AN INVESTIGATION INTO THE EFFECT OF IONIC STRENGTH OF PLANT WATER ON VALUABLE MINERAL AND GANGUE RECOVERY OF A PLATINUM BEARING ORE FROM THE MERENSKY REEF

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PLAGIARISM DECLARATION

I declare that the contents of this thesis, submitted to the University of Cape Town for the degree of Master of Science in Engineering, are original and have not been submitted prior to this for an academic examination towards any qualification at this university or any other institution.

I know the meaning of plagiarism and declare that all work included in this thesis is my own. Information gathered from other sources has been appropriately acknowledged and referenced using the Harvard referencing style.

Signed: ....

Malibongwe Shadrach Manono

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SYNOPSIS

Water in mineral processing environments is an essential as it is both a transport and process medium by which processes, such as flotation of sulphides, are made possible. Over the past years the demand and concerns on water usage have increased such that the mineral processing plants are left with no options but to recycle, reuse, and reduce water within their metallurgical circuits. It is suspected that this may impact the flotation performance of certain plant units such as concentrators due to the complexity of the selective flotation of sulphide minerals from hydrophobic gangue. The process is made intricate by diverse and complex chemical interactions; the presence of ions, either as hydroxo species or precipitates in the flotation pulp adds to the complexity of the process.

As a means to better understand the influence of water recycling in the flotation of a Merensky ore; this study investigated the interactive effects of **ionic strength and ion type in plant water**, **depressant dosage and type** on the recovery and grade of copper and nickel sulphides, water recovery, floatable and entrained gangue in the flotation of a platinum bearing ore from the Merensky reef. The Pt bearing ore consists of approximately 1% sulphide minerals in the form of chalcopyrite, pentlandite, pyrrhotite and pyrite and the PGEs are strongly associated with these sulphides.

This investigation was made possible by conducting stability tests as well as batch flotation tests. The stability tests were performed in a laboratory scale froth flotation column where various ions and ionic strength conditions were added in distilled/de-ionised water to test for bubble size, foam height and collapse time. Ions common to the water system such as Na^+, Cl^-, Ca^{2+} and Mg^{2+} were chosen in this project. These ions are believed to have an impact on the flotation behaviour as they can modify the behaviour of the depressing agents. Two types of polysaccharide depressants, namely, carboxymethyl cellulose (CMC) and modified guar gum (guar), were used as these are common in industrial flotation of the PGE bearing ores. Sodium isobutyl xanthate (SIBX) and polyglycol ether, namely, Dow 200, were used as the collector and frother respectively.

Batch flotation tests were performed to investigate the effect of different ionic strength conditions on the overall flotation performance. This gave an indication of how the depressant behaviour is affected in flotation and how the froth stability was affected by the changes in the ionic strength of plant water. Both guar and CMC depressants were investigated in the batch test work. The only conditions varied were, the addition of different ionic strength plant waters in the mill, depressant type and dosage in the batch cell. De-ionised water was modified by addition of inorganic salts to give the desired ionic conditions. Stainless steel rods were used in the mill to avoid the presence of Fe^{3+} ions in the flotation system. Sulphur and XRF analysis were done to determine the amount of S, Cu and Ni recovered.

Higher solids and water recoveries were obtained at higher ionic strength. The increase in the ionic strength in the absence of any depressant caused an increase in Cu and Ni recovery. Depressant type and dosage showed a strong influence on Cu and Ni recovery. Cu recovery decreased with increasing depressant dosage, the trend of a decrease was more pronounced in CMC than guar at all ionic strength. The same trend was observed for Ni recovery. The concentrate grades decreased with the increase in ionic strength. This work showed that the total recovery of NFG increased with increasing ionic strength. However the NFG recovery per unit water recovered decreased with increasing ionic strength showing a decrease. The decreasing trend in the degree of entrainment with increasing ionic strength was more pronounced for CMC than guar. These differences were attributed to the dispersing nature of the additional electrolytes, as well as the negatively charged CMC. At all plant water types, the addition of a depressant, either CMC or guar, decreased the recovery of NFG, and the reduction in NFG recovery was improved as the depressant dosage increased from 100 g/t to 500 g/t. The depressing ability of the two selected polysaccharides was different, because at both low and higher depressant dosages, CMC was a stronger depressant than guar owing to the difference in the adsorption mechanisms. Thus the addition of a depressant resulted in significant improvements in the concentrate grades for all BMS.

The floatability of the selected Merensky ore was shown to be susceptible to ion type, as the Na^+ ions showed higher solids recoveries than Ca^{2+} and Mg^{2+}, showing a cation effect on solids recovery. This gave rise to lower concentrate grades in the presence of the monovalent Na^+ than the divalent cations, due to the increase in mass pull or solids recovery. An anion effect became evident too, as NO_3^- resulted in lower solids recovery than Cl^- andSO_4^{2-}, and this resulted in higher concentrate grades in NO_3^- solutions. From the results on the ion type investigation it is postulated that the impact of ion type floatability is dependent upon the ability of the ion to activate or prevent gangue from reporting to the concentrate.

2-phase batch floats were performed to measure the water recovery against ionic strength. Foam column tests together with the UCT Bubble Size Analyzer were conducted to measure the foam height and foam collapse time and the bubble diameter, so as to determine foamability behaviour with increasing ionic strength of plant water. The increase in the ionic strength resulted in a decrease in the 2-phase water recovery, indicating an enhancement in the foam mobility as the ionic strength increased. Also, the foam height and the collapse time increased with increasing ionic strength, whereas the pulp bubble size diameter decreased with increasing ionic strength showing bubble coalescence was significantly retarded at higher ionic strengths owing to the frother-like properties of the electrolyte solutions. However, ion type at the lowest ionic strength selected did not show any significant differences in their foamability behaviour since the water recovery and bubble size diameter did not change with ion type.

This work has shown that if water at high ionic strength is to be used, depressant dosage should be increased to counteract the effects of ionic strength on gangue recovery, as it has been shown that neither the depressant nor ionic strength has any detrimental effect on BMS recovery. The use of plant water at high ionic strength or recycle water may be used to eliminate the need for the use of high frother dosages to increase froth stability.

ABBREVIATIONS

1Plant	Standard synthetic plant water
1SPW	Standard synthetic plant water, the same as 1Plant
Al^{3+}	Aluminium cation
BMS	Base metal sulphides
$Ca(NO_3)_2$	Calcium nitrate
Ca^{2+}	Calcium cation
$CaCl_2$	Calcium chloride
$Ca(NO_3)_2$	Calcium nitrate
$Ca(NO_3)_2.4H_2O$	Calcium nitrate 4-hydrate
$CaSO_4$	Calcium sulphate
C1	First concentrate
C2	Second concentrate
C3	Third concentrate
C4	Fourth concentrate
˚C	Degrees centigrade
Cl^-	Chloride anion
CMC	Carboxymethyl cellulose
cm	centimetres
Cu	Copper
$CuSO_4$	Copper sulphate
CMR	Centre for Minerals Research
DS	Degree of substitution
g/t	grams per ton
g/mol	grams per mol
Guar	guar gum
L/min	Litres per minute
K^+	Potassium cation
Mg^{2+}	Magnesium cation

$MgCl_2$	Magnesium chloride
$Mg(OH)_2$	Magnesium hydroxide
$Mg(NO_3)_2$	Magnesium nitrate
$Mg(NO_3)_2.6H2O$	Magnesium nitrate 6-hydrate
$MgSO_4.7H_2O$	Magnesium sulphate heptahydrate
mm	millimetres
M_r	Relative molecular weight
Na^+	Sodium cation
Na_2CO_3	Sodium carbonate
NaCl	Sodium chloride
$NaNO_3$	Sodium nitrate
Na_2SO_4	Sodium sulphate
NFG	Naturally Floatable Gangue
Ni	Nickel
PAX	Potassium amyl xanthate
PGE	Platinum Group Element
PGM	Platinum Group Mineral
Po	Pyrrhotite
P.Z.C.	Point of zero charge
rpm	revolutions per minute
s	seconds
SEX	Sodium ethyl xanthate
SIBX	Sodium isobutyl xanthate
SNPX	Sodium normal propyl xanthate
TDS	Total dissolved solids
UCT	University of Cape Town
µm	Micron
XRF	X-Ray Fluorescence

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1. INTRODUCTION

1.1 Background

Restrictions on water usage have become so stringent that many mining operations are required to recycle water within their operations. Water recycling and recirculation within mineral processing plants causes an increase in the amount of dissolved ions, which increases the ionic strength of the plant water, and this may affect plant performance. It is therefore of vital importance to understand the impact that water quality may have on flotation performance. Previous studies have been done to understand the behaviour of flotation reagents on selected Merensky ores, and to develop a reagent suite that would yield maximum valuable mineral recovery and grade. In these studies it was realised that water recycling led to the presence of ions such as calcium (Ca^{2+}), magnesium (Mg^{2+}), nitrate (NO_3^{2-}), sulphate (SO_4^{2-}) and chloride (Cl^-), which could impact the flotation process by affecting the surface reactions on the mineral surfaces, changing the hydrophobicity of the mineral (Bikerman, 1953). A change in the hydrophobicity of the mineral may thus affect mineral collection. The stability of the froth zone may be affected by a change in the ions present, which in turn would affect the flotation rate and gangue recovery. This led to the development of synthetic plant water (containing inorganic ions only) in order to mimic the typical plant water analysis of a selected Merensky concentrator (Wiese *et al.*, 2005). This water with a TDS (total dissolved solids) of 1023 mg/L was then used for all further studies into industrial flotation reagents within the Centre for Minerals Research (CMR).

The Merensky reef in the Bushveld Igneous Complex in South Africa contains platinum group minerals (PGM) as well as base metal sulphides (BMS) (Malysiak *et al.*, 2004). The Merensky reef contains a consistent BMS mineral content of approximately 1%; the predominant sulphide minerals being pentlandite, chalcopyrite and pyrrhotite, and the PGMs are strongly associated with these sulphide minerals (Wiese *et al.*, 2005).

The development of economic and optimum methods for the extraction and recovery of valuable minerals from the PGMs containing ores is a significant concern in mining and metallurgical processing plants (Mustafa *et al.*, 2004). The most commonly used method is froth flotation. The selective flotation of sulphides from non-sulphide gangue minerals such as pyroxene, feldspar along with minor quantities of talc, chlorite and chromite is increasingly important to the mineral processing industry. The process is very complex; it relies on the differences in the surface properties between the desired minerals and the unwanted gangue to effect separation (Bradshaw *et al.*, 2005). The application of reagents that will selectively float sulphides from gangue is an important concept that is well developed in literature. Although the application of these reagents, in particular polymeric depressants for Merensky reef ores, is well developed, their behaviour under high ionic strength conditions is not well understood. It has been suggested that the presence of ions in the flotation system adds to the complexity of the problem. Previous work has been done on this topic using BRPM and Lonmin Merensky ore (Corin et al., 2011; Mooruth and Booley, 2009). However, unlike previous studies, this project investigates the effect of an increase in the ionic strength of plant water up to 10 times that of normal synthetic plant water on the recovery of valuable minerals and gangue from a Merensky ore. Further ionic strength conditions with reduced ions or species are investigated in an attempt to better understand the effect each ion has individually.

The objective of this project was to better understand the effect that ionic strength of the plant water, as well as individual ions, may have on the flotation performance of a platinum bearing ore from the Merensky reef. Batch flotation tests were complemented by froth column studies and the roles of the various ions in the plant water investigated.

1.2 Scope of Work

This project evaluates the flotation performance of a platinum bearing ore from the Merensky reef by analysing the grade and recovery of the elements copper, nickel, and sulphur. Entrained and floating gangue recovery during batch flotation; depressant type and dosage, and various ionic strength conditions are evaluated against the performance of the Merensky ore. Furthermore batch flotation tests are complemented by 2-phase studies using the froth column, batch cell and bubble size analyser.

A schematic representation of all the parameters that are investigated in this project is shown in Figure 1.1.The effect of different ionic strength conditions, depressant dosage and type were investigated; physical and operational parameters were not investigated in this study. Figure 1.2 shows a more simplified and summarised schematic representation of the parameters which were studied in this project.

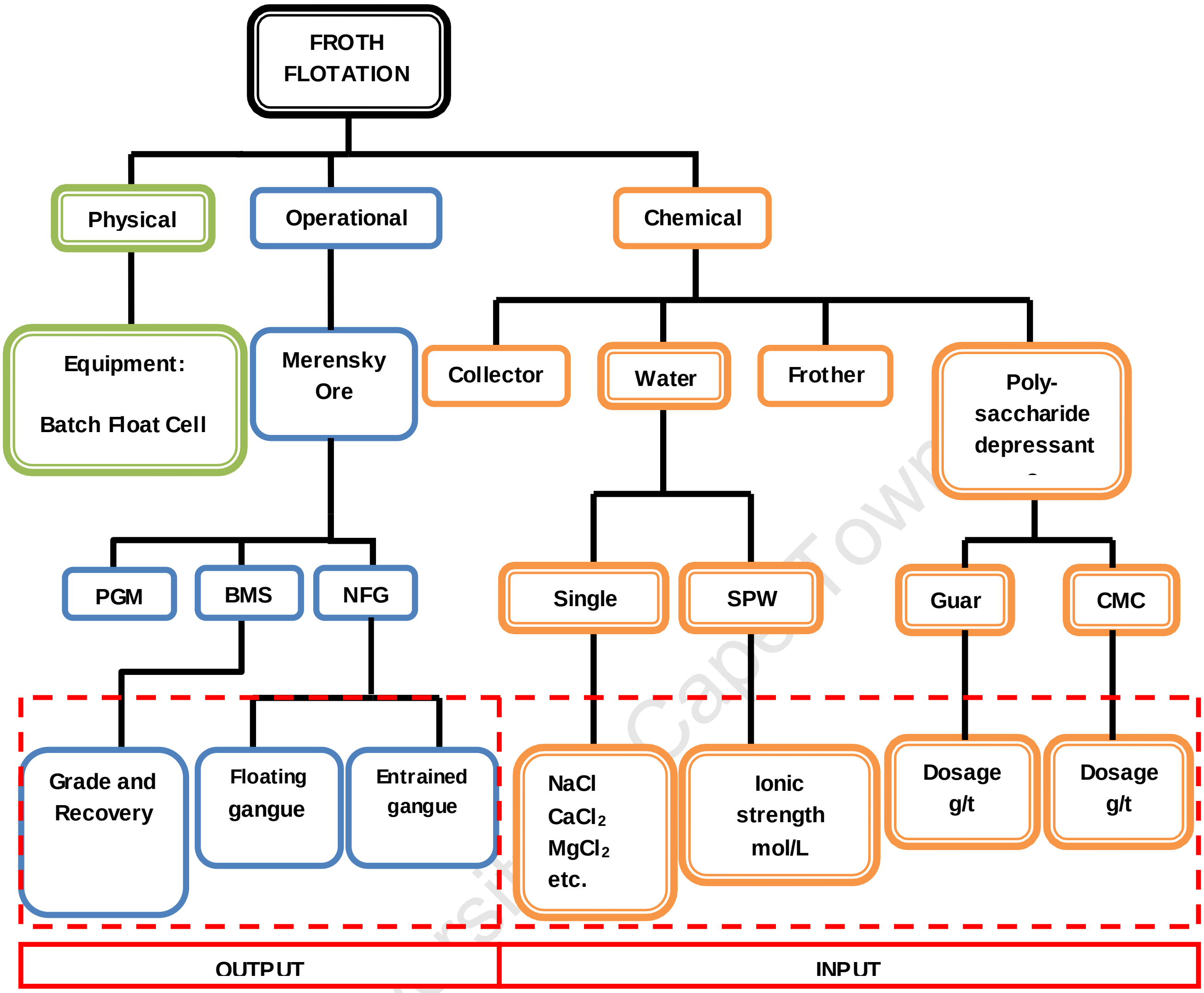


Figure 1.1: Schematic representation of the focus of this project (adapted from Wiese, 2009)

