, M4, M5 and M6 gives solids recovery, water recovery, copper recovery, copper grade, nickel recovery and nickel grade models, respectively (Page 65). It is worth noting that the term for collector was not statistically significant on nickel grade and recovery. However, since the interactions between the collector and ionic strength were statistically significant, for hierarchical purposes, the collector term was included in the model. Similarly, the

effect of frother was statistically insignificant on nickel recovery, however owing to the existence of the interaction with the depressant being statistically significant and therefore for correct hierarchy, frother was in the model as well. These are marked with asterisks in Table 4.9.

Figure 4.21 (Page 66) shows the effects of depressant and frother dosages under the two plant water types on the solids recovery. As already shown in the preceding sections, this figure confirms that solids recoveries increased with an increase in both frother dosage and ionic strength, indicating a more stable froth, which allows for high recovery of particles. Contrarily solids recoveries decreased with an increase in depressant dosage owing to the depression of the naturally floating gangue (NFG) particles that dilute the concentrate. It is worth noting that the effect of frother dosage on increasing solids recovery was only prominent at 100 g/t depressant dosage, and was minimal at 300 g/t depressant dosage. This is an indication that the extent to which frother dosage can improve the recovery of solid particles in the process is also dependent on the concentration of the depressant present in the system, hence there exists an interaction between the frother and depressant. While the effect of frother dosage at high depressant dosage was negligible under 1 SPW, it is clear that under 5 SPW this effect on increasing solids recovery was prominent, indicative of an interaction between the frother and ionic strength of the plant water. These interactions are vital to consider in process control because different conditions of a variable can lead to different performance depending on the levels of the other variables that also affect the process.

The effects of depressant and frother dosages as well as water quality, on water recovery, are shown in Figure 4.22 (Page 67). The stability of the froth increased with an increase in both frother dosage and ionic strength, and decreased with an increase in depressant dosage, as seen by the increase and decrease in water recovery, respectively. No interactions between the variables were observed for water recovery.

Figure 4.23 (Page 68) illustrates the results for the effect of depressant and frother dosages as well as ionic strength on copper recovery. Increasing both the frother

dosage and ionic strength over the two levels increased copper recovery by about 2 %, while increasing the depressant dosage from 100 to 300 g/ t decreased copper recovery by 3 %. This further attests to the effect that the depressant has on the froth stability, since it is not expected to adsorb onto the valuable mineral surfaces. It should also be highlighted that the extent of the effect of frother dosage on copper recovery was independent of the depressant and ionic strength levels, indicating that there were no interactions between the variables for copper recovery. This illustrates that the floatability of the mineral chalcopyrite is minimally affected by changes in the chemical environment.

It is shown in Figure 4.24 (Page 69) that copper grade was improved by about 1.2 % on average as a result of increasing the depressant dosage from 100 to 300 g/t. This figure also shows that an increase in frother dosage and ionic strength of the plant water negligibly decreased (about 0.3 % on average) copper grade. No interactions were found among the variables for copper grade.

Increasing nickel recovery by increasing frother dosage was only achieved at the lower depressant dosage, as shown in Figure 4.25 (a) (Page 70). However, the increase was insignificant, about 0.9 %. Of particular interest is that at the higher depressant dosage of 300 g/t, increasing the frother dosage did not improve the nickel recovery – illustrating the susceptibility of the sulphide mineral pentlandite to high depressant dosages. The effects of collector and depressant dosages on nickel recovery are also shown (Figure 4.25 b) (Page 70). It is shown that increasing the collector dosage, at a depressant dosage of 100 g/t, decreased the nickel recovery, this has been shown in the previous sections. Furthermore, it is interesting to note that at 300 g/t depressant dosage, the effect of collector dosage was negligible. These further attest to the characteristic floatability behaviour of the pentlandite mineral particularly in the presence of the depressant. It also follows that there exist interactions; between depressant and frother, as well as between collector and depressant, in nickel recovery.

Figure 4.26 (Page 71) illustrates results obtained for nickel grade at different levels of the depressant, frother and the ionic strength of the plant water. Increasing the

depressant dosage gave rise to 2.7 and 1.9 % increases in nickel grade under 1 SPW and 5 SPW, respectively, at a frother dosage of 50 g/t, showing the interactions between the depressant and ionic strength. At the frother dosage of 70 g/t, the increases in depressant dosage gave rise to increases in nickel grade of about 2.2 and 1.52 % – illustrating a further increase in the unselective recovery of particles owing to an increase in frother dosage.

The terms A, B, C and D in the models represent collector, depressant, frother and water quality, respectively.

***Table 4.7**: Summary of the main and interactive effects of the variables on solids and water recoveries at 95 % confidence level*

Response	Term	*P* value Prob > *F*	Effect on response	% Contribution
Solids recovery	Depressant	< 0.0001	Negative	78.17
	Frother	< 0.0001	Positive	9.88
	Ionic strength	< 0.0001	Positive	6.40
	Depressant and Frother	< 0.0001	Negative	2.48
	Frother and Ionic strength	0.0214	Positive	0.45
Water recovery	Depressant	0.0009	Negative	7.26
	Frother	< 0.0001	Positive	35.77
	Ionic strength	< 0.0001	Positive	46.27

***Table 4.8**: Summary of the main and interactive effects of the variables on copper grade and recovery at 95 % confidence level*

Response	Term	*P* value Prob > *F*	Effect on response	% Contribution
Copper recovery	Collector	0.0004	Negative	12.69
	Depressant	< 0.0001	Negative	31.05
	Frother	< 0.0003	Positive	13.52
	Ionic strength	< 0.0001	Positive	18.36
Copper grade	Depressant	< 0.0001	Positive	84.57
	Frother	< 0.0001	Negative	7.58
	Ionic strength	< 0.0001	Negative	4.84

***Table 4.9**: Summary of the main and interactive effects of the variables on nickel grade and recovery at 95 % confidence level*

Response	Term	*P* value Prob > *F*	Effect on response	% Contribution
Nickel recovery	Collector	0.1237*	Negative	2.79
	Depressant	< 0.0001	Negative	50.70
	Frother	0.2965*	Negative	1.25
	Collector and Depressant	0.0454	Positive	4.85
	Depressant and Frother	0.0108	Negative	8.24
Nickel grade	Collector	0.7862*	Negative	0.00079
	Depressant	< 0.0001	Positive	77.45
	Frother	< 0.0001	Negative	11.90
	Ionic strength	< 0.0001	Negative	6.55
	Collector and Ionic strength	0.0023	Negative	1.20
	Depressant and Ionic strength	0.0185	Negative	0.66

$$\boldsymbol{Water\ Recovery} = +\mathbf{521.62} - \mathbf{43.60} * \boldsymbol{B} + \mathbf{96.75} * \boldsymbol{C} + \mathbf{105.61} * \boldsymbol{D} \quad (\mathbf{M1})$$

$$\boldsymbol{Solids\ Recovery} = +\mathbf{27.61} - \mathbf{9.36} * \boldsymbol{C} + \mathbf{3.33} * \boldsymbol{C} + \mathbf{2.57} * \boldsymbol{D} - \mathbf{1.67} * \boldsymbol{B} * \boldsymbol{C} + \mathbf{0.71} * \boldsymbol{C} * \boldsymbol{D} \quad (\mathbf{M2})$$

$$\boldsymbol{Copper\ Recovery} = +\mathbf{69.76} - \mathbf{0.93} * \boldsymbol{A} - \mathbf{1.46} * \boldsymbol{B} + \mathbf{0.96} * \boldsymbol{C} + \mathbf{1.08} * \boldsymbol{D} \quad (\mathbf{M3})$$

$$\frac{\mathbf{1}}{\sqrt{\boldsymbol{Copper\ Grade}}} = +\mathbf{0.77} - \mathbf{0.12} * \boldsymbol{B} + \mathbf{0.0036} * \boldsymbol{C} + \mathbf{0.028} * \boldsymbol{D} - \mathbf{0.012} * \boldsymbol{B} * \boldsymbol{C} \quad (\mathbf{M4})$$

$$\boldsymbol{Nickel\ Recovery} = +\mathbf{48.54} - \mathbf{0.42} * \boldsymbol{A} - \mathbf{1.80} * \boldsymbol{B} - \mathbf{0.28} * \boldsymbol{C} + \mathbf{0.56} * \boldsymbol{A} * \boldsymbol{B} - \mathbf{0.73} * \boldsymbol{B} * \boldsymbol{C} \quad (\mathbf{M5})$$

$$\log(\boldsymbol{Nickel\ Grade}) = +\mathbf{0.51} - \mathbf{0.0014} * \boldsymbol{A} + \mathbf{0.13} * \boldsymbol{B} - \mathbf{0.052} * \boldsymbol{C} - \mathbf{0.037} * \boldsymbol{D} - \mathbf{0.017} * \boldsymbol{A} * \boldsymbol{D} - \mathbf{0.012} * \boldsymbol{B} * \boldsymbol{D} \quad (\mathbf{M6})$$

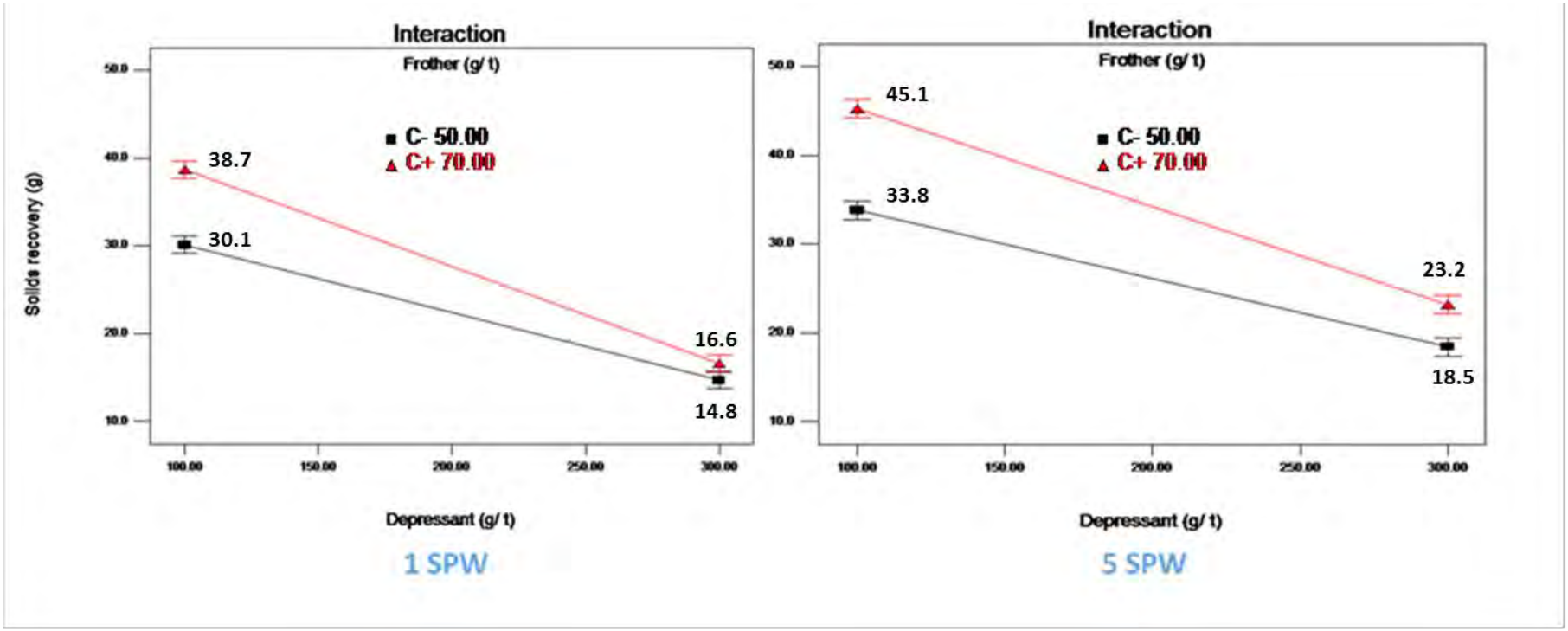


***Figure 4.21**: Effect of depressant and frother dosages and ionic strength on solids recovery. The curves with the square and triangle markers are for the tests conducted at 50 and 70 g/ t frother dosages, respectively.*