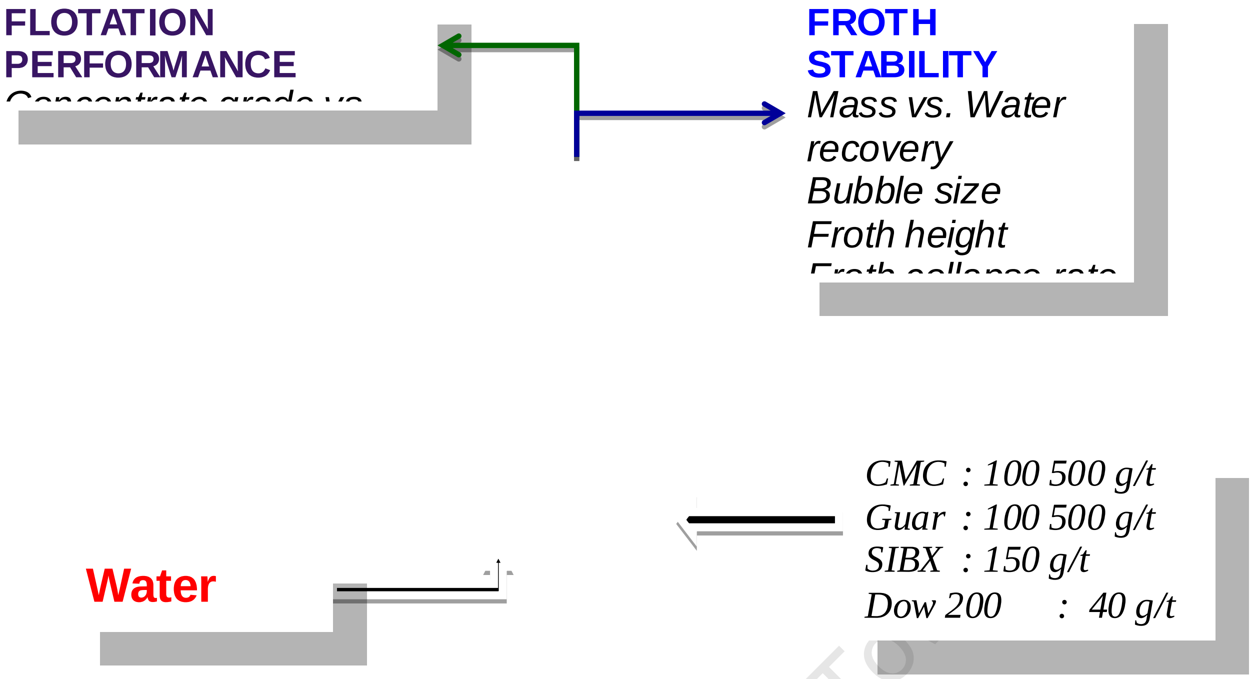


Figure 1.2: Summarised schematic representation of the parameters to be studied.

1.3 Value of Work

Various ions, e.g. Mg^{2+} and Ca^{2+} are often found in high concentrations in the process water that is recycled thought the plant. A lot of research is needed in this area to bring a fundamental understanding as to what happens between the ions and the reagents/mineral and the effect this will have on the grades and recoveries of the minerals of interest.

This work intends to give some insight into the behaviour of polymeric depressants at various dosages under various ionic strength conditions by carefully evaluating the batch flotation performance and froth stability tests, and thus predict the impact that water recycling could have on an industrial flotation process.

2. LITERATURE REVIEW

2.1 Platinum Bearing Ore from the Merensky Reef

2.1.1 Mineralogy

The Bushveld Complex in South Africa contains the world's largest deposit of PGEs. Several reefs are exploited for PGMs including the Merensky reef, UG2, and Platreef. Figure 2.1 shows the massiveness of the Bushveld Igneous Complex (BIC) with surface area of 66 000 km^2 in the central Gauteng and North West Province. This study focused on the Merensky reef. The Merensky reef consists mainly of the chromitite-pyroxene-norite triplet; however the chromite is poorly developed. The width of the pyroxenite mineral varies from approximately 60 cm to a maximum of 3 m. The Merensky reef that is found in the Western Limb of the BIC consists of a coarse-grained pegmatoidal feldspathic pyroxenite containing phlogopitic mica, with width varying from 15 – 45 cm. Thin chromitite layers mark the top and bottom of the contacts of the coarse-grained material, and above this layer is a brownish pyroxenite that is approximately 60 cm thick known as the Merensky pyroxenite. Typical mineralogy of a platinum bearing ore from the Merensky reef is given in Table 2.1.

Table 2.1: Typical Mineralogy of a Merensky ore (Liddell et al., 1986)

Mineral	*Abundance (%)*
Talc	0.5 - 2
Feldspar	20 - 40
Pyroxene	50 - 70
Sulphides	<1
Other	6-7

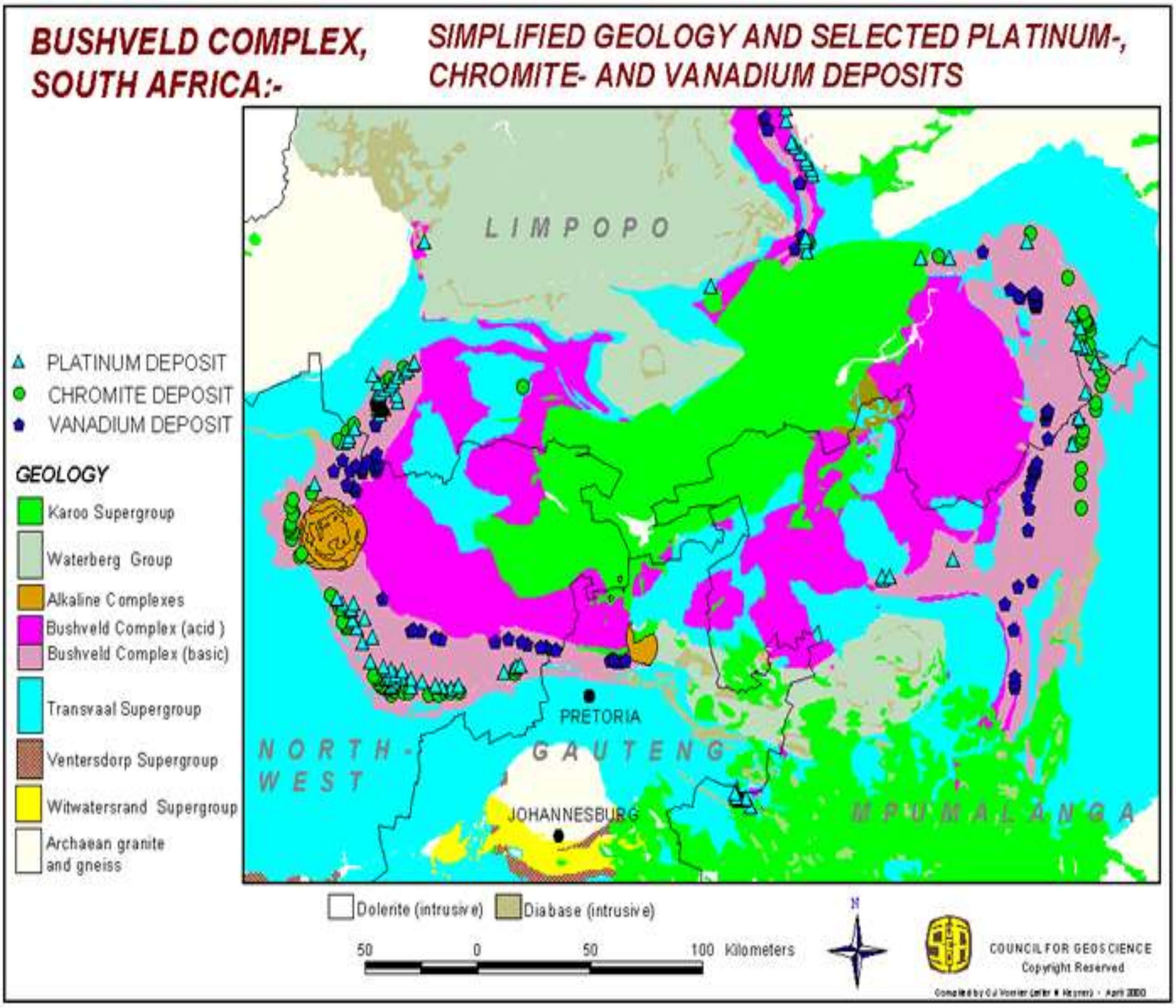


Figure 2.1: Bushveld Igneous Complex (BIC) South Africa (http://www.northern-shield.com/bushveld.html)

2.1.2 Valuable Minerals

The PGMs often occur in association with the (BMS). The PGEs include platinum (Pt), rhodium (Rh), palladium (Pd), ruthenium (Ru), iridium (Ir) and osmium (Os), and together with gold (Au) and silver (Ag) are known as the precious metals. The Merensky reef consists of three major BMS, namely, pyrrhotite ($Fe_{1-x}S$), pentlandite ($Fe_9Ni_9S_8$), and chalcopyrite ($CuFeS_2$), and are here given in their order of decreasing abundance. Substantial amounts of the PGMs are associated with these base metal sulphides, thus the Merensky reef yields copper, iron, and nickel as by-products. These are not restricted to the Merensky reef, but are disseminated for some way into the hanging wall pyroxenite and the footwall norite (Hochreite *et al.*, 1985). The Merensky horizon varies though the BIC, and therefore alterations in the amounts of PGMs and BMSs occur. The map presented in Figure 2.2 shows the locality of the BIC and some PGM mining operations.

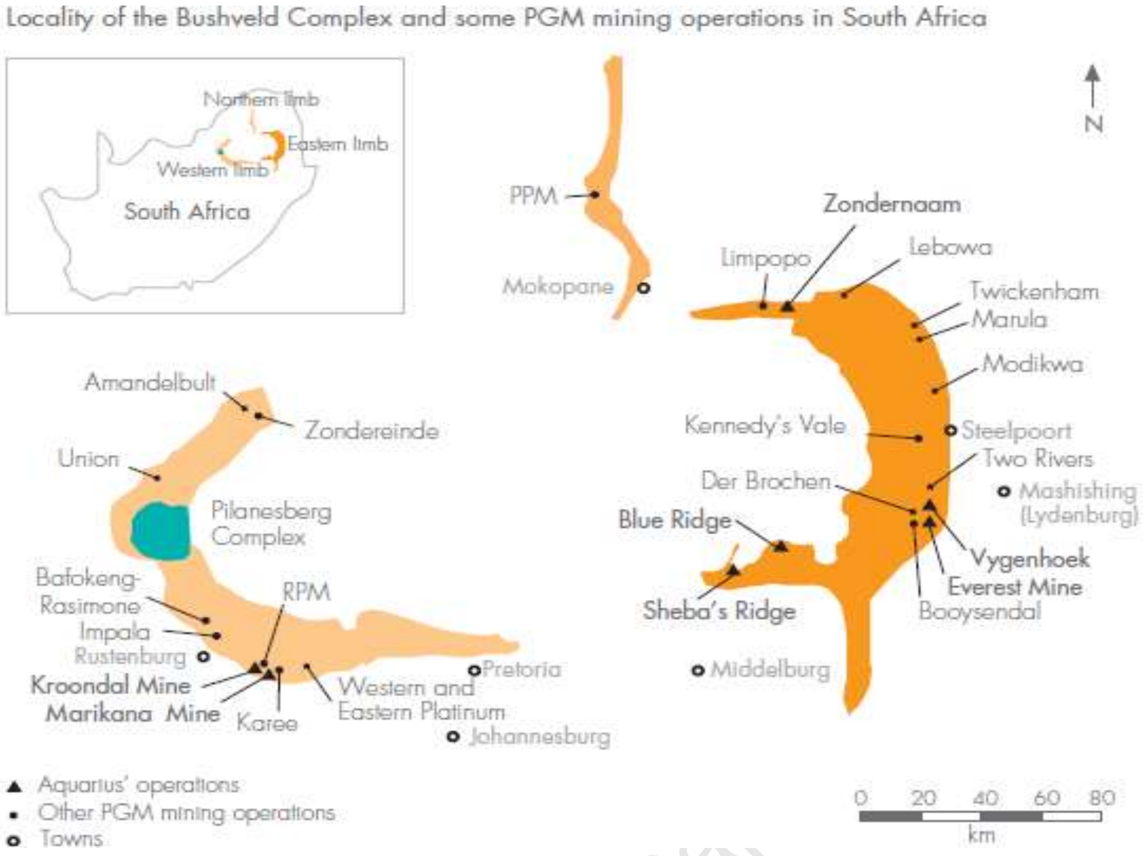


Figure 2.2: PGM Mining Operations in South Africa (http://www.aquariusplatinum.com)

The platinum bearing ores from the Merensky reef contain approximately 1 % BMS. The BMS content is typically, pyrrhotite at 45 %, pentlandite at 32 %, and chalcopyrite at 16 % (Liddel *et al.*,1986). The PGMs are strongly associated with these sulphide minerals. These sulphide minerals have a lattice crystal structure with covalent bonds which are broken during grinding to form fresh surfaces (Dalvie, 2001; Dippenaar and Harris, 1978; Lovell, 1976). These freshly formed surfaces after wet milling or grinding are highly reactive, and oxidised readily in the presence of oxygen and water.

2.1.3 Gangue

Gangue minerals are the unwanted minerals in the flotation of sulphide minerals for the recovery of the PGMs. These are present in the Merensky reef ores as silicates. They are the most abundant minerals in the earth's crust. Silicates occur as gangue minerals in many ore deposits. They form a group of minerals of great chemical and physical complexity. In Table 2.1 it is shown that the Merensky ore contains a large amount of gangue material such as pyroxene, feldspar and talc. The silicates range from simple structures like quartz to more complex ones such as talc. Most of these minerals are naturally floatable (Fuerstenau, 1982). Table 2.3 gives a more detailed ore composition of the silicates. These minerals range from having a hydrophobic surface, a fixed surface charge, and extensive metal surface sites; to having broken Si-O bonds that control surface behaviour. Formation of an electrical double layer at the interface between silicate minerals and an aqueous medium has long being considered to be controlled by broken –Si-O and –M-O bonds at the surface of the mineral, where M is a metal, e.g. Al in the case of aluminosilicates (Fuerstenau, 1982).

Table 2.2: Silicate Minerals Composition in the Merensky reef ores (Liddell et al., 1986)

Mineral	*Composition (%)*
Orthopyroxene	60
Plagioclase feldspar	20
Pyroxene	15
Phlogopite	5
Olivine, Talc, Serpentine, Chlorite	Varies

Talc is responsible for the majority of the naturally floatable gangue material though it is present in small quantities in the Merensky ore. The pyroxene contains small amounts of talc within its veins or on its surfaces in the form of talc rims (Wiese *et al.*, 2008). Since froth flotation depends on mineral surface properties, the presence of talc and its associated veins and rims play a significant role, thus talc has a disproportionate effect on gangue floatability.

2.2 Froth Flotation

Flotation is a complex physico-chemical separation process that utilises the differences in surface properties of materials to separate valuable minerals from unwanted gangue (Schulze, 1984). Figure 2.3 shows a simplified schematic diagram of the flotation process. There are two distinct zones in the flotation process, the pulp phase in which mineral recovery occurs, and the froth zone in which the concentrated valuable minerals are separated from the bulk (Goodall, 1992). Particles suspended in a flotation pulp report to the concentrate as a result of two distinct mechanisms, namely, true flotation and entrainment (Laskowski, 1998; Klimpel and Isherwood, 1991; Zieminski *et al.*, 1967).

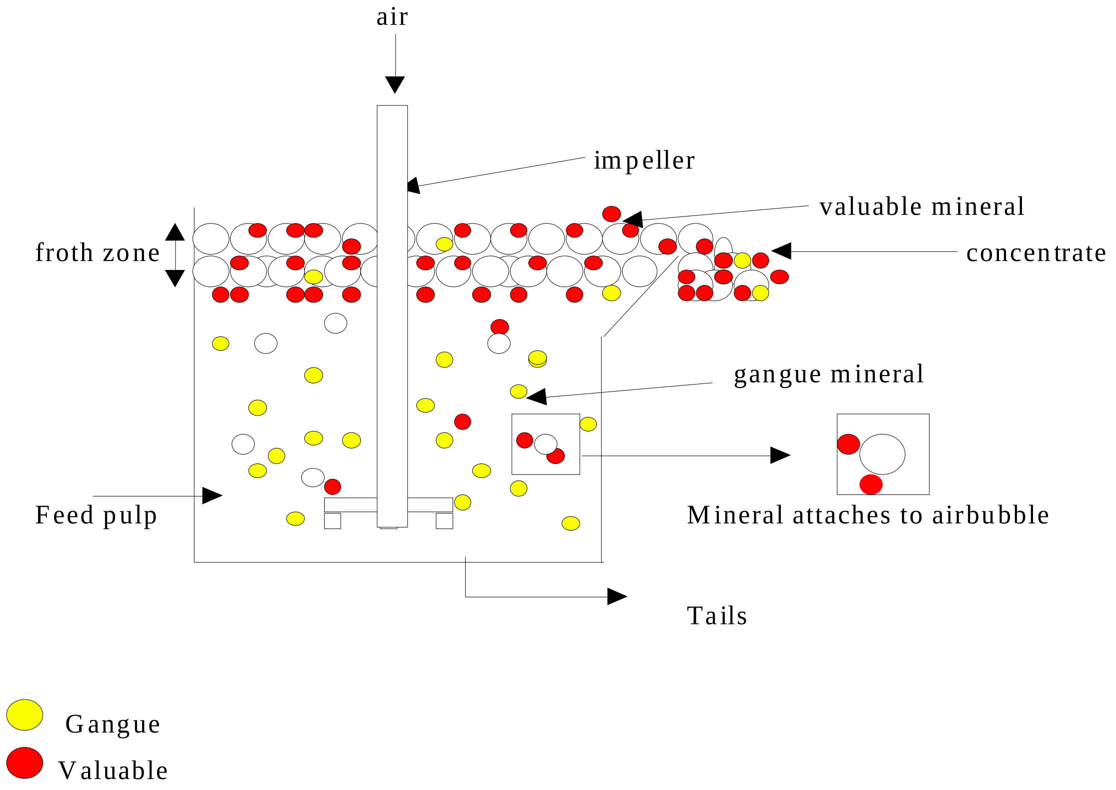


Figure 2.3: Schematic of Flotation (Martinovic, 2004)

2.2.1 Flotation Fundamentals

Froth flotation is a process used to separate minerals, suspended in liquids, by attaching them to gas bubbles to provide selective levitation of the solid particles (Harris, 1982). It is the most extensively used process for the separation of minerals, to concentrate ore for economic smelting. Rock from the mine is typically crushed and milled to below 100 µm and the subsequent fine, mineral slurry is contacted with air in a flotation circuit.

Bulk flotation is a term that covers nearly all the normal rougher or scavenger flotation, where a single mineral or a group of related minerals is separated from gangue and other low value minerals in a single flotation step.

Differential flotation describes the separation of complex ores, and is generally restricted to describing the separation of similar minerals from each other (e.g. copper, lead, zinc, cobalt and silver) where the successful and economic recovery of each component involves the sophisticated use of collectors, depressants and flotation activators (King, 1982). Floatable minerals can be classified into polar and non-polar types (Wills, 1992). The segregation into these two types of minerals is based on their surface bonding. The surface of non-polar minerals have relatively weak molecular bonds, are difficult to hydrate, and as a consequence such minerals are hydrophobic.

Non-polar minerals include graphite, sulphur, diamond, coal, and talc, which are all naturally floatable in the pure state. The ores containing these minerals for beneficiation usually require the addition of non-specific collectors to their pulp to aid natural hydrophobicity of the floatable fraction. Polar minerals (e.g. oxide minerals) have a strong covalent or ionic surface bonding, and exhibit high free energies at their surfaces. Therefore, surface hydration is rapid due to the strong reaction with water molecules, which form multi-layers on the mineral. Thus these species are hydrophilic and need surface modifiers to render them amenable to flotation (Fuerstenau, 1982).

2.2.2 Mechanism of Flotation

There are two distinct zones in the flotation process: The *pulp zone*, in which the mineral recovery occurs and the *froth zone*, in which the concentrated mineral is separated from the bulk as shown in Figure 2.3 (Goodall, 1992). Particles can either reach the froth by being attached to the bubbles, true flotation or by entrainment in the physical movement of the water passing from the pulp zone to the froth zone (Laskowski, 1998; Liddell *et al.*, 1986).

While the former process (true flotation) is selective and is responsible for the collection of the hydrophobic valuables, the latter (entrainment) is unselective and results in unwanted gangue reporting to the flotation concentrate (Smith and Warren, 1989; Yianatos *et al.*, 1988)). It is thus desirable to maximise the recovery by true flotation and to minimise the contribution by entrainment. The contribution of the entrained material to overall flotation increases linearly with an increase in water recovery (Warren, 1985).

The froth zone provides the environment for the separation of the valuable mineral from the gangue, allowing drainage of the entrained material back into the pulp (Harris, 1982). It is very critical for the flotation system to exhibit optimum froth stability for optimum flotation performance (Wiese *et al.*, 2011). When the froth is not stable enough, the bubbles rupture before collection, when the froth is too stable, not enough drainage occurs and the water and gangue recoveries are too high. The nature and dosage of the frother as well as the nature of the particles in the froth affect the stability (Wiese *et al.*, 2010; Finch and Smith, 1979; Dippenaar and Harris, 1978).

In the flotation process a physical separation of minerals is achieved by the use of chemical reagents. These reagents are chosen so that they will impart a hydrophobic character to the minerals to be floated and a hydrophilic character to the unwanted gangue when the mineral-containing ore is conditioned with them (Lovell, 1982).

This hydrophobic coating may consist of only a monolayer of molecules, or may even consist of multi layers of molecules on the surface of the mineral. When air is dispersed and bubbled through a pulp, the particles that have acquired a hydrophobic coating will adhere to the air bubbles rising through the pulp to a froth layer that forms at the top of the flotation cell. This froth layer can then be removed and usually becomes the concentrate. Hydrophilic particles remain in the pulp within the flotation cell and are discarded to the tails.

In an ideal flotation separation of minerals and gangue, the collector should be adsorbed only onto the surfaces of the desired mineral particles. In other words, the collecting agent would ideally be capable of a precise, selective separation between the wanted and unwanted minerals. Although much research has been carried out to produce such specific collectors, the majority of the collectors in use today are not completely selective in their action (Bradshaw *et al.*, 1998).

As collectors alone cannot selectively separate minerals during flotation, use is made of particular chemical agents called depressants, which ensure that unwanted minerals such as gangue do not float by enhancing their hydrophilic character (Corin and Harris, 2010; Wiese *et al.*, 2005; Lovell, 1982).

For froth flotation to occur successfully (i.e. for a mineral particle to be selectively removed from the pulp and to report to the concentrate), a number of independent sub-processes must take place (Sweet, 1999). King (1982) identified three broad areas that cover the sub-processes of froth flotation. These three areas are conditioning, particle collection and froth removal, and each of these will be briefly discussed.

2.2.2.1 Conditioning

A mineral is able to adsorb many flotation reagents almost instantaneously. However, a number of flotation reagents require some time to complete their reaction with the mineral surface. This period of time is referred to as conditioning time and the process as conditioning (Sweet, 1999).

2.2.2.2 Particle Collection

Air is introduced into the cell after appropriate reagent conditioning; an impeller is used not only to adequately mix the pulp, but also to disperse the bubbles throughout the cell. Collisions between bubbles and hydrophobic particles result in the particles becoming attached to the bubbles (Goodall, 1992; Tucker *et al.*, 1991). These particle-bubble aggregates now need to be sufficiently buoyant to rise through the pulp and reach the surface (Deglon and O'Connor, 1997). At the pulp-froth interface, particle-bubble aggregates leave the pulp and the transition to the froth phase. Hydrophilic mineral particles remain uncollected in the pulp and report to the cell tailings (Martinovic, 2004; Laskowski, 1998; Harris, 1982).

2.2.2.3 Froth Removal

As aggregates enter the froth phase they begin to rise through the froth to the surface, where they are removed from the cell as concentrate. There is also a flow of particles back into the pulp phase, as drainage of entrained gangue particles occurs, along with detachment of some of the hydrophobic particles and their subsequent return to the pulp zone (Neethling and Cilliers, 2009; Subrahmanyam and Forssberg, 1987; Warren, 1985).

2.2.3 Parameters Affecting Flotation

There are many variables which affect the flotation process, both directly and indirectly. (Crozier, 1992). Crozier (1992) listed up to 25 clearly identifiable parameters which affect froth flotation performance, although this can be more fully described by over 100 variables. Klimpel (1984) divided the major variables into three interactive groups, namely, the equipment components, the operation components, and the chemical components as shown in Figure 2.4. As this figure highlights, this project falls within the chemistry group and the primary parameter of focus is on ions.

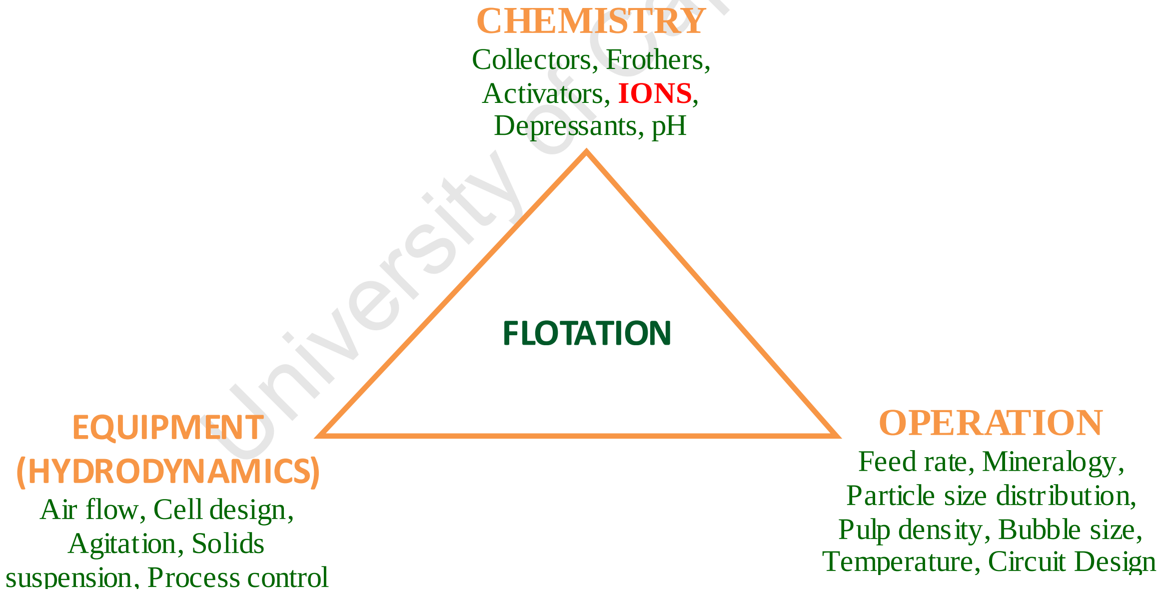


Figure 2.4: Summary of the variables in the flotation system (Klimpel, 1984)

2.2.4 Entrainment

Entrainment is a non-selective process by which particles report to the concentrate. Entrainment occurs as a result of mineral particle concentration in the pulp which enters the froth phase. It is known that particle size and shape, pulp density, particle density, water recovery, froth structure and froth residence time are the major factors affecting entrainment (Savassi *et al.*, 1998; Smith & Warren, 1989).

Savassi (1998) suggested that the ratio of the recovery of non-floating gangue to water can be used as a measure of entrainability or the degree of entrainment. The degree of entrainment has been shown to be a strong determining factor of the flotation separation efficiency between valuable minerals and gangue (Zheng *et al.*, 2006). Smith and Warren (1989) have shown that the degree of entrainment is a strong function of the particle size; however for particle sizes larger than 50 µm, the degree of entrainment depends strongly on the froth properties.

2.3 Flotation Reagents

Various reagents are used in flotation so as to manipulate the chemical environment and optimise the recovery and grade of valuable minerals, and thus optimise the flotation performance. These include among others, frothers, collectors, activators and depressants. According to Wiese *et al.* (2007) the reagent suite needs to be selected carefully for maximum PGE recovery, and an optimized BMS recovery. Reagents are added to perform specific roles that manipulate the pulp chemistry and enhance the differences in mineral surface hydrophobicity to facilitate the froth phase. Bradshaw *et al.* (2005) have shown that it is necessary to assess the behaviour of the reagent holistically and evaluate its effects both in the pulp and froth phases, as material is recovered by true flotation and by entrainment.