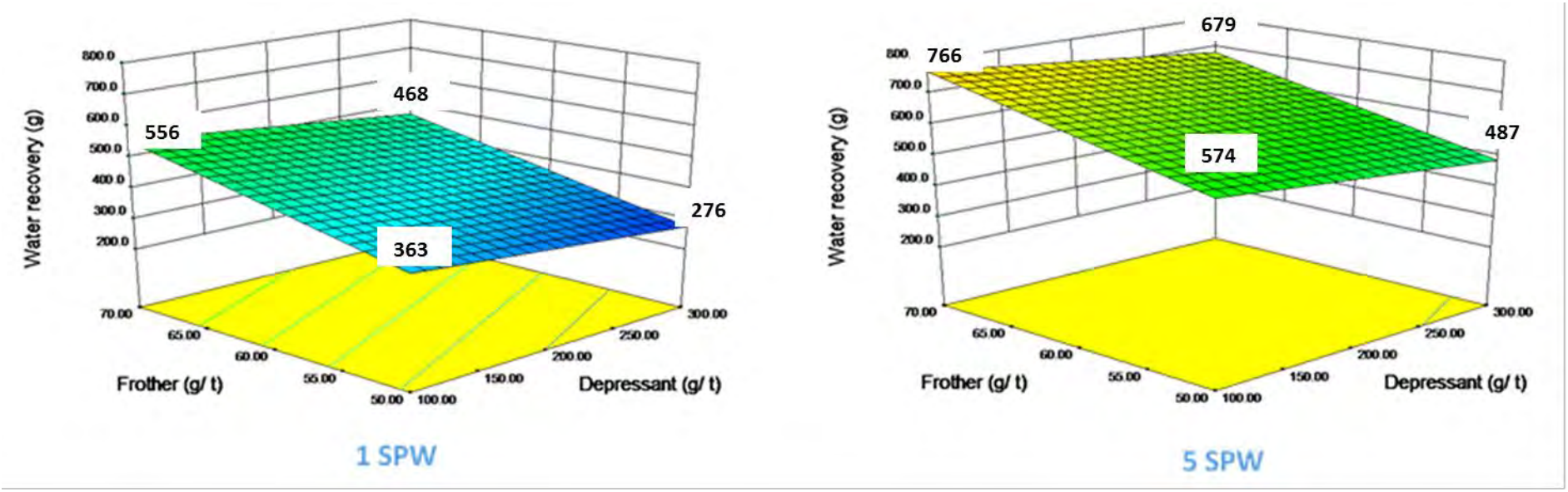


***Figure 4.22**: Effect of depressant and frother dosages and ionic strength on water recovery*

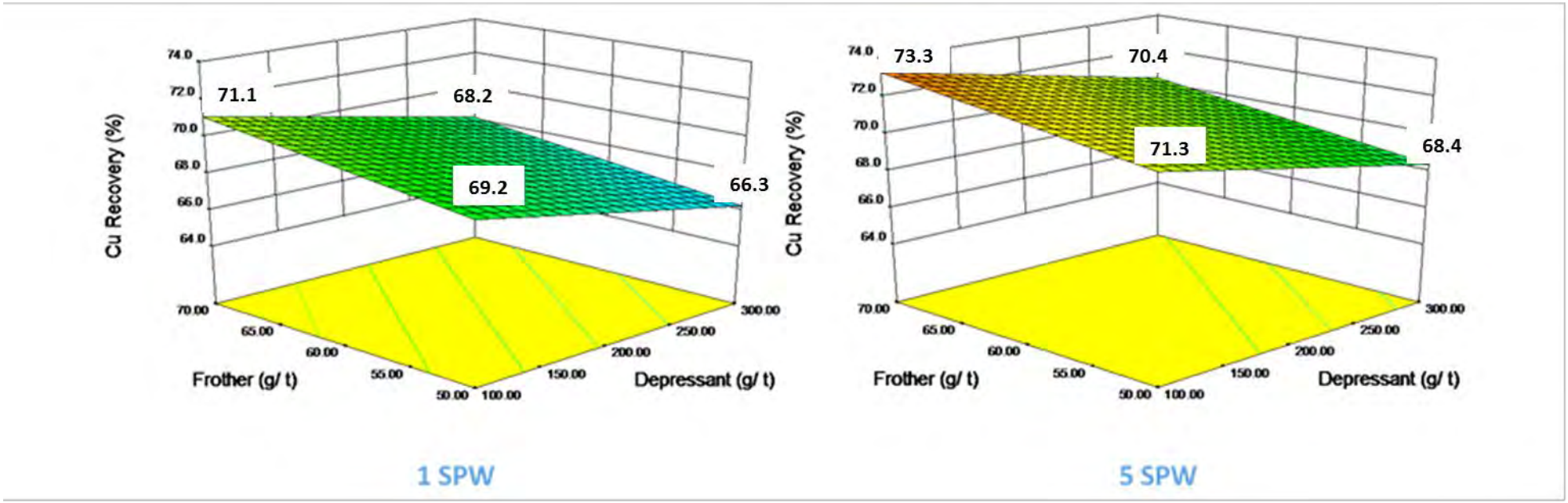


***Figure 4.23**: Effect of depressant and frother dosages and ionic strength on copper recovery*

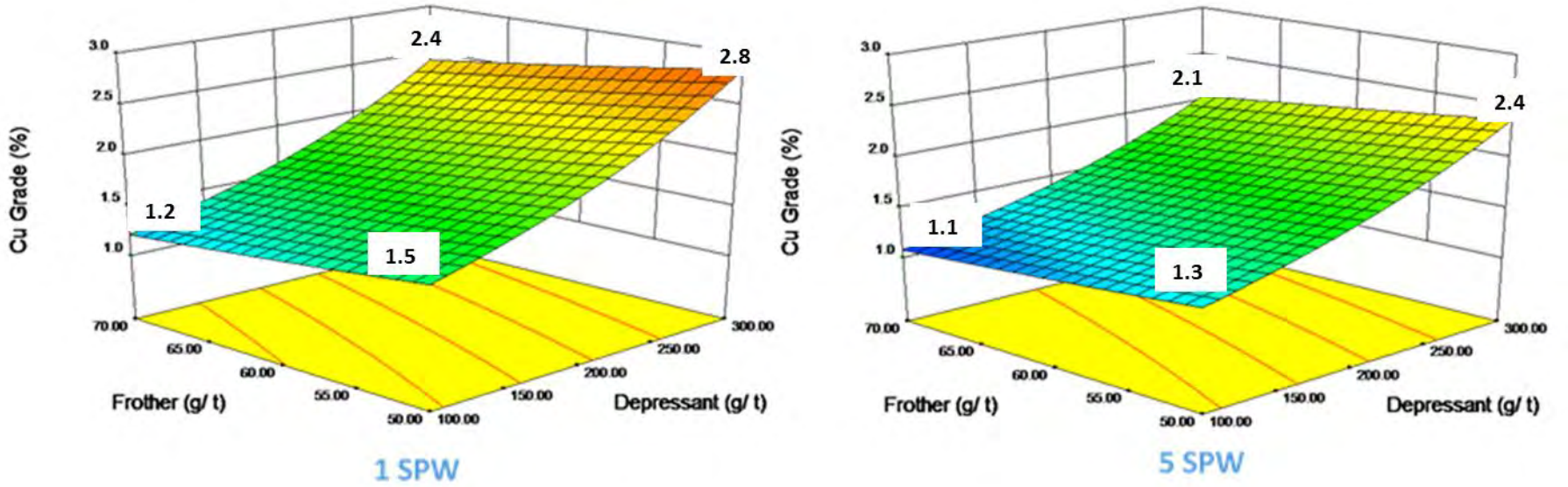


***Figure 4.24**: Effect of depressant and frother dosages and ionic strength on copper grade.*

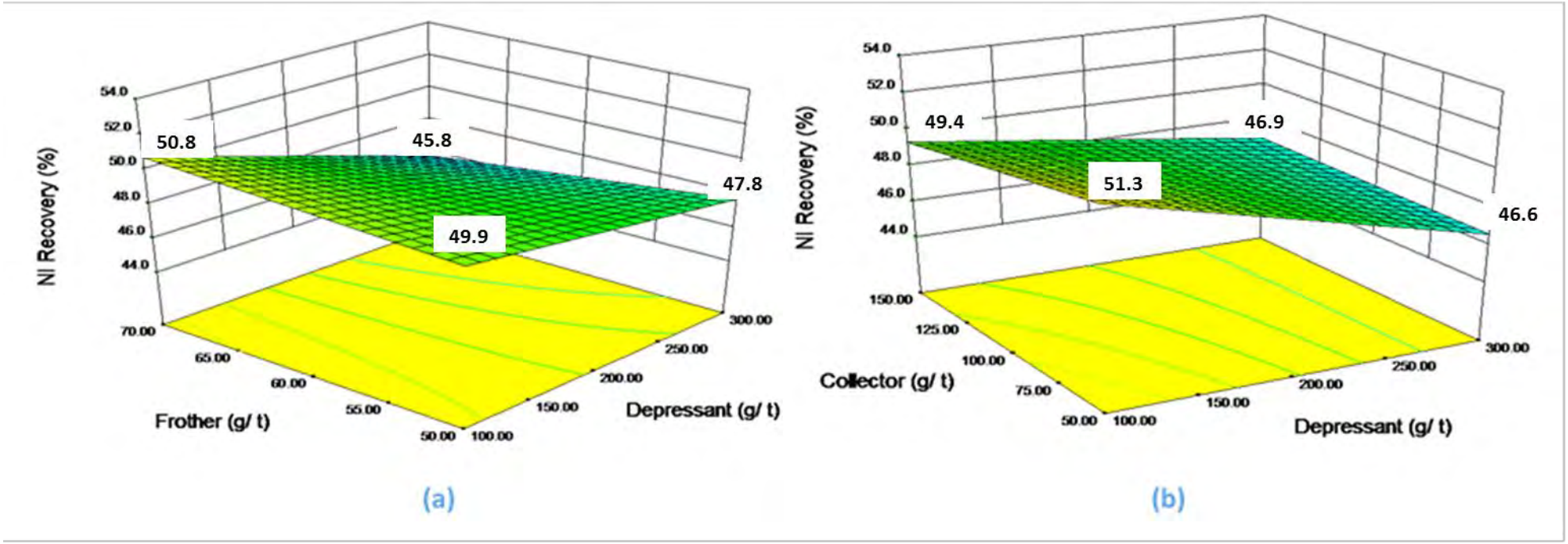


***Figure 4.25**: Effect of (a) depressant and frother dosages (b) collector and depressant dosages on nickel recovery.*

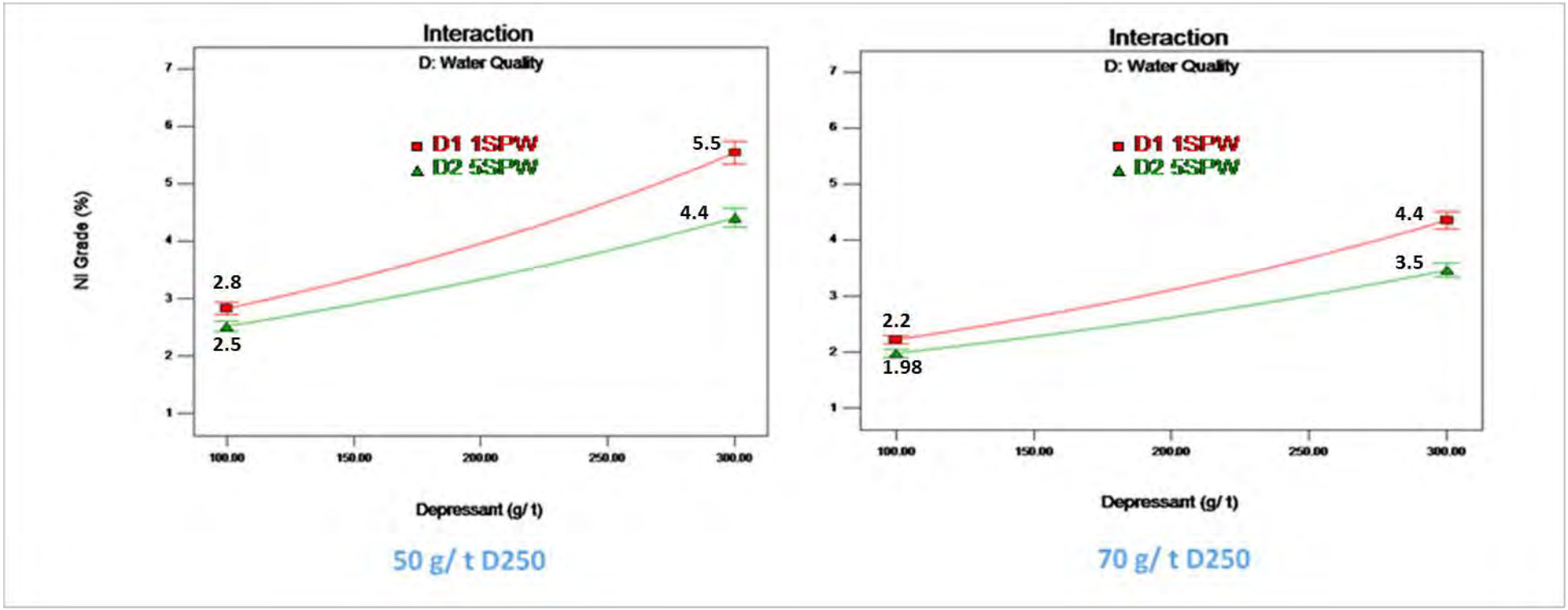


***Figure 4.26**: Effect of depressant and frother dosages and ionic strength on nickel grade. The curves with square and triangle markers are for tests conducted at 1 SPW and 5 SPW, respectively.*