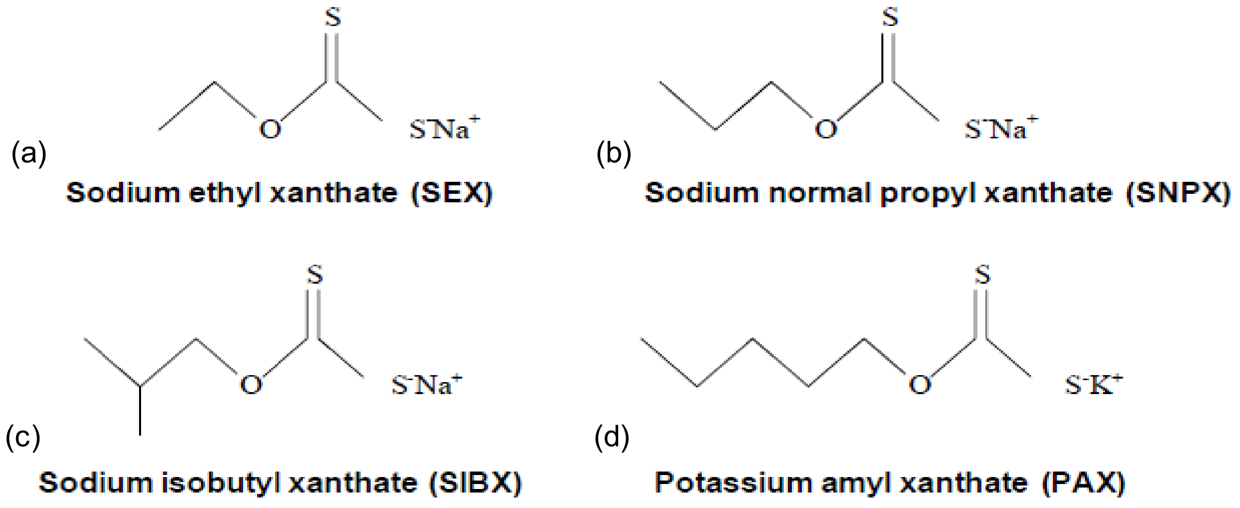
This sub-chapter provides a review of the most common industrial flotation reagents. Reagents used in froth flotation of minerals can be broadly classified into three types, namely, collectors, frothers and regulators (Lovell, 1982).

2.3.1 Collectors

King (1982) identifies collectors as chemical species which consist of a polar functional group, hydrophilic in nature and through which they attach to the mineral, and a non-polar portion, hydrophobic in character, through which they attach to the bubble, and thus enhance bubble-particle attachment. The hydrophobic tail of the collecting reagent is commonly a hydrocarbon. These reagents are useful in froth flotation in that they render the mineral hydrophobic. Collectors can in turn be classified into a number of sub-groups based on the functional group involved in the hydrophilic end of the molecule and on the type of mineral to be collected. However in this study a thorough background is given on xanthates, which are of the thiol type, as applicable for this investigation. Xanthates are the most commonly used collector in PGM industrial operations.

2.3.1.1 Xanthates

A xanthate collector, namely, sodium isobutyl xanthate (SIBX), with its structure given in Figure 2.5(c), is used in this study. Xanthates have been the most commonly used collectors in the flotation of sulphide minerals because of their efficient role in mineral collection and low cost (Wiese *et al.*, 2005; Lovell, 1982). They are known to be very good collectors for many heavy and precious metal sulphides. Ethyl, isopropyl, isobutyl, amyl, and hexyl xanthates, with structures shown in Figure 2.5, are some of the most widely used xanthates in industrial flotation of sulphide minerals (Fuerstenau, 1982).



(a) **Sodium ethyl xanthate (SEX)**

(b) **Sodium normal propyl xanthate (SNPX)**

(c) **Sodium isobutyl xanthate (SIBX)**

(d) **Potassium amyl xanthate (PAX)**

Figure 2.5: Structures of four common xanthates

Xanthates are industrially prepared from an aliphatic alcohol, carbon disulphide and an alkali hydroxide. These are non-frothing and therefore can be employed at any dosage necessary without the danger of excess frothing (Dhliwayo, 2005). Xanthates are readily soluble in water. In solution, the collector dissociates to form a metal cation and the anion made up of the hydrocarbon chain and hydrophobic head of the molecule. These are stable in the alkaline pH range of 8 - 13 and tend to hydrolyse to a weak acid in acidic medium (Poling, 1976).

2.3.2 Frothers

In the flotation of non-sulphide minerals, the collectors used are normally strong surface active agents and thereby provide their own frothing action. With sulphide flotation, however, the thiol collectors are usually not adequately surface active and hence reagents specifically designed to produce froth are necessary (King, 1982). Frothers are surface active, usually non-ionic, molecules whose function in the flotation system is to provide a large air-water interface of sufficient stability to ensure that a floated particle will not fall back into the flotation pulp before it can be removed (Lovell, 1982). It is known that frothers also have an influence on the kinetics of the attachment of the particle to the bubble (Klimpel and Isherwood, 1991; Klimpel, 1984). In many sulphides mineral flotation operations, the polyglycol ethers are the most commonly used frothers, because of their strong froth stabilising effect which also enhances the particle-bubble attachment sub-process of flotation (Sweet, 1997).

2.3.3 Depressants

Naturally floatable gangue enters the concentrate by true flotation; therefore depressants are used to increase the selectivity of the flotation process by adsorbing onto the surface of the hydrophobic gangue particles (Dhliwayo, 2005). There are many types of depressants, inorganic or organic.

Several inorganic depressants have been routinely used as flotation reagents but are extremely toxic and environmentally intolerable. Examples of these inorganic depressants are sodium cyanide, sodium dichromate and sulphur dioxide. Some of these inorganic depressants are reducing agents and thus have a tendency to oxidise in aerated flotation pulps resulting in high reagent consumption (King, 1982).

Organic depressants have been used in the mineral processing industry for almost 70 years (Laskowski *et al.*, 2007; King, 1982). These depressants are natural polymers and are non-toxic and biodegradable. These organic depressants are cheaper, environmentally friendly and more resistant to oxidation than inorganic depressants. Organic depressants are usually natural products or modified natural products of high molecular masses (above 10 000 $g.mol^{-1}$) and contain numbers of strongly hydrated polar groups, which are the basis of their depressant action (King, 1982). Organic depressants can essentially be divided into three groups, polyglycol ethers, polyphenols, and polysaccharides, such as CMC and guar gums.

In the South African platinum industry the most commonly used depressants are polysaccharides. Two classes of depressants can be distinguished: the ones that disperse (e.g. carboxymethyl cellulose (CMC)) and the ones that do not disperse (e.g. guar gum (guar)). The role of depressants is to reduce the collection of unwanted gangue material (Wiese *et al*., 2008). This is done by either enhancing the hydrophilic nature of the gangue surface or by preventing the formation of hydrophobic species on the mineral surface. Dispersants achieve this by preventing the coating of unwanted slimes on the mineral surface. Mechanisms of depression also include the formation of large aggregates and the complexation of the collector in solution (Shortridge *et al.*, 1999; Pugh, 1989).

The polysaccharides differ structurally and are often multipolar, although some are non-ionic. The mechanism of adsorption of these reagents on the mineral surface is not completely clear. Steenberg and Harris (1984) propose hydrogen bonding of the large number of hydroxyl groups to the charged sites on the mineral surface to be the adsorption mechanism of these polymers. They also reported that for hydrophilic minerals, polymer adsorption is characteristic of the polymer rather than of the composition of the hydrophilic solid surface. The conformation, which the depressant exhibits, can influence its depressant action. The charge on the molecules enhances uncoiling of the polymer chain, which improves its adsorption on the mineral surface (Wesseldijk *et al.*, 1999). A thorough literature review is given for polysaccharide type depressant as relevant for the results and discussion chapters.

2.3.3.1 Polysaccharide Depressants

The polysaccharide depressants such as CMC and guar are widely used as selective depressants for talc and siliceous materials in PGE flotation. Polysaccharides are natural products which can be modified or substituted to impart improved selectivity (Lovell, 1982). The two types of polysaccharide depressants selected for this investigation CMC and guar have found widespread use in the processing of PGM ores in the BIC in South Africa. In some cases, these depressants constitute the largest plant reagent cost (Shortridge, 2002).These are vital polymers made up of many monosaccharide units with an average molecular mass of 3 – 6 x 10^5 g/mol. These long chain molecules contain many hydroxyl groups, which allow them to form strong hydrogen bonds with the water molecules, this feature is essential in rendering naturally hydrophobic gangue hydrophilic upon adsorption of the depressant (Laskowski *et al*., 2007; Steenberg and Harris, 1984). The difference in structure and charge of these depressants as illustrated in Figure 2.6 and 2.7 influences their adsorption onto gangue minerals and the mechanism of depression of natural floatable gangue.

2.3.3.1.1 Carboxymethyl Cellulose

CMCs are anionic linear polymers of β-anhydroglucose units industrially prepared from cellulose. CMC's are generally classified according to three properties (Burdukova, 2007). The first property is the "Active content" which indicates the percentage CMC in a particular product. Typical CMC's used in flotation are not purified and are thus about 70 % CMC by weight, the remaining mass being glycolates and salt. The second characteristic of a polymer is the molecular weight, or the degree of polymerisation. This can be controlled in the modification process for CMC. Molecular weight is typically in the order of 10^5-10^6 g/mol for CMC (Shortridge, 2002). The viscosity of the polymer in solution is proportional to the molecular weight.

A third characteristic of CMC is the degree of carboxymethyl substitution. This affects the charge of the polymer in solution since the carboxyl group becomes negative in solution and needs at least a degree of substitution of 0.5 for sufficient solubility (Khraisheh *et al.*, 2005). The degree of substitution (DS) is defined as the number of hydroxyl groups in the anhydroglucose unit which have reacted to form derivatives (Dhliwayo, 2005; Pugh, 1989). CMC has a DS of up to 3, but usually the DS range for commercially available CMC is approximately 0.5-1.5, and this parameter affects the extent to which the CMC can dissolve in polar solvents such as water (Wiese, 2009).CMC contains carboxymethyl functional groups which render it negatively charged in solution. Hence, the adsorption of CMC onto a particle surface renders it negatively charged too. If particles are all negatively charged they repel one another and tend to be dispersed, or become independent of one another. Increased dispersion has shown to increase the recovery of valuable minerals through cleaning the surfaces of slimed particles. The recovery of gangue is reduced through rendering natural floatable gangue (NFG) non-floatable (Robertson, 2003). Shortridge *et al.* (2003) have shown that the depression of gangue minerals such as talc is improved in the presence of divalent cation such as Mg^{2+} and Ca^{2+}, and that the ionic strength of the solution plays a crucial role in CMC adsorption onto talc.

CMCs have been widely used in the flotation of sulphide minerals to depress natural floatable gangue such as talc, and its orthopyroxene/talc composite (Becker *et al.*, 2009). Figure 2.6 shows the structure of a CMC molecule.

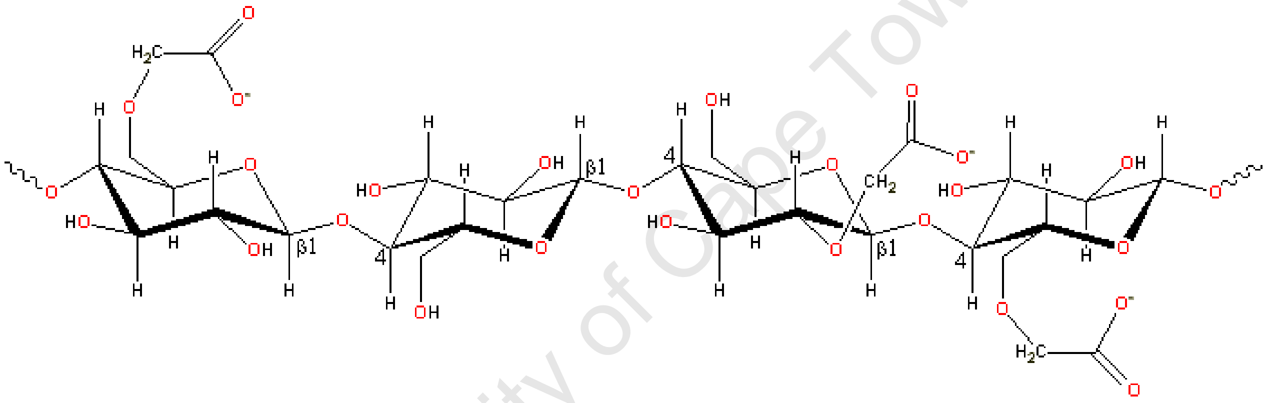


Figure 2.6: Partial structure of a CMC molecule. (http://www.lsbu.ac.uk/water/hycmc)

2.3.3.1.2 Guar Gum

Guar gum is a branched polysaccharide belonging to the group of galactomannans. It consists of β-D-mannose monomers attached to α-D-galactose units as shown in Figure 2.7. Guar has a low degree of substitution yet is soluble in water. It is thought that the cis-configuration of the hydroxyl groups and the branched nature of the guar increase the solubility (Dalvie, 2001). Guars are characterised as being long-chain, viscous polymers.

Guar gum molecules are non-ionic in solution and give high viscosity aqueous solutions (Pugh, 1989). These promote the opposite effect of dispersion; coagulation. This arises from their ability to attach themselves onto more than one particle surface as there are no like charges to create repulsion. Thus the effect of coagulation from using guar gum mimics the effect one would observe in changing the particle size. In essence, the more coagulated a pulp suspension is, the greater the particle size.

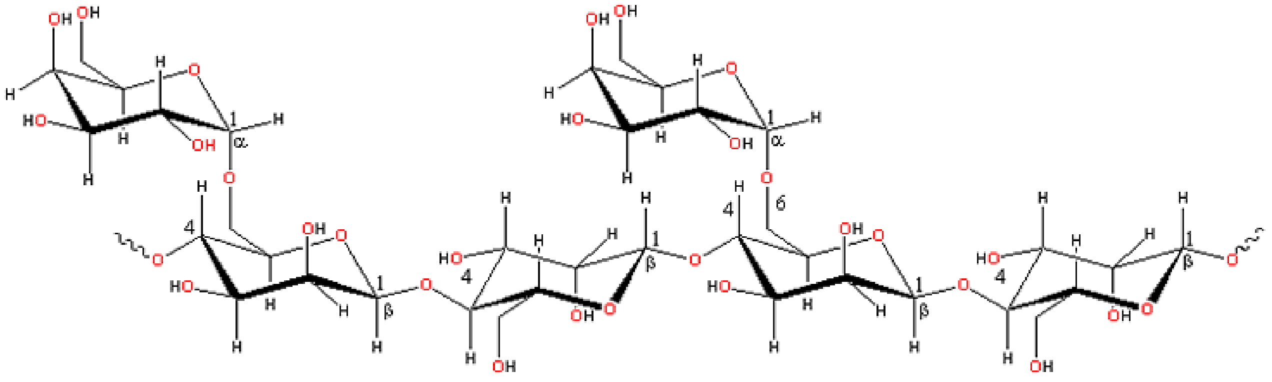


Figure 2.7: Partial Structure of a guar gum molecule. (http://www.lsbu.ac.uk/water/hyguar)

2.3.3.2 Interaction of Polysaccharides and Mineral Surfaces

Interactions of polymers with gangue surfaces are very complex and not well understood. The adsorption interactions proposed by many authors include electrostatic interactions, hydrophobic and hydrogen bonding (Steenberg and Harris, 1984; Morris, 1997). The hydrocarbon backbone of the polysaccharide can cause hydrophobic interactions with gangue (e.g. talc) surfaces (Pugh, 1989). Polysaccharides possess depressant capabilities owing to their containing a large number of hydroxyl groups. Their observed depressant functions were attributed to hydrogen bonding of the hydroxyl groups to mineral surfaces. For pure polysaccharides, the hydroxyl groups are the only polar groups available in the polymer chain. However, naturally occurring polysaccharides always contain impurities, resulting in the presence of varying amounts of carboxylate, phosphate and amino acid groups which could deter the depressant activity of the polysaccharide.

In mineral suspensions the hydroxyl groups on the mineral surfaces can either donate or accept a proton, thus behaving as Bronstead acids/bases (Liu *et al.*, 2000). The Bronstead acidity depends on the metal atom to which the hydroxyl group is attached. A higher positive valence on the metal atom results in a weaker attachment between the proton and the oxygen atom thus increasing the acidity of the hydroxyl group. It has been suggested that mineral surface metal-hydroxylated species behave as a Bronstead base during the interaction with polysaccharides. The stronger the basicity of the hydroxylated group, the stronger the interaction of the mineral surface with the polysaccharide. Steenberg and Harris (1984) established that for all polymers, adsorption onto talc, a sheet silicate, occurs first on the hydrophobic basal planes and then on the talc edges. Furthermore, when the charge was measured on three polysaccharides, namely, CMC and guar different charge characteristics were observed. CMC was strongly negatively charged, whereas guar was slightly negatively charged due to its very low degree of substitution. Gangue minerals with negative zeta potential such as talc do not involve electrostatic attraction forces in the adsorption of the polymers, since both the mineral and gangue are negative (Steenberg and Harris, 1984).

Wiese (2009) has shown that the use of polysaccharides at high dosages (300 g/t to 500 g/t) can totally prevent naturally floatable gangue from reporting to the concentrate. This finding has made it possible for the Reagent Research Group (RRG) in CMR to quantify the amount of gangue that reports to the concentrate by entrainment.

2.3.4 Effect of Ions on Polysaccharide Depressant Behaviour

In most metallurgical operations the process water used in units such as froth flotation, contains high amounts of dissolved ions which contribute to the complexity of the flotation process, and these can negatively affect the efficiency of the flotation process (Slatter *et al.*, 2009). This has therefore led to many studies being carried out to determine how the presence of ions in plant water will affect the depression of NFG (Corin *et al.*, 2011; Becker *et al.*, 2009; Mooruth & Booley, 2009; Wiese, 2009; Khraisheh *et al.*, 2005; Shortridge *et al.*, 2003). It is known that polymer adsorption on talc and the subsequent depression of NFG is influenced by many variables. These include polymer type and concentration, molecular weight, degree of substitution, pH, and ionic strength (Parolis *et al.*, 2008; Shortridge *et al.*, 2003; Shortridge *et al.*, 1999; Khraisheh *et al.*, 2005). These studies have shown that in the presence of cations such as Ca^{2+} and Mg^{2+}, the depression activity of carboxymethly celluloses on talc is enhanced, however a detrimental effect of these ions is that they may activate the unwanted gangue, or depress the targeted mineral. It is therefore of vital importance to understand the behaviour of NFG targeting depressants in the presence of high ionic strength plant water so as to predict the optimum plant performance.

2.4 Water Quality

Water quality can significantly affect the performance of flotation systems. With the current environmental issues around water usage, and South Africa being a water scarce country, mining operations are required to recycle and reuse water within their operations; it is therefore necessary to understand the impact that water could have on a flotation plant and recreate alternative operating conditions at which flotation could still occur without significant impact (Corin *et al.*, 2011; Mooruth and Booley, 2009; Slatter *et al.*, 2009; Levay, 2001).

2.4.1 Ionic Strength

Ionic strength is the relation useful in comparing solutions of diverse compositions because the specific electrical effects of the interactions of the various charged ions present are taken into consideration, ionic strength gives a more useful criterion of the behaviour of a solution than does concentration (Garrels and Christ, 1990).Thus, the ionic strength of an electrolyte solution is a measure of the average electrostatic interactions of the ions in solution which may be determined by the following equation:

$$I = \frac{1}{2}\sum_{i=species}^{n} m_i z_i^2$$

Where m_i is the molality and z_i is the charge of the ith ion in solution, the summation being taken over all ions, positive and negative, present in solution (Garrels and Christ, 1990).

2.4.2 Ions and Plant Water Chemistry

Recycled water in most cases is used as make-up water, which is usually obtained from the water used in other process environments on the plant, for example the water obtained from the roasting (Ross *et al.*, 1984) and milling (Viviers, 1979) processes. According to Barker (1986) ions present in plant recirculation water can be divided into three categories:

✓ Ions common to the water system, viz., CO_3^{2-}, HCO^{3-}, Cl^-, Ca^{2+} & Mg^{2+}.

✓ Ions added during leaching, namely, H^+ & SO_4^{2-}.

✓ Ions obtained during milling and roasting, viz., Fe^{2+} & Fe^{3+}.

The anions are analysed in terms of acid-base system, and cations are analysed in terms of their complex formation. Metals in solution are hydrolysed to form intermediate species that may be unstable (Barker, 1986). The hydroxides formed, through the addition of the OH^- ions to the cation to form a complex, are relatively insoluble in alkaline solutions (Fuerstenau *et al.*, 1988).

2.4.2.1 Formation of Complexes

The cations like Mg^{2+} and Ca^{2+} have been investigated (Parolis *et al.*, 2008; Shortridge *et al.*, 2003; Iwasaki et al., 1980). These metal ions are hydrolysed in solution to form intermediate species which may be unstable. The hydroxides of these metal cations are relatively insoluble and precipitate out in alkaline conditions (Barker, 1986). The formation of the hydroxides is regarded as being the addition of ligands, viz. the OH^- ions, to a central metal ion, the cation, to form a complex.

There are two types of complexes that form, namely, mononuclear and polynuclear. In mononuclear complexes, only one metal cation is present in the complex e.g. Ca^{2+}, Mg^{2+} or Fe^{2+}. In polynuclear complexes several hydroxide complexes are formed which may contain several metal atoms e.g. hydroxides of Fe^{3+} (Fuerstenau, 1982).

In mononuclear complexes the following reactions occur in solution:

For Ca^{2+}

$Ca^{2+} + OH^{-} = Ca(OH)^{+}$

$Ca(OH)^{+} + OH^{-} = Ca(OH)_2(s)$

Similarly for Mg^{2+}

$Mg^{2+} + OH^{-} = Mg(OH)^{+}$

$Mg(OH)^{+} + OH^{-} = Mg(OH)_2(s)$

In polynuclear complexes hydrolysis of the Fe^{3+} ions result in the formation of $Fe(OH)^{2+}$, $Fe(OH)^{2+}$, $Fe_2(OH)_2^{4+}$ and $Fe(OH)_3(s)$ in alkaline conditions.

2.5 Effect of Ions on the Flotation System

Flotation depends directly on the nature and properties of the mineral water interface. Two factors affect these properties: the interaction of water molecules with the mineral surface, and the electrical double layer at the mineral water interface. Orientated water layers at mineral surfaces have a significant effect on the wettability of minerals and also on the nature of adsorption at the interface (Fuerstenau, 1982). When the mineral surface is brought into contact with a polar medium like water, several ions from the mineral surface are transferred into solution (Klaasen & Mokrousov, 1963). This causes the mineral to become electrically charged.

Ions of the opposite charge, counter ions, in water are attracted towards the surface, whereas ions of the same charge, co-ions, are repelled from the surface. This produces an electrical double layer, a system in which by definition, there exists a separation of electrical charge at the interface, that is, the positive and negative charge, with the whole system being electrically neutral (Fuerstenau, 1982). Figure 2.8 represents a mineral surface and the electrical double layer. This is known as the Stern model of the electrical double layer (Fuerstenau, 1982; Gaudin, 1932).

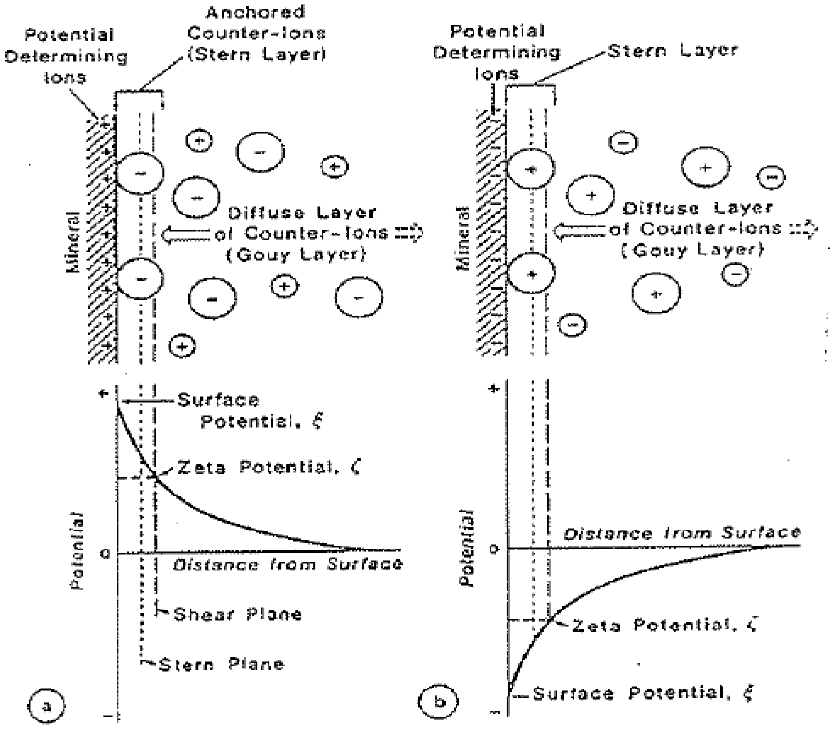


Figure 2.8: The electrical double layer at a mineral surface in aqueous solution (Fuerstenau, 1982)

These ions that are chemisorbed on the mineral surface establish the surface charge and are termed potential determining ions. The potential determining ions may be ions of which the mineral is composed, hydrogen or hydroxyl ions, collector ions that form insoluble salts with ions in the mineral surface, or ions that form complex ions with the ions on the mineral surface (Fuerstenau and Mishra, 1980; Klaasen & Mokrousov, 1963).

The surface charge on a mineral is determined by the adsorption density of the potential determining ions on the mineral surface. The adsorption of ions from solution at the mineral water interface is dependent on the chemical composition and the structure of the mineral surface and the electrical double layer at the interface. The adsorption can be due to chemical reactions between the adsorption species and the ions comprising the mineral surface, that is, chemisorptions, or it can be physical adsorption of counter ions in the double layer (Fuerstenau, 1982).

In a study of the adsorption of the collector sodium dodecyl sulfonate on alumina, the adsorption isotherm and the corresponding zeta potential data shown in Figure 2.9 were reported (Kelly and Spottiswood, 1982)

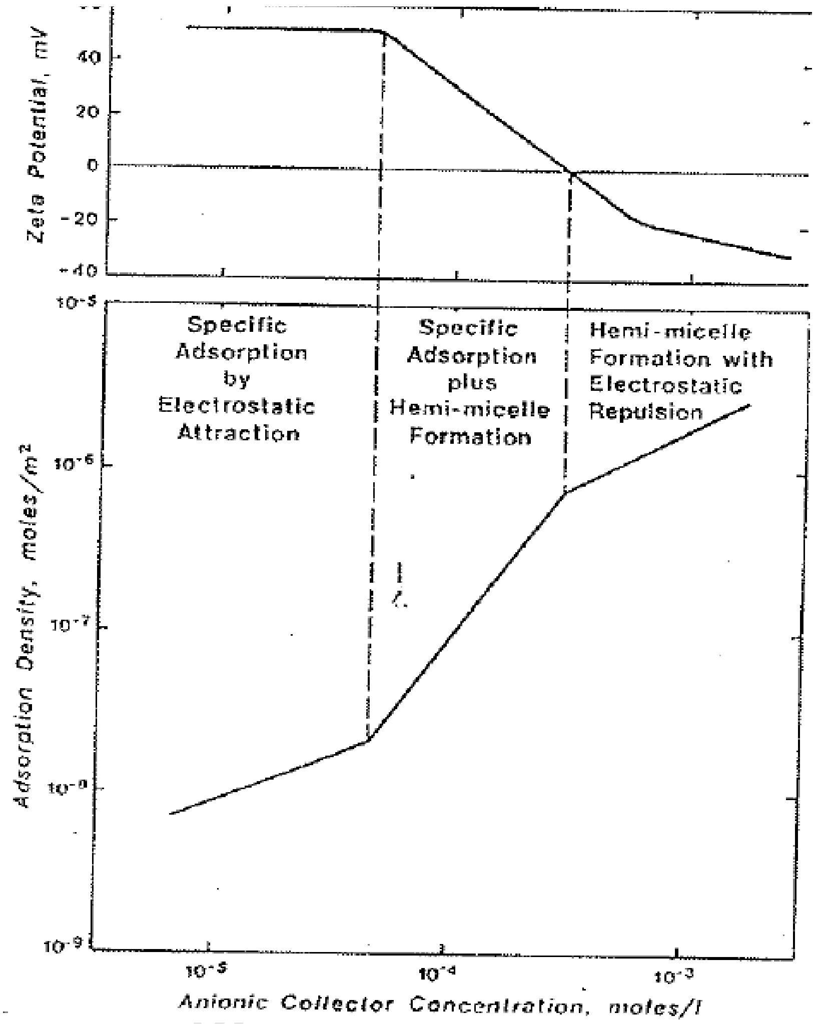


Figure 2.9: Adsorption isotherm and corresponding zeta potential

The adsorption isotherm has three distinct regions where the concentration of the collector is low, anions adsorb by electrostatic attraction at the positively charged alumina surface, when the concentration of the anions is increased the adsorption density becomes sufficiently high for interaction between the hydrocarbon chains to occur. This results in hemi-micelle formation (Kelly and Spottiswood, 1982). Once the ions of a collector reach a concentration at the mineral water interface of about the same level as the critical micelle concentration of the bulk solution, the adsorbed ions associate into patches on the mineral surface in much the same way as micelles form in the bulk solution, this is shown in Figure 2.10.