4.5 Key findings

This section presents the summary of the major findings in this study with regards to the experimental results obtained;

- ✓ An increase in collector dosage resulted in a decrease in both solids and water recovery under the standard synthetic plant water (1 SPW). An increase in both solids and water recovery was observed when the collector was increased under the high ionic strength plant water (5 SPW). However, statistical analysis highlights that the effect of collector dosage on solids and water recovery was not statistically significant.
- ✓ An increase in collector dosage decreased copper and nickel recoveries under 1 SPW. Under 5 SPW, the effect of collector dosage on decreasing recoveries was only evident at high frother dosage. Copper and nickel grades were minimally affected.
- ✓ The effect of increasing the frother dosage on increasing solids recovery was minimal at high depressant dosage under 1 SPW. However at 5 SPW, this effect was prominent. These observations indicate the interaction between the frother and depressant, as well as between the frother and ionic strength.
- ✓ The depressant, at higher dosage, was seen to override the effects of collector and frother dosage on nickel recovery. This is an indication of the susceptibility of the mineral pentlandite to high depressant dosage. This further illustrates the interaction of the depressant with both collector and frother.
- ✓ Increasing the ionic strength of the plant water increased solids, water, copper and nickel recoveries. However, the statistical analysis shows that this effect on nickel recovery was not significant, probably owing to the slower flotation kinetics of pentlandite.
- ✓ No interactions between the variables were found for copper recovery, indicating that chalcopyrite is minimally affected by the chemical environment. Moreover, nickel recoveries were more affected than copper recoveries – illustrating the differences in the floatability of the sulphide minerals chalcopyrite and pentlandite.
- ✓ Optimum recoveries were obtained under the test condition [50 g/t SIBX, 100 g/t guar, 70 g/t D250 and 5 SPW] indicating that this may be the optimum operating condition.

5. Discussion

The primary aim of this research project was to investigate the simultaneous effects of the changes in the dosages of collector, depressant and frother, as well as the ionic strength of the plant water on flotation outcomes; solids and water recoveries, copper and nickel recoveries and grades. It is well known that the interpretation of the behaviour of flotation reagents can be complex owing to the existence of primary, secondary and interactive effects which may be present (Bradshaw et al. 2005). There exists an interaction between two or more independent variables if and only if the effect of one of the variables on a given response depends on the level of the other variables. Moreover, during grinding the particles are not fully liberated, and hence a composite valuable-gangue mineral particle can either be recovered or depressed. The recovery of this particle will depend on the concentration of the collector and depressant in the pulp, and other chemical species that affect the adsorption of such reagents. It is therefore virtually impossible to precisely assess the contribution of a reagent to the overall flotation performance. The practice of water recycle and reuse in certain parts of a processing circuit leads to accumulation of pollutants, which alter the chemical environment of the process and hence affect the overall metallurgical performance (Rao & Finch 1989). This further complicates the process and hence the need for a holistic approach when evaluating the effects of the chemical parameters affecting the process. This study adopted a factorial design approach so as to evaluate the simultaneous effects of the chemical parameters as well as to determine the possible interactions between the chosen parameters.

In light of this, in order to achieve the main objective of this study, answers to the following key questions were sought, with the metallurgical performance indicators being the solids and water recoveries, as well as copper and nickel grades and recoveries.

- ✓ *What are the possible interactive effects that could exist among the chemical parameters with reference to the flotation reagents; collector, depressant and frother, as well as the ionic strength of the plant water?*

- ✓ *How does the change in water quality (ionic strength), owing to the practice of water recycle and reuse, affect the metallurgical performance as well as the role of the flotation reagents with particular reference to the collector, depressant and frother, on the metallurgical performance of the ore in question? With particular emphasis on the following;*

    - ✓ What is the effect of increasing the concentrations of the ions, present in the plant water, in the pulp on the adsorption behaviour of the ionic type collector, SIBX, and non-ionic depressant, guar, used in this study?

    - ✓ What is the effect of increasing the concentrations of the ions, in the plant water, on the frothing properties of the polyglycol ether, which is non-ionic in nature?

This Chapter presents a critical discussion of the findings presented in Chapter 4 in view of these questions.

5.1 The effect of collector and possible interactions with the other parameters on the metallurgical performance of the ore.

The primary role of a collector is to selectively enhance/impart hydrophobicity on the valuable mineral particles, and hence increase their recovery in a flotation process. The hydrophobicity of the collector-coated particles can be altered by changing two variables of the collector molecule; the alkyl chain length and dosage. However, in this study, the chain length was fixed, and the hydrophobicity was changed by varying the collector dosage. Furthermore, a secondary effect associated with particle hydrophobicity is the influence on froth stability. It has been reported that there exists an optimum particle hydrophobicity or contact angle beyond which particles have been shown to destabilise froths (Johansson & Pugh 1992; Schwarz & Grano 2005). This has been shown in Chapter 4, increasing the collector dosage

from 50 to 150 g/t decreased solids and water recoveries under the standard synthetic plant water (1 SPW). This therefore suggests that the resultant collector-coated particles were hydrophobic enough to cause bubble rupture; froth destabilisation, and ultimately a reduction in both solids and water recoveries, which should then infer that a reduction in the amount of valuable mineral particles reporting to the concentrate would occur. A reduction was indeed observed for both copper and nickel recoveries. The observation of reduction in recoveries as a result of increasing collector dosage supports the theory, through studies conducted by a number of authors (Wiese et al. 2011; Bradshaw et al. 2005; Schwarz & Grano 2005; Johansson & Pugh 1992), that highly hydrophobic collector-coated valuable mineral particles have an adverse effect on the nature of the froth. Nonetheless, this effect was negligible for nickel recovery, particularly at high depressant dosage, 300 g/t, implying that the effect of collector on nickel recovery was dependent on the concentration of the depressant in the pulp.

Generally, the effect of increasing collector dosage on the recoveries under the high ionic strength plant water, 5 SPW, was minimal, and in some cases there was a slight increase in solids and water recoveries. It can be postulated that the presence of the ions in high concentrations in the pulp induced some electrostatic interactions with the collector molecules, or led to precipitation onto the mineral surface, or a combination of the two. This in turn had the effect of weakening the adsorption of the collector ions onto the mineral, or hindering the collector molecules from fully adsorbing on the mineral surface, therefore an increase in the collector dosage would have a negligible effect. Moreover, the slight increase in solids recovery could be due to the ions inhibiting bubble coalescence (Quinn et al. 2007; Craig 2004), thereby inducing a froth sufficiently stable to withstand the dynamic forces imposed by the highly hydrophobic collector-coated particles. As a result, the froth can resist the change and ultimately allow for adequate recovery of particles to the concentrate. In this study a xanthate type collector, SIBX, was used. As this is an ionic collector, it is not surprising that its effect on the solid particles would be affected by an increase in the ionic strength of the process water.

5.2 The effect of depressant and possible interactions with the other parameters on the metallurgical performance of the ore.

While the role of a collector is to promote the recovery of the economically valuable minerals, the depressant ensures that the recovery of the undesired gangue minerals is inhibited. Solids recoveries decreased with an increase in depressant dosage owing to the reduction in the amount of naturally floatable gangue (NFG) reporting to the concentrate. This occurs through adsorption of the depressant molecules (guar gum) onto the gangue mineral surface, presumably *via* hydrogen or hydrophobic bonding, or a combination of the two (Wang et al. 2005; Jenkins & Ralston 1998; Rath et al. 1997; Rath et al. 1995; Steenberg & Harris 1984), and rendering these unwanted mineral particles hydrophilic and hence ineligible to be recovered by true flotation. A reduction in water recoveries was also observed when the depressant dosage was increased. This is an indication of a reduction in froth stability, owing to the removal of the moderately hydrophobic NFG gangue particles which possess froth-stabilising properties (Wiese et al. 2011; Wiese 2009; Wiese et al. 2008; Wiese et al. 2007; Bradshaw et al. 2005). This was further followed by a reduction in valuable mineral recovery as seen by both copper and nickel recoveries. Nickel recoveries were more affected than copper recoveries, probably owing to the differences in floatability of the sulphide minerals; chalcopyrite and pentlandite. The latter is known to be slow floating and hence more prone to be affected by changes in froth stability. This can be ascribed to the effect that solid particles and moderately hydrophobic particles have on the froth. It has been reported that fine solid particles can stabilise the froth, probably due to the formation of layers on the thin film between the air bubbles thereby inhibiting bubble coalescence (Horozov 2008).