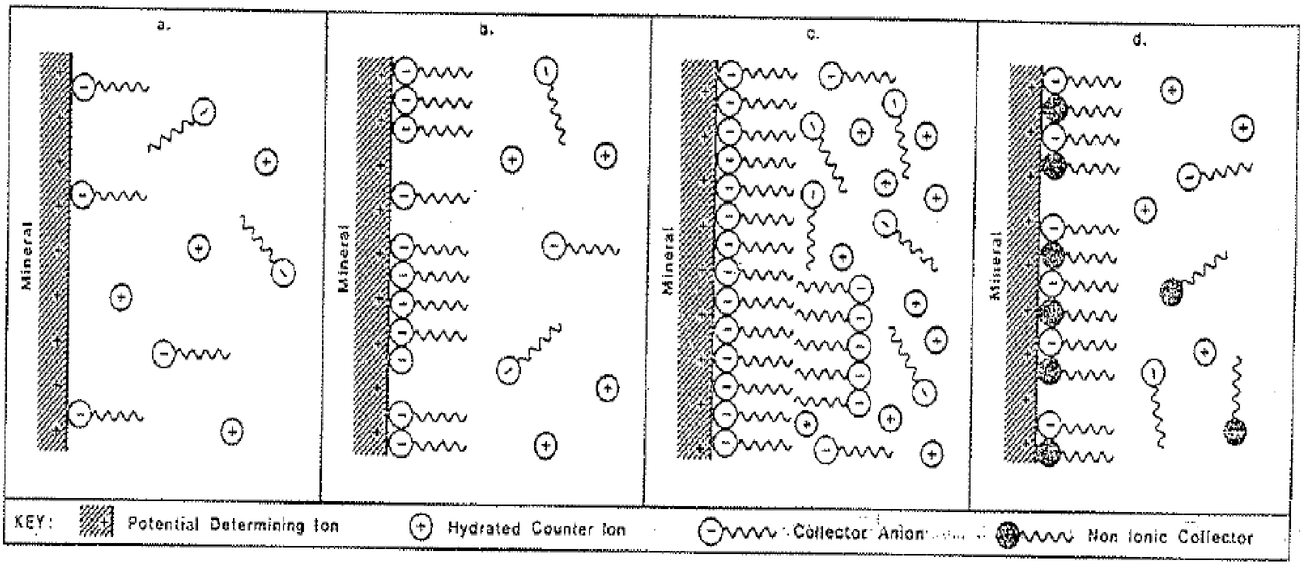


Figure 2.10: Schematic representation of the mineral solution interface in the presence of an anionic collector (a) Single adsorption at low concentration (b) Hemi-micelle (c) Multilayer adsorption (d) Co-adsorption of the neutral molecules (Gaudin, 1932).

The sign of the zeta potential changes from positive to negative when the concentration of the collector anion in Figure 2.10 is increased again. The electrostatic interaction opposes the specific adsorption effects, so the slope of the adsorption isotherm decreases. It should be realised, however, that adsorption continues to increase. For adsorption beyond a complete monolayer, multilayer adsorption can occur as shown in Figure 2.10, and this is clearly undesirable when a hydrophobic surface is required. Hemi-micelles, and also micelles are limited to a maximum number of surfactant ions because of the electrostatic repulsion between the charged “heads” of the ions. Figure 2.10 (d) represents the lowering of the critical micelle concentration at the mineral surface. Changes in zeta potential can show the effects of the adsorption of ions whether by electrostatic attraction, chemisorptions or chemical reaction. The relationship between the electrophoretic velocity and zeta potential depends on the magnitude of the product K_a, which is, relative magnitudes of the particle radius and a double layer thickness. The zeta potential value can be reduced either by change of the potential determining ion concentration or by increase in the ionic strength of the solution (Gaudin and Charles, 1953; Gaudin, 1932).

There is a qualitative parallel between flocculation and small zeta potential (attraction) and dispersion and large zeta potential (repulsion). The attachment of the mineral to the bubble consists of the following steps: the approach of the bubble to the solid, the formation of the thin water film between the bubble and the solid, the rupture of this film due to thinning, the retreat of the water and the establishment of a contact angle (Finch and Smith, 1979; Fuerstenau and Mishra, 1980). The general condition for the three phase equilibrium is defined by young’s equation for the system depicted schematically in Figure 2.11.

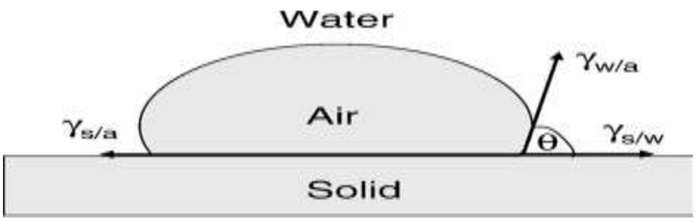


Figure 2.11: Schematic representation of the equilibrium contact between an air bubble and a solid particle immersed in a liquid (Chau *et al.,* 2009).

2.5.1 The Pulp Phase

Processes occurring in the pulp phase can be divided mainly into two parts, first the reactions between the collector and mineral to render the mineral hydrophobic; and then secondly the attachment of the mineral particles to air bubbles rising through the pulp (Goodall, 1992) (see Figure 2.3).

The formation of the hydrophobic surface is dependent on the surface properties of the mineral. Both the electrical double layer at the mineral-water interface and the interaction of water molecules with the surface affects the surface properties (Fuerstenau, 1982). Contact of the mineral water releases ions into solution and causes the surface to become electrically charged, that is, the pulp solution affects the electrical double layer. Ions of opposite charge are attracted to the surface whereas those of like charge are repelled which affects mineral-bubble attachment (Fuerstenau and Mishra, 1980).

2.5.1.1 Effect of Ions on Sulphide Minerals

The detrimental effect of ions has been associated with either depression of the target mineral or activation of the unwanted gangue (Zhang et al., 1997). In general, the effect of ions on sulphide minerals is not well documented in literature but the effect of calcium and magnesium ions on pyrite has been investigated (Barker, 1986). Calcium adsorption on pyrite is reported to increase with increasing pH and calcium concentration (Gaudin and Charles, 1953). Barker (1986) showed that an increase in the concentration of the divalent cations, calcium and magnesium, resulted in an increase in the recovery of pyrite, and a dramatic decrease in gangue recovery. The froth stability was also increased with the addition of these divalent cations. An increase in the concentration of the monovalent cation, sodium, resulted in an increase in pyrite recovery and a slight decrease in gangue recovery, and also sodium ions addition improved froth stability. A recent study by (Corin et al., 2011) on the effect of the ionic strength of plant water on a Merensky type ore showed that an increase in the ionic strength of plant water from 0.0241 to 0.0723 mol.L-1 did not affect the recovery of the sulphide minerals and that only the concentrate grades were decreased significantly as froth stability was noted to increase and thus the higher mass and water recoveries at higher ionic strength resulted into more NFG reporting to the concentrate. In an alkaline medium calcium reacts with products of sulphur oxidation and atmospheric carbon dioxide to form calcium sulphate and calcium carbonate films, these films usually increase the hydration of pyrite and thus increase the depression of pyrite (Glembotskii et al., 1972; Klaasen and Mokrousov,1963). Calcium ions added as slime used for pH adjustment are reported to contribute to the depression of gangue minerals (Burdukova, 2007; Barker, 1986; Iwasaki et al., 1980). Above pH 7, the surface of pyrite is negatively charged, and calcium adsorbs readily by electrostatic attraction. The presence of calcium ions hinders the collector to mineral reaction on the pyrite surface.

2.5.1.2 Effect of Ions on Gangue

Multivalent cations have profoundly influenced the flotation of silicates and their effects are well reported. Salts of divalent ions such as Ca^{2+} and Mg^{2+} were found to coagulate silica more readily (Yarar and Kitchener, 1970). On quartz, calcium is thought to be adsorbing as $CaOH^+$ and magnesium as the $Mg(OH)_2$ precipitate. These ions are thought to be responsible for the flocculation of quartz suspension and the depression in cationic flotation of silica in an alkaline pulp solution (Iwasaki *et al.*, 1980). Calcium has been reported to activate quartz in anionic flotation (Lloyd, 1981).

The mechanism for the adsorption of these cations is said to be due to hydrogen ions and the presence of $M\text{-}OH^+$ complexes (M being the metal ion). This results in a decrease in the negative charge of the quartz surface (Fuerstenau *et al.*, 1970; Palmer *et al.*, 1975). Activation by $M\text{-}OH^+$ ions in flotation is due to the dehydration of the surface allowing the air solid interface to hold little or no water. Metal ions are, however, adsorbed as hydrated ions. A layer of water molecules then separates the bubble from the solid thus depressing the quartz (Fuerstenau *et al.*, 1970)

Multivalent cations have the ability to hydrolyze in aqueous solutions, depending on their chemical structure and the pH and can have the following effects (Fuerstenau *et al.*, 1988):

- ✓ to reverse the zeta potential of the negatively charged oxide surfaces,
- ✓ to enhance the flotation of the negatively charged oxide minerals with anionic collectors,
- ✓ and to adsorb on positively charged oxide surfaces

Studies on floatability, coagulation, adsorption and electrokinetics have shown that the adsorption of cations increases sharply near the pH at which the metal hydrolyzes. Many researchers in this field have proposed different theories explaining the effect of ions and these are summarised below.

- ✓ Morgan and Stumm (1964) have explained the effect of the multivalent cations in terms of surface complex formation.

- ✓ Fuerstenau and Palmer (1976) have identified the metal hydroxo complexes as the responsible species.

- ✓ Hall (1966) and James and Healy(1972) have suggested that the metal hydroxides form at the solid/liquid interface itself under the conditions where the hydroxide is still soluble in the bulk solution.

The differences in the postulated theories have been attributed to the narrowness of the pH range over which hydrolysis of the metal cations and precipitation of metal hydroxides occur (Fuerstenau *et al.*, 1988)

It is suggested that for polar solids, the interfacial pH is different from that of the solution (Hall, 1966). Non polar solids like talc have the advantage that their surface charge is low and as a result the hydrogen ion activity at the solid/liquid interface must not be appreciably different from the bulk. The effects of cations on non polar solids have not received much attention (Fuerstenau *et al.*, 1988)

2.5.2 The Froth Phase

The froth phase is an important part of the flotation system. The froth phase must be of sufficient volume and stability in order to act as a good medium of separation of valuables from gangue. If the froth is too stable, the separation of gangue does not occur effectively, and if the froth is not stable enough, the recovery of valuable minerals is not achieved. In general, factors that reduce the rate of drainage of the froth films will increase the stability of the froth (Harris, 1982)

Factors affecting the stability of the froth phase can be summarised as follows:

- ✓ Surface tension of the solution: the lower the surface tension the more stable the froth. (Barbian *et al.*, 2003)

- ✓ Viscosity of the solution: the more viscous the medium, the slower the drainage of the liquid from between the bubbles and hence the slower the rate of coalescence (Stewart, 1995; Oolman and Blanch, 1986).

- ✓ Bubble size: the smaller the bubbles forming the froth, the greater the stability of the froth formed (Finch *et al.*, 2008; Harris, 1982).

- ✓ The presence of fine hydrophilic solids can stabilise the froth (Dippenaar, 1982; Bikerman, 1953).

Barker, (1986) showed that an increase in the ionic strength of solutions containing covalent ions such as Mg^{2+} and Ca^{2+} increased the kinematic viscosity. This type of increase causes an increase in the film thickness which causes slower drainage and thus a more stable froth (Harris, 1982). It has also been reported that an increase in the ionic strength of metal hydroxides increased the froth stability (Bikerman, 1953). The presence of ions in solution has also been reported to cause a decrease in the surface tension, which leads to decreased bubble sizes and increased froth stability (Barker, 1986).

3. RESEARCH KEY QUESTIONS, HYPOTHESES AND OBJECTIVES

Based on the outcomes of the literature review in Chapter 2, the following **key questions** are put forward:

- ✓ How does the increase in ionic strength of plant water affect the behavior of depressants in the flotation of the selected Merensky ore? With key factors being:
    - Mass pull
    - Water recovery
    - Entrainment
    - Valuable mineral recovery
    - Concentrate grade
- ✓ How does the flotation behaviour of selected ions compare with that of 1Plant on a Merensky ore? With key factors being:
    - Mass pull
    - Water recovery
    - Entrainment
    - Valuable mineral recovery
    - Concentrate grade
- ✓ How does foamability change with increasing ionic strength? With key factors being:
    - Water recovery
    - Foam height
    - Bubble size
- ✓ How does foamability change with different ions?
    - Water recovery
    - Foam height
    - Bubble size

In line with the research key questions and the literature review, the following **hypotheses** are put forward:

- ✓ The increase in the ionic strength of plant water causes an increase in the solids and water recovery with a consequent decrease in the concentrate grade because the presence of ions increases frothability.
- ✓ The increase in ionic strength in the 2-phase system will cause a decrease in the pulp bubble size; consequently the foam height will increase because the presence of the ions improves foamability due to the froth-like properties of the electrolyte solutions..
- ✓ Ion type in synthetic plant water may yield different flotation results due to differences in frothing properties.

The overall **objective** of this study is to investigate the effect that the ions present in synthetic plant water may have on the flotation performance of a platinum bearing ore from the Merensky reef.

4. EXPERIMENTAL METHODS AND MATERIALS

4.1 Ore

A sample of Merensky ore was obtained from an operation in the Bushveld Igneous Complex in the North West province of South Africa. The Merensky ore consists of PGMs, BMS and gangue minerals. The bulk sample was crushed, blended, riffled and split using a rotary splitter into 1 kg samples.

Table 4.1 shows the mean copper, nickel and sulphur values for the ore, which were determined from the reconstituted feed, by using the concentrate and tailings values from the batch flotation tests.

Table 4.1: Mean calculated feed composition for the ore.

Copper, wt%	Nickel, wt %	Sulphur, wt%
0.048	0.135	0.221

4.2 Water

All batch flotation tests were conducted using synthetic plant water, whereby distilled water was modified by the addition of inorganic salts to ensure that the water contained similar amounts of ions typically found in Merensky ore flotation plants (Wiese, 2009). The amounts of chemical salts that were added to modify distilled water are shown in Table 4.2.

Table 4.2: Inorganic salts' required for a 20 L batch of 1SPW

Chemical salt	Formula	Mass in 20 L, g
Magnesium sulphate	$MgSO_4.7H_2O$	12.3
Magnesium nitrate	$Mg(NO_3)_2.6H_2O$	2.14
Calcium nitrate	$Ca(NO_3)_2.4H_2O$	4.72
Calcium chloride	$CaCl_2$	2.22
Sodium chloride	$NaCl$	7.12
Sodium carbonate	Na_2CO_3	0.60

The amounts shown in Table 4.2 are necessary to give synthetic plant water the desired ions, and the TDS shown in Table 4.3. For this study it was necessary to synthesize four water types, namely, 1, 3, 5 and 10 synthetic plant water as well as single salt solutions as shown in Table 4.3 in order to investigate the controlling ions in process water. Na^+, Ca^{2+} and Mg^{2+} ions were tested in order to investigate the effect of valence number.

Table 4.3: The concentration of ions present in the synthetic plant water

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	Ionic Strength [M]
1SPW	80	70	153	287	240	176	-	17	1023	0.0213
3SPW	240	210	459	861	720	528	-	51	3069	0.0620
5SPW	400	350	765	1435	1200	880	-	85	5115	0.0977
10SPW	800	700	1530	2870	2400	1760	-	850	10230	0.1860
NaCl	-	-	554	854	-	-	-	-	1408	0.0213
$NaNO_3$	-	-	554	-	-	1494	-	-	2048	0.0213
Na_2SO_4	-	-	369	-	772	-	-	-	1141	0.0213
$CaCl_2$	322	-	-	570	-	-	-	-	892	0.0213
$CaSO_4$	322	-	-	-	-	996	-	-	1318	0.0213
$Ca(NO_3)_2$	241	-	-	-	579	-	-	-	820	0.0213
$MgCl_2$	-	195	-	570	-	-	-	-	765	0.0213
$MgSO_4$	-	195	-	-	-	996	-	-	1191	0.0213
$Mg(NO_3)_2$	-	145	-	-	579	-	-	-	725	0.0213

4.3 Flotation Reagents

4.3.1 Collector

SIBX with a purity of 90 %, supplied by Senmin, was used as the standard collector. A 1 % solution SIBX was prepared fresh each day using distilled water. The collector dosage was kept constant at 150 g/t and was calculated on an “as is” basis (i.e. not corrected for active content). The properties of SIBX are shown in Table 4.4.

Table 4.4: SIBX properties

Collector	M_r, g/mol	Density, g/mL	% Purity	1 % Solution, g/t
SIBX	200	1	90	150

4.3.2 Depressants

Polysaccharide depressants, namely, guar and CMC were used under all test conditions as gangue depressants. The guar depressant, Stypress 504, a modified guar gum, was manufactured by Chemquest. The CMC, Depramin 267, was supplied by AKZO Nobel Functional Chemicals. 1 % solutions were prepared for each of the depressants for use in the batch flotation tests by adding the required amount of dry depressant into distilled water for two hours using a magnetic stirrer to allow complete dissolution (Wiese, 2009). Both depressants were varied at two dosage levels of 100 and 500 g/t, and were not corrected for active content. The 1 % depressant solutions were prepared fresh every 5th day. The properties of the two depressants are shown in Table 4.5.

Table 4.5: Depressants properties

Depressant	M_r, g/mol	Density, g/mL	% Purity	DS	1%Solution, g/t
CMC: Depramin 267	325 000	1.43	72	0.68	100 and 500
Guar: Stypress 504	230 000	1.1	89	-	100 and 500

4.3.3 Frother

DOWFROTH 200, polyglycol ether, supplied by Betachem, was used in all batch flotation tests. A frother dosage of 40 g/t was used in all batch flotation tests.

4.4 Milling

An Eriez stainless steel rod mill with a diameter of 200 mm, charged with 20 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. For the flotation tests, 1 kg portions of ore were milled at 66 % solids in synthetic plant water to achieve a grind of 60 % passing 75 µm. This grind was chosen because it matches the primary rougher grind used by industrial mining operations processing Merensky ore. The milling curve for the ore is shown in Figure 4.1. The milling tests established that this grind was achieved in 13.55 minutes. In all tests conducted, SIBX was added to the mill before grinding at a dosage of 150 g/t.

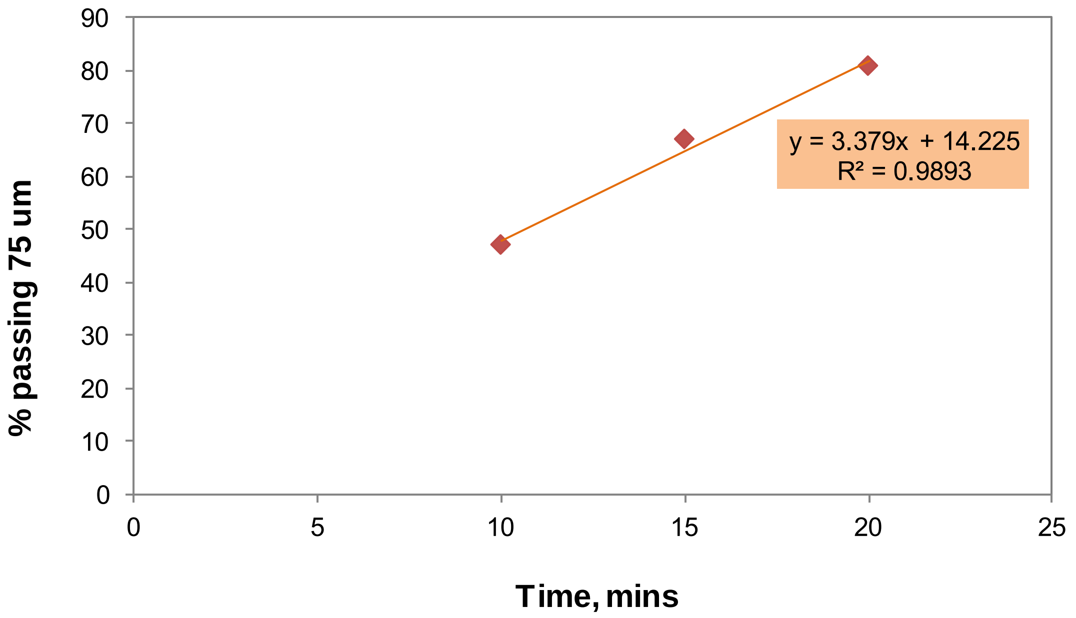


Figure 4.1: Milling curve for the Merensky ore

4.5 Flotation Equipment and Reagents

A 3-litre modified Leeds laboratory flotation cell, as shown in Figure 4.2, was used for all batch flotation tests. The cell is fitted with a variable speed drive. The pulp level was controlled manually. Table 4.6 shows the standard flotation conditions and variables. Only the water type, depressant type and depressant dosage were varied.

Table 4.6: Standard and variable flotation cell conditions

Standard Cell Conditions	Variables
Aeration rate: 7 L/min Impeller speed: 1200 rpm Collector type: SIBX at 150 g/t Frother type : Dow 200 at 40 g/t	Depressant(Guar, CMC) Dep. Dosage (100, 500) g/t Water type (1, 3, 5, 10) SPW

Figure 4.2: The UCT modified Leeds 3 Litre Flotation Machine

4.6 Batch Flotation Procedure

A 1 kg ore sample was milled as described above in the presence of a collector. The milled slurry was transferred to the flotation cell and the volume made up to 3 litres with the required synthetic water to produce about 35 % solids. The impeller speed was set at 1200 rpm. The required reagents were added to the slurry. The sequence and conditioning time are shown in Table 4.7.

Table 4.7: Flotation reagent suite and conditioning time

Reagent	Reagent function	Conditioning time in minutes
SIBX	Collector	13.55 in the mill
Guar or CMC	Depressant	2
Dow 200	Frother	1

After the addition of reagents, the air was turned on at a flow rate of 7 l/ min and the froth height allowed to build up. A froth height of 2 cm was kept constant throughout the float. Four concentrates were collected: C1 for 2, C2 for 4, C3 for 6 and C4 for 8 minutes. Feed and tailing samples were taken before and after each flotation test. The amount of water recovered with each of the four concentrates was measured. All the tests were performed in duplicate. The samples were filtered, dried and weighed before analysis. Copper and total nickel analysis of all samples was conducted using a Bruker X Ray Fluorescence (XRF) S4 Explorer Spectrometer. Sulphur analysis was carried out using a LECO DR423 sulphur analyser. A summary of the batch flotation procedure used in this study is given Table 4.8.

Table 4.8: Summary of the Batch Flotation Procedure

Action	Time (minutes)
Milling	13.55
Collector	Added to mill prior to grinding
Depressant	0
Frother	2
Air turned on and froth allowed to develop	3
C1	5
C2	9
C3	15
C4	23

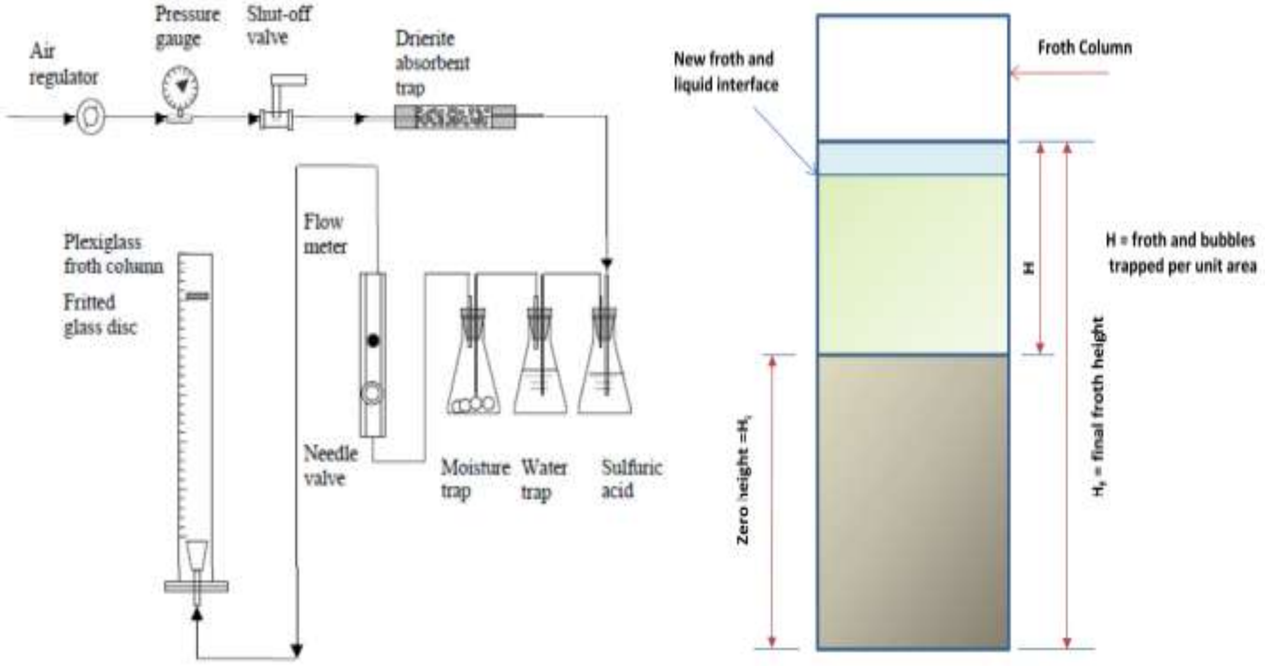
4.7 Foam Column

The effect of increasing ionic strength of plant water on foamability was investigated using a 2-phase foam column test rig. This test work was considered necessary since both the 3-phase and 2-phase batch flotation results obtained by Corin et al. (2011) and Mooruth and Booley (2009), suggested that the presence of the ions affected froth stability. The foam height, *H*, was used as a measure of the foamability of the different water types, and is expressed by Equation (i), where H_f and H_i are the final foam height and the pulp-foam interface height respectively.

$$H = H_f - H_i \qquad \text{............ (i)}$$

4.7.1 Foam Height Experimental Procedure

A schematic flow diagram of a typical foam column test rig is shown in Figure 4.3 (a), and a schematic diagram showing the foam and pulp (liquid) interfaces in a foam column is illustrated by Figure 4.3 (b). The cylindrical column has an internal diameter of 44 mm and a total height of 1700 mm. An air flow rotameter was connected to the rig to control the air flow rate to a maximum capacity of 3 L/min, and a pressure regulator was also connected to the pipes of the rig to set the air pressure at 200 kPa. A sparger of constant pore size was fitted to the bottom of the foam column to allow air flow through to the column (Bezuidenhout, 2011).



(a)

(b)

Figure 4.3: Schematic representation of: (a) a typical foam column test rig, (b) the pulp and froth interfaces in a foam column (Xia, 2000).

Each water type was dosed with 5 g /t DOW 200 before being added into the column where the zero height was measured as shown in Figure 4.3 (b). Air was introduced to the column at a flow rate of 2 L/min, which allowed the development of the foam phase until an equilibrium froth height was attained. This equilibrium condition was reached after 3 minutes for all tested water types. The equilibrium condition is defined as the state at which bubble collapse rate at the top of the foam is equal to the air flow rate through the sparger which is situated at the bottom of the column. (Bezuidenhout, 2011) .Upon reaching equilibrium it was possible to measure the final foam height as shown in Figure 4.3 (b). The tested conditions are given in Table 4.9, and all experiments were performed in duplicate to minimise uncertainty.

Table 4.9: Foam Column Test Experiments

Fixed Conditions	Variables
Aeration rate: 2 L/min	Water type: Distilled 1SPW 3SPW 5SPW 10SPW
Frother dosage: 5 g/t DOW 200	

4.8 UCT Bubble Size Analyser

The effect of increasing ionic strength of plant water, and that of single salt solutions on the pulp phase bubble diameter was investigated using a 2-phase foam column connected to the UCT Bubble Size Analyser. The experimental setup is shown in Figure 4.4 which consists of a glass capillary placed inside a glass column, which is filled with the solution of interest, a detector head which contains two optical detectors mounted at right angles to each other, detector electronics, a microprocessor, a computer, a peristaltic pump and a gas burette. The tested conditions are shown in Table 4.10, and all experiments were performed in duplicate to minimise uncertainty. The experimental procedure is given in Appendix B.