Although collectors and depressants type and dosage are usually only chosen to control the recovery of the valuable material, the secondary effects of collector and depressant on the nature of the froth support the theory that moderately hydrophobic particles can stabilise the froth, whereas highly hydrophobic particles destabilise the froth. It is evident from the present study that the tested range of the collector dosage led to particle hydrophobicity beyond the optimum particle hydrophobicity above which the particles started to destabilise the froth. If collectors and depressants are to be tailored on an industrial concentrator plant for optimal

recoveries, conditions that will compensate for their effects on the nature of the froth should also be considered.

Both copper and nickel grades increased in conjunction with an increase in depressant dosage due to the reduction in the amount of NFG reporting to the froth, and thus less dilution of the concentrate. It was also determined that the depressant effect on reducing the amount of solids recovered was to the same extent under both 1 SPW and 5 SPW. This implies that the presence of the ions in the pulp did not affect the adsorption strength of the depressing agent, and this can be expected since guar is a non-ionic polymeric depressant, and therefore its characteristic adsorption is minimally affected by changes in solution; conditions such as ionic strength and pH (Morris et al. 2002). This is unlike ionic polymeric depressants, like carboxymethyl cellulose (CMC), the adsorption strengths of which have been shown to be affected by changes in ionic strength and pH of the pulp (Parolis et al. 2008; Khraisheh et al. 2005; Bicak et al. 2007; Wang et al. 2005). Khraisheh et al. (2005) showed that CMC adsorption on talc was enhanced by increasing the concentrations of the magnesium (Mg^{2+}), calcium (Ca^{2+}), and potassium (K^{2+}) ions in the process water. The enhancement is likely to be attributed to the fact that by virtue of chemistry and laws of electrostatics, oppositely charged species will be attracted to each other whereas likely charged species will repel one another. As a result, the increase in the concentration of the cations in the pulp will reduce any electrostatic repulsions, which may hinder the closest approach of the depressant to the gangue, between the negatively charged surfaces of the CMC and gangue owing to the adsorption of the cations on the negatively charged sites of the CMC molecules (Khraisheh et al. 2005).

5.3 The effect of frother and possible interactions with the other parameters on the metallurgical performance of the ore.

As the final separation phase in the flotation process, and hence the overall metallurgical performance determinant, it is clear that the froth phase is the ‘heart’ of the flotation process and therefore its stability is of crucial importance. The stability of this phase is directly controlled by addition of frothing agents, which adsorb onto the air-water interface of the bubbles, thereby regulating the physical properties of the bubbles such as size and burst rate. It is evident from results shown in Chapter 4

that increasing the frother dosage increased both solids and water recoveries, indicating an increase in froth stability. However, this was also expected to result in a reduction in the grade of the valuable minerals in the concentrate owing to the increase in nonselective recovery of the particles; entrainment, which has been reported to be proportional to water recovery (Ekmekçi et al. 2003; Yang & Aldrich 2006; Boylu & Laskowski 2007). Moreover, this may also result in an increase in recovery of the valuables, owing to the entrapment of fine particles between the air bubbles. A noteworthy observation was made on nickel recovery as it was discovered that the primary objective of increasing frother dosage, in order to increase recovery as a result of a more stable froth, was not achieved for nickel recovery, particularly at high depressant dosage. However, an increase was achieved for copper recovery as a result of increasing the frother dosage. By virtue of copper recovery being improved, even at high depressant dosage, as a result of increased frother dosage, it then suggests that the flotation response of nickel cannot be due to a froth phenomenon, but rather a liberation phenomenon, and thus this behaviour is likely to be attributed to the surface liberation of pentlandite in the ore. Therefore it can be postulated that the pentlandite particles were not sufficiently liberated in the ore, and having the polymer at sufficiently high concentration in the pulp can drastically lower its recovery due to the depression of the pentlandite-gangue composite particles. Consequently it is likely that any chemical manipulation in the pulp at high depressant dosage would have a negligible impact on the floatability of pentlandite. It was also evident that changing the collector dosage had a negligible effect on nickel recovery at high depressant dosage. The poor floatability of pentlandite at high depressant dosage is not a novel discovery, other researchers have also observed this phenomenon (Corin et al. 2011; Wiese et al. 2007; Bradshaw et al. 2005). These studies highlight the interactive effects between the frother and depressant, as well as between collector and depressant, whereby the effect of both collector and frother on nickel floatability depends on the concentration of the depressant in the pulp. Interactions are important effects to note in such a complex system particularly when formulating and selecting reagent suites because different flotation performances will be obtained when different interactive effects are present between the variables.

5.4 The effect of water quality on the metallurgical performance of the ore and the behaviour of the flotation reagents.

Owing to the practice of water recycle and reuse at concentrator plants, it was imperative to understand the behaviour of the process subject to a change in the quality of the process water, as well as understanding the behaviour of the flotation reagents under such conditions. As already mentioned, the parameter of interest was the ionic strength of the plant water. The 1 SPW was used as a baseline and a simulator to the process water used at the industrial plants concentrating the Merensky ore. This study revealed that increasing the concentrations of the inorganic ions present in the synthetic plant water increased the stability of the froth phase. This was seen by an increase in solids, water, copper, and nickel recoveries. Nonetheless, the increase in recoveries was not very pronounced particularly at high depressant dosage especially for nickel, owing to the disproportionate effect of the depressant on froth stability. It was thus revealed that the inorganic ions, at high concentrations in the process water exhibit frothing properties. This phenomenon of ions at high concentrations stabilising froths has been reported by a number of researchers (Corin & Wiese 2014; Corin et al. 2011; Manono et al. 2012; Kurniawan et al. 2011). It is generally attributed to reductions in bubble size and retardation of bubble coalescence under high ionic strength plant water (Manono et al. 2012; Kurniawan et al. 2011; Castro et al. 2013; Quinn et al. 2007; Wang & Peng 2014), and therefore improved froth stability, and hence recovery.

In addition, this led to a reduction in the concentrate grade as was seen by both copper and nickel grades. This is due to a more stable froth, and hence an increase in entrainment, the nonselective recovery of particles which allows for more gangue recovery. As already highlighted, the change in the ionic strength of the plant water did not have any effect on the behaviour of both the depressing and frothing agents. However, its influence on the behaviour of the collector will require further studies.

- ✓ *Is a factorial experimental design an appropriate tool to use in holistically evaluating the effects of reagents, and understanding the nature of the possible interactive effects among the process variables in question, in a quest to predict and determine optimum operating conditions?*

As already highlighted in Chapter 4, statistical analysis (Section 4.4) was carried out on the data, incorporating a 95 % confidence limit, using the Design Expert 8.0 software (Anderson & Whitcomb, 2000). The software considers the contribution of the variables to the overall performance of the process simultaneously to develop a response factor model. This is particularly useful for identifying the major and interactive effects of the variables in question on the overall performance of such a complex process.

Models developed by the software are given in Chapter 4 (Page 65). This study found that the contribution of the collector to the overall recovery of the solids particles, as well as copper recovery, was statistically insignificant in relation to the contribution of the other variables. Moreover, the contribution of the change in water quality on the recovery of nickel was also noted to be statistically insignificant (Section 4.4, Chapter 4).

Wiese et al. (2011**)** showed that the secondary effect of the depressant on froth stability can be compensated for by increasing frother concentration in the pulp. This was indeed revealed by the model analysis. However, it was noted that at high depressant dosage, 300 g/t, the effect of increasing frother concentration on solids recoveries was negligible. This illustrates that the effect of frother on solids recovery is dependent on the concentration of the depressant in the pulp, hence the interaction between these variables (shown in Model 2, Chapter 4). Of crucial importance is that at 300 g/t depressant dosage, almost all the moderately hydrophobic froth-stabilising NFG particles will be depressed (Wiese et al. 2007), and as such the froth is highly unstable; increasing the frother dosage may not counteract the effect of the depressant. On the other hand, under 5 SPW, the effect of frother on increasing solids recoveries was prominent, illustrating the interaction between the frother and ionic strength of the plant water, also shown in Model 2. This is recognised as a synergetic phenomenon between the frother and the ions

since they stabilise the bubbles to a greater extent together over the sum of each variable alone.

None of the variables showed any interactions in the water recovery model (M1). However, it is important to highlight that the software revealed that water recoveries were more strongly affected by the frother than the depressant. This is likely to be attributed to the fact that frothing agents adsorb at the air-water interface thereby regulating the surface tension of the air bubbles, which affect the stability of the froth and hence water recovery. Hence the effect is direct while the depressant indirectly affects water recovery, by regulating the amount of the NFG talc particles reporting to the froth. Ionic strength was observed to be the most influential variable on water recovery, illustrating the enhanced frothing properties of the ions present at high concentrations in plant water.

The susceptibility of the sulphide mineral pentlandite to depressant dosage was further attested to by the overall contribution of the depressant term to nickel recovery, on negatively affecting the recovery of nickel, with a contribution of 50.7 % (Table 4.7 in chapter 4). On the other hand, as it was expected, the depressant was the most influential factor on concentrate grade, contributing 84.6 and 77.5 % for copper and nickel, respectively. Thus factorial design is a powerful tool in determining the major effects, as well as possible interactions in such a complex system. This in turn allows for prediction of optimum operating conditions in process control, which will also depend on the philosophy of the concentrator plant in question – whether it is recovery-driven, or grade-driven.

6 Conclusions and Recommendations

6.1 Conclusions

This study adopted a factorial experimental design as a tool to holistically evaluate the effects of the chemical parameters; collector, depressant, frother and ionic strength of the plant water, as well as making an effort to reveal the possible interactive effects among these parameters.

It was shown that the tested range of the collector dosage gave rise to particles sufficiently hydrophobic to destabilise the froth as was seen by the reductions in recoveries under the standard synthetic plant water, indicating that it was beyond the optimum particle hydrophobicity. Therefore if elevated collector dosages are to be tailored at an industrial concentrator, this should be done under conditions that will compensate for the effect of highly hydrophobic collector-coated particles on the nature of the froth. It is also of crucial importance for concentrators to know the exact collector dosage that yields maximum recoveries for the ore in question in order to optimise reagents cost. The effect of elevated collector dosages on adversely affecting the recoveries was minimal under the high ionic strength plant water, indicating that the adsorption of the collector molecules on the mineral particles was possibly weak. It can therefore be concluded that the accumulation of the dissolved ions in the process water owing to the practice of water recycle can affect the adsorption of the collector, thereby impacting the efficiency of the metallurgical operation.

It is evident that the presence of the moderately hydrophobic NFG particles in the froth plays a crucial role in the metallurgical performance of the ore, as recoveries were observed to decline as a result of a less stable froth, owing to the depression of the froth-stabilising gangue particles. This is the secondary effect associated with increased concentration of depressant in the process. Therefore if concentrate grade is of crucial importance at a given concentrator, and hence the need for elevated depressant dosages, it will be imperative to run the process under conditions that will compensate for the effect of the depressant on the valuable mineral recovery as a result of imposing dynamic forces on the nature of the froth. Therefore it will depend

on the operating philosophy of an operation in question and operation constraints that will determine whether the process is recovery-driven, or grade-drive. For example in processing the PGM-bearing ore from the UG-2 reef in the Bushveld complex, the operation has to be run under conditions that will minimise the recovery of the spinel mineral chromite due to the implications in the downstream smelting process, as chromite is known to be capable of reducing the efficiency of the smelter due to the formation of stable species (Ekmekçi et al. 2003). The performance of the depressing agent guar gum on reducing the amount of NFG particles reporting to the froth was seen to be minimally affected by change in water quality. Therefore accumulation of dissolved ions in process water should not present an adverse effect on the adsorption behaviour of guar gum, or any other typical non-ionic polymeric depressant.

The effect of high depressant dosage on froth stability, and hence on mineral recovery, was further confirmed to be compensated for by increasing the frother dosage. However, this was only achieved for copper, and was never achieved for nickel, probably owing to the differences in the floatability of the sulphide minerals chalcopyrite and pentlandite. Therefore it is of particular importance to take into account the factors that affect the stability of the froth when concentrating ores bearing minerals of low floatability such as pentlandite. It can also be concluded that the sulphide mineral pentlandite was less liberated in the ore, and hence the pentlandite-gangue composite particles were depressed in the presence of the polymer at high concentrations, as the collector was as well observed to have a negligible effect on the recovery on nickel at high depressant dosage. This will however have to be verified mineralogically.

The increase in the ionic strength of the plant water led to an increase in the stability of the froth phase, as seen by the increase in water recovery as well as solids recovery. An increase in copper and nickel recoveries was also observed. Although the effect was minimal, this occurred at the expense of the concentrate grade. This was attributed to the ions, at high concentrations in the plant water, acting as frothing agents. It was also observed that the use of high ionic strength plant water gave rise to higher recoveries than the use of high frother dosages, this is an indication that the use of saline water can replace the use of frothing agents and hence reduce the reagent costs on typical operations. Moreover, generally the behaviour of the

flotation reagents did not seem to change as the ionic strength of the process water was increased, although this will have to be verified for the collector. Therefore the practice of water recycle should not impose any adverse effects on the metallurgical performance of operations concentrating the PGM bearing ores from the Merensky reef. This is based on the assumption that the BMS are a good proxy to the flotation behaviour of the PGMs because of the strong association of the BMS and PGMs in the Merensky reef.

This study has shown that of the four parameters investigated, depressant has been shown to be the most dominant parameter on solids recovery, as well as on copper and nickel recoveries and grades. On the other hand, ionic strength was noted to be the most dominant parameter on water recovery. The following interactive effects were revealed;

- ✓ Depressant and frother on solids recovery
- ✓ Frother and ionic strength on solids recovery
- ✓ Collector and depressant on nickel recovery
- ✓ Depressant and frother on nickel recovery
- ✓ Collector and ionic strength on nickel grade
- ✓ Depressant and ionic strength on nickel grade

These are important effects to consider in process control because different grades and recoveries will be obtained at different levels of interacting parameters. For example, nickel recovery was improved by increasing frother dosage at low depressant dosage, however this was never achieved at high depressant dosage. Therefore such a holistic approach, coupled with a full mineralogical analysis of the feed ore, will be key to understanding such a complex system.

In view of the hypotheses that were put forward in Chapter 2;

- ✓ *H1: The factorial experimental design is an appropriate tool for a holistic evaluation of the effects of the flotation reagents since it allows for simultaneous evaluation of the effects of more than one variables. This will also reveal any possible interactions between the variables in question, and subsequently allow for prediction of optimum operating conditions within the range of the chosen variables.*

- ✓ *H2: An increase in the concentration of the ions present in the synthetic plant water will increase recoveries, however, this may occur at the expense of the concentrate grade because the presence of the ions at high concentration have been reported to exhibit strong frothing properties. This is not expected to influence the behaviour of the non-ionic depressing and frothing agents. However, this may have some effects on the behaviour of the ionic collector, owing to possible electrostatic interactions between the collector ions and the ions present in the plant water.*

This study has demonstrated that the factorial design is an appropriate tool to adopt in the holistic evaluation of the effects of the variables in question, their individual contribution to the overall response of the process, as well as possible interactions existing among them. This understanding can enable prediction of optimum operating conditions within a given margin of the variables in question. The build-up of dissolved ions in the plant water induced a more stable froth and allowed for an improvement in recoveries. Moreover, there was no apparent effect on the behaviour of the depressant and frother as a result of changing the ionic strength of the plant water. However, the behaviour of the collector was observed to be inconsistent owing to an increase in the ionic strength of the plant water, illustrating some dynamics imposed on this reagent by the build-up of ions in the process. Therefore it can be concluded that these hypotheses are supported by this work.

6.2 Recommendations

In light of the findings and contributions from the present study, the following recommendations for further studies are made:

- ✓ Adsorption studies should be conducted on the xanthate type collector, which is ionic in nature, under different concentrations of the typical ions present in process water. This will elucidate whether accumulation of ions can influence the adsorption behaviour of an ionic type collector, or whether this may lead to precipitation of the ions on the mineral surface thereby hindering the collector molecules from fully adsorbing on the surface and subsequently affecting the recovery.

- ✓ The adsorption behaviour of the flotation reagents should be evaluated in the presence of other pollutants present in typical process water such as organics, flotation reagents residues, etc. in order to gain a holistic understanding of the implications of water recycle at metallurgical circuits.

- ✓ Full mineralogical and liberation analysis on the feed ore, at the chosen grind, will have to be carried out in order to gain a better understanding of its behaviour in the presence of flotation reagents.

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8 Appendices

8.1 Appendix A: Batch flotation data for tests conducted under 1 SPW

8.2 Appendix B: Batch flotation data for tests conducted under 5 SPW

Test conditions	Time (mins)	Sample	Solids Rec (g)	Cum Solids Rec (g)	Cum Water Rec (g)	Cum Cu Grade (%)	Cum Cu Rec (%)	Cum Ni Grade (%)	Cum Ni Rec (%)
	2	C1	6.10	6.10	46.70	5.09	48.00	7.42	25.81
50 g/t SIBX	6	C2	7.42	13.52	137.5	3.06	64.07	5.45	42.00
100 g/t Guar	12	C3	7.78	21.30	244.9	2.07	68.07	3.91	47.56
50 g/t D250	20	C4	12.29	33.59	415.4	1.37	71.14	2.65	50.80
1 SPW		Feed	1004.83						
		Tails	971.24						
	2	C1	6.72	6.72	53.03	5.00	51.19	7.50	28.49
50 g/t SIBX	6	C2	7.01	13.73	135.2	3.09	64.6	5.58	43.31
100 g/t Guar	12	C3	9.19	22.92	235.7	1.97	68.8	3.85	49.84
50 g/t D250	20	C4	8.89	31.81	365.3	1.47	71.01	2.91	52.34
1 SPW		Feed	1003.1						
		Tails	971.27						
	2	C1	6.35	6.35	108.0	5.59	56.58	4.61	17.79
50 g/t SIBX	6	C2	3.49	9.84	192.1	4.02	63.11	5.9	35.33
300 g/t Guar	12	C3	3.04	12.88	275.5	3.23	66.3	5.52	43.26
50 g/t D250	20	C4	3.61	16.49	383.5	2.61	68.54	4.76	47.77
1 SPW		Feed	1010.43						
		Tails	993.94						
	2	C1	5.12	5.12	90.30	6.67	55.44	4.700	14.45
50 g/t SIBX	6	C2	3.24	8.36	169.1	4.61	62.52	6.23	31.3
300 g/t Guar	12	C3	3.2	11.56	243.2	3.53	66.15	6.00	41.69
50 g/t D250	20	C4	3.65	15.21	346.0	2.78	68.61	5.16	47.19
1 SPW		Feed	985.01						
		Tails	969.80						

Test conditions	Time (mins)	Sample	Solids Rec (g)	Cum Solids Rec (g)	Cum Water Rec (g)	Cum Cu Grade (%)	Cum Cu Rec (%)	Cum Ni Grade (%)	Cum Ni Rec (%)
	2	C1	1.66	1.66	2.930	9.60	23.98	6.45	6.160
150 g/t SIBX	6	C2	6.57	8.230	56.68	4.36	54.04	6.01	28.46
100 g/t Guar	12	C3	8.86	17.09	130.7	2.45	63.00	4.32	42.46
50 g/t D250	20	C4	10.92	28.01	270.5	1.59	67.05	2.92	46.99
1 SPW		Feed	1011.88						
		Tails	983.87						
	2	C1	1.59	1.59	1.880	7.77	16.71	8.33	6.100
150 g/t SIBX	6	C2	5.63	7.22	48.39	4.08	42.48	8.26	32.78
100 g/t Guar	12	C3	8.76	15.98	118.2	2.74	63.95	6.30	44.43
50 g/t D250	20	C4	10.87	26.85	248.4	1.89	74.46	4.69	50.01
1 SPW		Feed	997.43						
		Tails	970.58						
	2	C1	3.1	3.1	31.43	7.77	36.77	8.33	15.24
150 g/t SIBX	6	C2	3.64	6.74	95.71	5.22	53.66	8.28	32.95
300 g/t Guar	12	C3	2.88	9.620	164.6	4.14	60.83	7.20	40.93
50 g/t D250	20	C4	3.75	13.37	258.3	3.16	64.5	5.84	46.10
1 SPW		Feed	986.34						
		Tails	972.97						
	2	C1	4.74	4.74	46.41	5.89	44.58	9.82	25.04
150 g/t SIBX	6	C2	3.5	8.24	112.8	4.41	57.53	8.66	39.73
300 g/t Guar	12	C3	2.4	10.64	154.2	3.72	62.47	7.51	44.73
50 g/t D250	20	C4	3.09	13.73	239.3	3.01	65.14	6.24	48.14
1 SPW		Feed	995.89						
		Tails	982.16						

Test conditions	Time (mins)	Sample	Solids Rec (g)	Cum Solids Rec (g)	Cum Water Rec (g)	Cum Cu Grade (%)	Cum Cu Rec (%)	Cum Ni Grade (%)	Cum Ni Rec (%)
	2	C1	9.13	9.13	97.03	4.21	59.3	6.21	33.63
50 g/t SIBX	6	C2	8.56	17.69	231.3	2.49	67.99	4.44	46.64
100 g/t Guar	12	C3	9.81	27.50	391.1	1.68	71.39	3.11	50.72
70 g/t D250	20	C4	10.79	38.29	556.4	1.24	73.45	2.35	53.36
1 SPW		Feed	980.06						
		Tails	941.77						
	2	C1	9.98	9.98	108.8	4.01	59.71	5.27	29.84
50 g/t SIBX	6	C2	8.32	18.30	234.3	2.43	66.38	3.92	40.76
100 g/t Guar	12	C3	11.04	29.34	404.9	1.57	68.55	2.62	43.65
70 g/t D250	20	C4	10.17	39.51	543.3	1.22	71.91	2.16	48.54
1 SPW		Feed	1012						
		Tails	972.5						
	2	C1	6.45	6.45	109.8	5.64	56.15	5.40	20.13
50 g/t SIBX	6	C2	3.65	10.10	200.6	4.13	64.42	6.01	35.12
300 g/t Guar	12	C3	3.43	13.53	286.8	3.23	67.54	5.4	42.21
70 g/t D250	20	C4	4.06	17.59	417.9	2.56	69.58	4.52	45.92
1 SPW		Feed	1008.3						
		Tails	990.71						
	2	C1	5.33	5.33	95.87	6.46	54.37	5.05	15.89
50 g/t SIBX	6	C2	3.5	8.830	184.9	4.50	62.78	6.07	31.63
300 g/t Guar	12	C3	3.43	12.26	274.2	3.40	65.9	5.47	39.6
70 g/t D250	20	C4	3.92	16.18	403.0	2.66	67.98	4.63	44.20
1 SPW		Feed	1002.37						
		Tails	986.19						

Test conditions	Time (mins)	Sample	Solids Rec (g)	Cum Solids Rec (g)	Cum Water Rec (g)	Cum Cu Grade (%)	Cum Cu Rec (%)	Cum Ni Grade (%)	Cum Ni Rec (%)
	2	C1	9.20	9.20	89.21	3.96	56.62	6.20	32.84
150 g/t SIBX	6	C2	8.40	17.60	217.7	2.38	65.21	4.42	44.72
100 g/t Guar	12	C3	8.90	26.50	355.9	1.67	68.8	3.18	48.46
70 g/t D250	20	C4	10.88	37.38	542.8	1.23	71.19	2.38	51.25
1 SPW		Feed	995.45						
		Tails	958.07						
	2	C1	6.75	6.75	61.99	4.77	51.28	4.99	20.39
150 g/t SIBX	6	C2	8.55	15.30	184.1	2.61	63.57	4.12	38.22
100 g/t Guar	12	C3	10.13	25.43	327.7	1.68	68.13	3.01	46.36
70 g/t D250	20	C4	11.65	37.08	510.4	1.18	70.05	2.18	48.93
1 SPW		Feed	1010.5						
		Tails	973.45						
	2	C1	5.15	5.15	62.57	5.61	48.78	8.37	25.37
150 g/t SIBX	6	C2	3.53	8.68	147.3	4.09	59.99	7.10	36.29
300 g/t Guar	12	C3	3.51	12.19	254.1	3.08	63.44	5.72	41.02
70 g/t D250	20	C4	4.42	16.61	392.2	2.35	66.03	4.60	44.93
1 SPW		Feed	974.15						
		Tails	957.54						
	2	C1	6.05	6.05	85.43	5.46	49.84	8.03	26.67
150 g/t SIBX	6	C2	3.63	9.680	174.9	4.02	58.77	6.81	36.17
300 g/t Guar	12	C3	3.62	13.30	255.1	3.10	62.11	5.69	41.54
70 g/t D250	20	C4	5.02	18.32	397.2	2.33	64.44	4.54	45.60
1 SPW		Feed	1021.2						
		Tails	1002.9						

Test conditions	Time (mins)	Sample	Solids Rec (g)	Cum Solids Rec (g)	Cum Water Rec (g)	Cum Cu Grade (%)	Cum Cu Rec (%)	Cum Ni Grade (%)	Cum Ni Rec (%)
	2	C1	8.29	8.29	102.0	4.61	59.88	6.47	30.97
50 g/t SIBX	6	C2	5.77	14.06	210.3	3.00	66.10	5.13	41.67
100 g/t Guar	12	C3	8.81	22.87	371.1	1.95	69.68	3.64	48.02
50 g/t D250	20	C4	9.93	32.80	555.9	1.40	71.84	2.68	50.77
5 SPW		Feed	997.26						
		Tails	964.46						
	2	C1	5.92	5.92	62.23	5.74	54.32	7.43	24.83
50 g/t SIBX	6	C2	5.79	11.71	165.6	3.36	62.98	5.88	38.9
100 g/t Guar	12	C3	7.87	19.58	299.4	2.14	67.12	4.19	46.28
50 g/t D250	20	C4	11.26	30.84	503.5	1.42	69.95	2.86	49.75
5 SPW		Feed	1009.6						
		Tails	978.73						
	2	C1	6.92	6.92	141.3	5.41	55.99	3.66	14.43
50 g/t SIBX	6	C2	3.23	10.15	226.9	4.14	62.78	5.18	29.95
300 g/t Guar	12	C3	3.81	13.96	330.3	3.18	66.31	5.16	41.02
50 g/t D250	20	C4	4.19	18.15	468.2	2.53	68.75	4.57	47.25
5 SPW		Feed	1013.7						
		Tails	995.58						
	2	C1	6.9	6.90	139.4	5.22	54.42	3.84	14.96
50 g/t SIBX	6	C2	3.64	10.54	235.5	3.93	62.58	5.39	32.12
300 g/t Guar	12	C3	3.77	14.31	348.8	3.06	66.17	5.32	43.00
50 g/t D250	20	C4	4.74	19.05	490.6	2.39	68.76	4.57	49.21
5 SPW		Feed	1017.8						
		Tails	998.78						

Test conditions	Time (mins)	Sample	Solids Rec (g)	Cum Solids Rec (g)	Cum Water Rec (g)	Cum Cu Grade (%)	Cum Cu Rec (%)	Cum Ni Grade (%)	Cum Ni Rec (%)
	2	C1	7.82	7.82	85.06	4.43	54.74	5.49	25.35
150 g/t SIBX	6	C2	6.78	14.60	199.6	2.74	63.14	4.53	39.05
100 g/t Guar	12	C3	8.95	23.55	350.8	1.81	67.42	3.34	46.50
50 g/t D250	20	C4	11.9	35.45	562.9	1.25	70.17	2.39	50.08
5 SPW		Feed	1008.2						
		Tails	972.76						
	2	C1	7.69	7.69	78.26	4.73	54.68	5.55	25.39
150 g/t SIBX	6	C2	7.48	15.17	198.6	2.82	64.22	4.43	40.00
100 g/t Guar	12	C3	8.93	24.10	339.4	1.89	68.47	3.32	47.56
50 g/t D250	20	C4	12.2	36.30	562.9	1.31	71.18	2.38	51.27
5 SPW		Feed	1017.7						
		Tails	981.42						
	2	C1	5.56	5.56	75.20	5.95	52.63	7.90	24.12
150 g/t SIBX	6	C2	3.43	8.990	161.0	4.16	59.55	7.01	34.58
300 g/t Guar	12	C3	4.35	13.34	290.8	3.01	63.83	5.68	41.59
50 g/t D250	20	C4	5.42	18.76	473.7	2.23	66.64	4.48	46.17
5 SPW		Feed	1011.8						
		Tails	993.03						
	2	C1	6.14	6.14	93.40	5.45	56.4	6.48	26.28
150 g/t SIBX	6	C2	3.28	9.420	181.8	3.98	63.27	6.11	37.97
300 g/t Guar	12	C3	3.43	12.85	290.0	3.09	67.02	5.31	45.04
50 g/t D250	20	C4	4.95	17.80	470.3	2.23	69.84	4.29	50.39
5 SPW		Feed	989.97						
		Tails	972.17						

Test conditions	Time (mins)	Sample	Solids Rec (g)	Cum Solids Rec (g)	Cum Water Rec (g)	Cum Cu Grade (%)	Cum Cu Rec (%)	Cum Ni Grade (%)	Cum Ni Rec (%)
	2	C1	13.49	13.49	193.1	3.19	63.9	4.61	36.30
50 g/t SIBX	6	C2	6.94	20.43	317.3	2.26	68.73	3.76	44.87
100 g/t Guar	12	C3	10.84	31.27	526.1	1.55	71.94	2.68	48.94
70 g/t D250	20	C4	13.11	44.38	793.3	1.12	74.17	2.00	51.87
5 SPW		Feed	1006.4						
		Tails	962.06						
	2	C1	12.41	12.41	193.0	3.49	63.59	5.19	37.21
50 g/t SIBX	6	C2	9.51	21.92	352.7	2.16	69.29	3.73	47.18
100 g/t Guar	12	C3	12.02	33.34	597.1	1.45	72.32	2.60	50.93
70 g/t D250	20	C4	12.43	46.37	888.3	1.09	74.25	1.99	53.42
5 SPW		Feed	1030.1						
		Tails	983.69						
	2	C1	7.07	7.07	138.2	5.37	59.31	4.48	19.12
50 g/t SIBX	6	C2	3.98	11.05	259.8	3.77	65.07	4.59	30.60
300 g/t Guar	12	C3	4.54	15.59	421.6	2.81	68.48	4.26	40.08
70 g/t D250	20	C4	5.07	20.66	628.6	2.19	70.8	3.69	45.95
5 SPW		Feed	931.75						
		Tails	911.09						
	2	C1	7.17	7.17	143.1	5.35	58.82	6.05	25.83
50 g/t SIBX	6	C2	4.06	11.23	261.7	3.73	64.34	5.19	34.69
300 g/t Guar	12	C3	4.93	16.16	440.6	2.72	67.47	4.37	42.04
70 g/t D250	20	C4	6.26	22.42	689.9	2.02	69.68	3.49	46.56
5 SPW		Feed	1005.2						
		Tails	982.73						

Test conditions	Time (mins)	Sample	Solids Rec (g)	Cum Solids Rec (g)	Cum Water Rec (g)	Cum Cu Grade (%)	Cum Cu Rec (%)	Cum Ni Grade (%)	Cum Ni Rec (%)
	2	C1	10.27	10.27	114.7	3.69	57.04	4.83	28.66
150 g/t SIBX	6	C2	8.75	19.02	260.7	2.29	65.54	3.81	41.85
100 g/t Guar	12	C3	13.39	32.41	519.7	1.43	69.95	2.54	47.47
70 g/t D250	20	C4	14.23	46.64	824.9	1.03	72.4	1.88	50.77
5 SPW		Feed	1003.5						
		Tails	956.87						
	2	C1	9.86	9.86	88.53	4.02	57.53	4.98	26.65
150 g/t SIBX	6	C2	10.54	20.40	242.4	2.24	66.44	3.72	41.18
100 g/t Guar	12	C3	12.34	32.74	456.4	1.47	69.93	2.56	45.52
70 g/t D250	20	C4	13.19	45.93	716.1	1.08	72.16	1.94	48.43
5 SPW		Feed	1077.4						
		Tails	1031.5						
	2	C1	10.61	10.61	207.3	3.64	62.36	3.8	25.77
150 g/t SIBX	6	C2	3.25	13.86	317.2	2.99	66.77	3.82	33.85
300 g/t Guar	12	C3	3.74	17.60	470.6	2.45	69.63	3.52	39.65
70 g/t D250	20	C4	5.43	23.03	725.9	1.94	71.94	3.07	45.21
5 SPW		Feed	931.39						
		Tails	908.36						
	2	C1	9.59	9.59	167.7	4.33	60.38	4.81	26.67
150 g/t SIBX	6	C2	3.18	12.77	262.8	3.50	65.01	4.86	35.86
300 g/t Guar	12	C3	4.93	17.70	428.2	2.66	68.39	4.23	43.30
70 g/t D250	20	C4	6.63	24.33	680.6	2.00	70.87	3.46	48.67
5 SPW		Feed	1011.2						
		Tails	986.83						