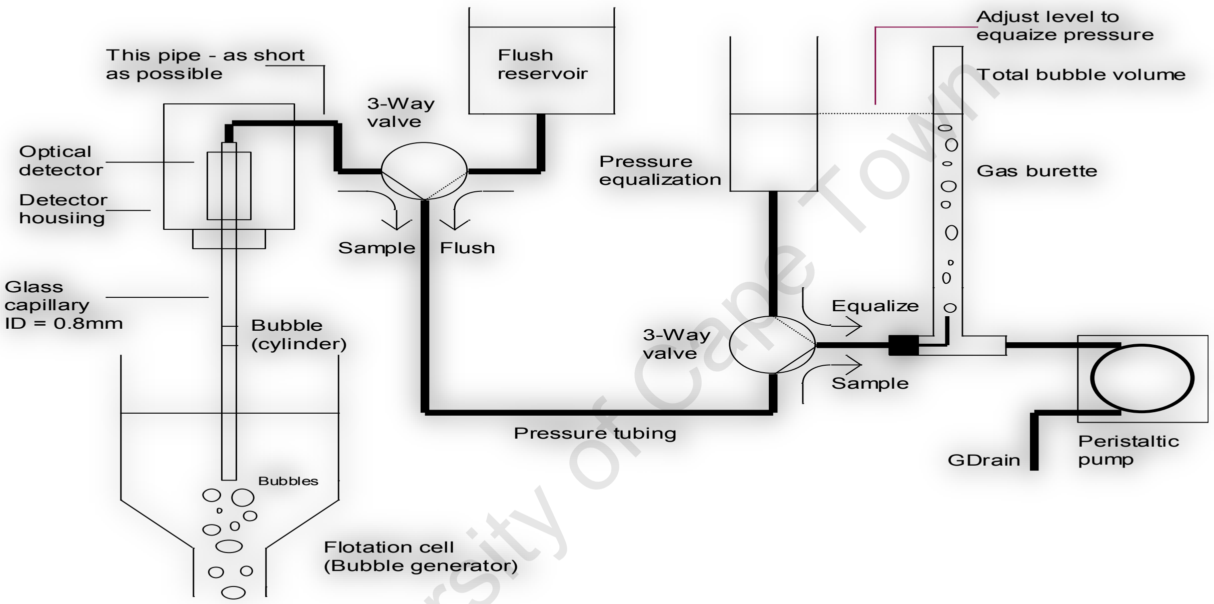


Figure 4.4: A schematic representation of the experimental setup of the UCT Bubble Size Analyser (Randall, 2009).

Table 4.10: Bubble Size Measuring Experiments

Fixed Conditions	Variables
Aeration rate: 2 L/min	Water type: Distilled 1SPW 3SPW 5SPW 10SPW Single salts
Frother dosage: 5 g/t DOW 200	

5. EFFECT OF IONIC STRENGTH, DEPRESSANT TYPE AND DOSAGE ON THE FLOTATION BEHAVIOUR OF GANGUE AND VALUABLE MINERALS IN A PLATINUM BEARING ORE FROM THE MERENSKY REEF

The aim of this work was to investigate the effect of increasing the ionic strength of plant water on the recovery of gangue and valuable minerals of a platinum bearing ore from the Merensky reef, the influence of depressant type (i.e. CMC and guar) and dosage were also investigated under the selected ionic strength conditions shown in Table 5.1.

This chapter is divided into three sections. In Section 5.1 the reproducibility of the testwork is examined. In Section 5.2 the effect of ionic strength of plant water, depressant dosage, and type on the flotation performance are evaluated by comparing the recovery and grade of valuable minerals, and the amount of entrained and floating gangue recovered. Section 5.3 describes the key findings. The complete set of flotation results is given in Appendix A.

5.1 Reproducibility

Batch flotation tests were performed in duplicate for every condition tested in this study in order to determine and minimise the standard error associated with an experimental result. The variables which were key in determining reproducibility were the mass pull or solids recovery, water recovery, concentrate assays and metal recovery. The sample standard deviation was calculated for every condition, and also the sample standard error was calculated simply by dividing the sample standard deviation by the square root of the sample size. The UCT Standard Batch Flotation Procedure requires that the standard error in solids recovery be at most 5 % of the total amount of solids recovered, and in the water recovery the standard error should be 10 % of the total amount of water recovered. For all batch float data presented in this thesis, the calculated standard error was found to be within accepted limits. Notice that the values presented for each condition are the average values between tests which were performed in duplicate and the error bars represent the standard deviation between duplicate tests.

5.2 Effect of Ionic Strength, Depressant Type and Dosage

5.2.1 Test Conditions

The conditions used to elucidate the effect of ionic strength of plant water, guar and CMC at varying dosages on the flotation behaviour of gangue and sulphide minerals from a Merensky ore are shown in Table 5.1.

Table 5.1: Tests conditions for the investigation of the impact that ionic strength, depressant type at varying dosages might have on a PGM ore.

Description	Condition
Water type and ionic strength	1SPW 3SPW 5SPW 10SPW
Depressant type and dosage	Guar – Stypres 504 CMC – Depramin 267 100 and 500 g/t
Collector and dosage	SIBX at150 g/t
Frother and dosage	Dow 200 at 40 g/t

5.2.2 Summary of Mass Balancing

A summary of the findings obtained for all tested conditions is given in Table 5.2. The final copper and nickel recoveries and grades, solids mass and water recovered, entrained and floating gangue are summarised in Table 5.2. Notice that the values presented for each condition are the average values for tests which were performed in duplicate.

Table 5.2: Summary of results obtained for all tests investigating the effect of ionic strength on floatability

Flotation Condition	Mass recovered (g)	Water recovered (g)	Cu recovery (%)	Cu grade (%)	Ni recovery (%)	Ni grade (%)	Entrained gangue (g)	Floating gangue (g)
1SPW								
0 g/t Depressant	71.22	619.28	88.03	0.80	60.51	1.38	32.76	32.21
100 g/t CMC	39.90	421.98	83.38	1.01	53.26	1.93	31.27	5.13
500 g/t CMC	88.69	89.48	80.57	3.79	45.71	5.96	6.63	0.00
100 g/t guar	33.32	416.35	91.73	1.98	61.56	3.26	22.02	7.05
500 g/t guar	16.26	191.29	86.48	2.83	53.58	5.43	10.12	0.44
3SPW								
0 g/t Depressant	76.07	759.98	88.03	0.77	61.06	1.32	39.75	29.68
100 g/t CMC	43.03	563.27	85.96	1.11	58.08	2.18	37.57	5.23
500 g/t CMC	109.56	111.58	84.34	3.58	45.10	5.18	7.44	0.04
100 g/t guar	42.75	582.29	90.11	1.27	60.84	2.48	30.45	7.11
500 g/t guar	20.65	300.52	87.96	2.42	56.48	4.45	15.72	0.00
5SPW								
0 g/t Depressant	84.63	1070.35	88.66	0.70	63.10	1.22	47.84	30.86
100 g/t CMC	48.66	682.17	84.28	1.15	57.13	2.41	34.65	5.30
500 g/t CMC	165.01	166.35	83.90	3.36	47.80	5.43	8.45	0.40
100 g/t guar	50.72	807.73	90.16	1.10	62.87	2.24	36.11	7.30
500 g/t guar	23.92	418.64	86.80	2.00	52.95	3.68	18.71	0.00
10SPW								
0 g/t Depressant	108.45	1570.89	89.64	0.57	66.50	1.03	70.06	30.69
100 g/t CMC	56.81	927.11	86.29	0.88	63.65	2.13	41.07	5.45
500 g/t CMC	275.63	276.69	84.44	2.42	49.04	4.25	12.26	0.44
100 g/t guar	60.07	1126.09	90.18	0.90	63.15	1.87	50.22	7.90
500 g/t guar	29.89	568.06	87.43	1.74	55.75	3.07	25.34	0.00

5.2.3 Final Solids and Water Recovery

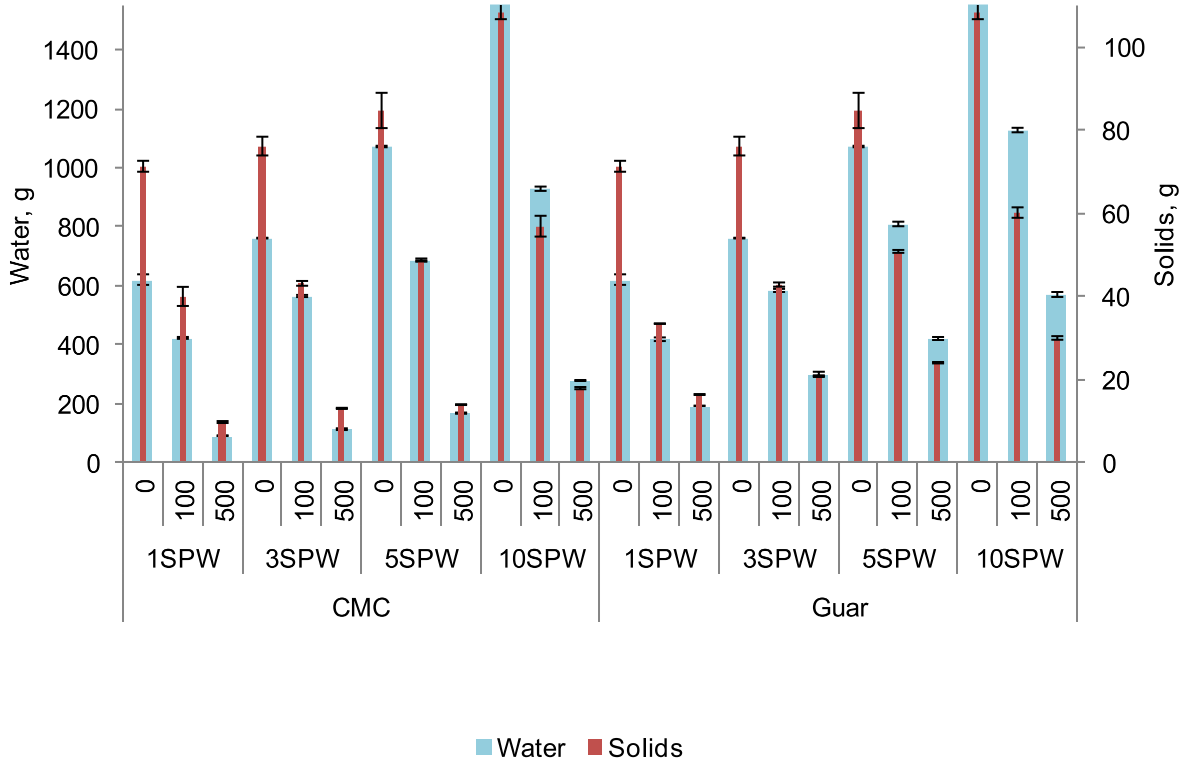


Figure 5.1: Final solids and water recovery for all synthetic plant water types and depressant dosages.

Figure 5.1 illustrates the effect of increasing the ionic strength of plant water under three depressant (CMC and guar) dosages on the amount of solids recovered and water recovered as indicated by the brown and the light blue bars respectively. As the ionic strength increased, both the amount of solids and water recovered increased at all depressant dosages. It can also be noted that the amount of solids and water recovered decreased with increasing depressant dosages and that at higher dosages of 500 g/t the CMC depressant gave a notably greater depression of solids than the guar depressant at 5SPW and 10SPW. These results are further magnified in Figure 5.2 and Figure 5.3.

5.2.3.1 Solids Recovered vs. Water for all CMC dosages

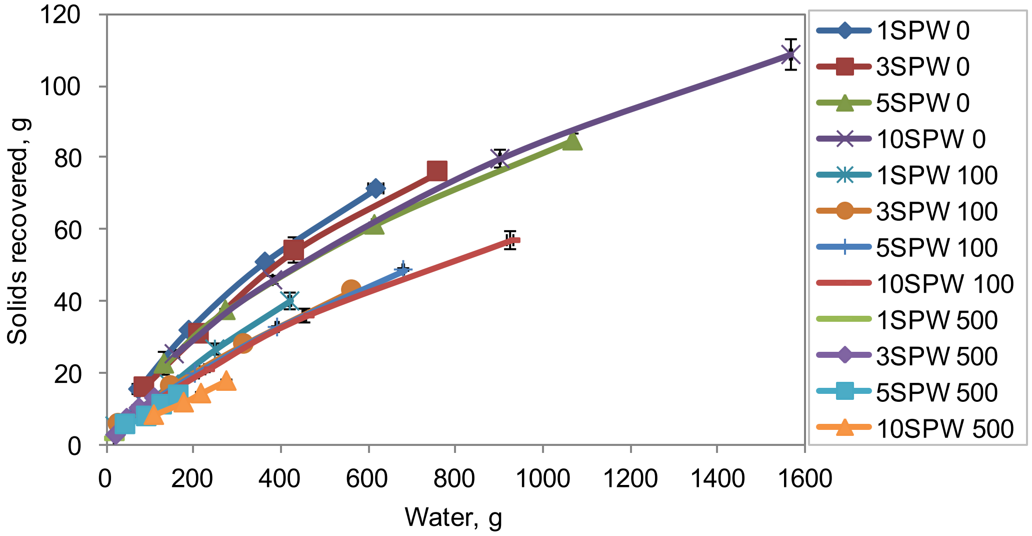


Figure 5.2: Solids recovered vs. water for all CMC dosages under all synthetic plant waters.

5.2.3.2 Solids Recovered vs. Water for all guar dosages

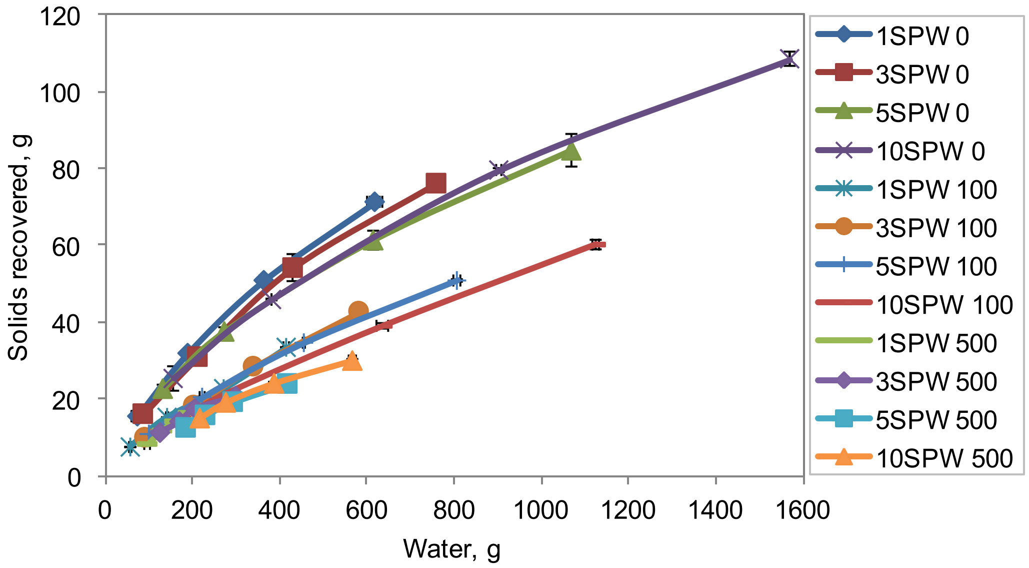


Figure 5.3: Solids recovered vs. water for all guar gum dosages under all synthetic plant waters.

5.2.4 Cu Recovery and Grade

Section 5.2.4 evaluates the effect of ionic strength, depressant type and dosage on the flotation performance of a Merensky ore by comparing the recovery and grade of the copper mineral.

5.2.4.1 Final Cu Recovery and Grade

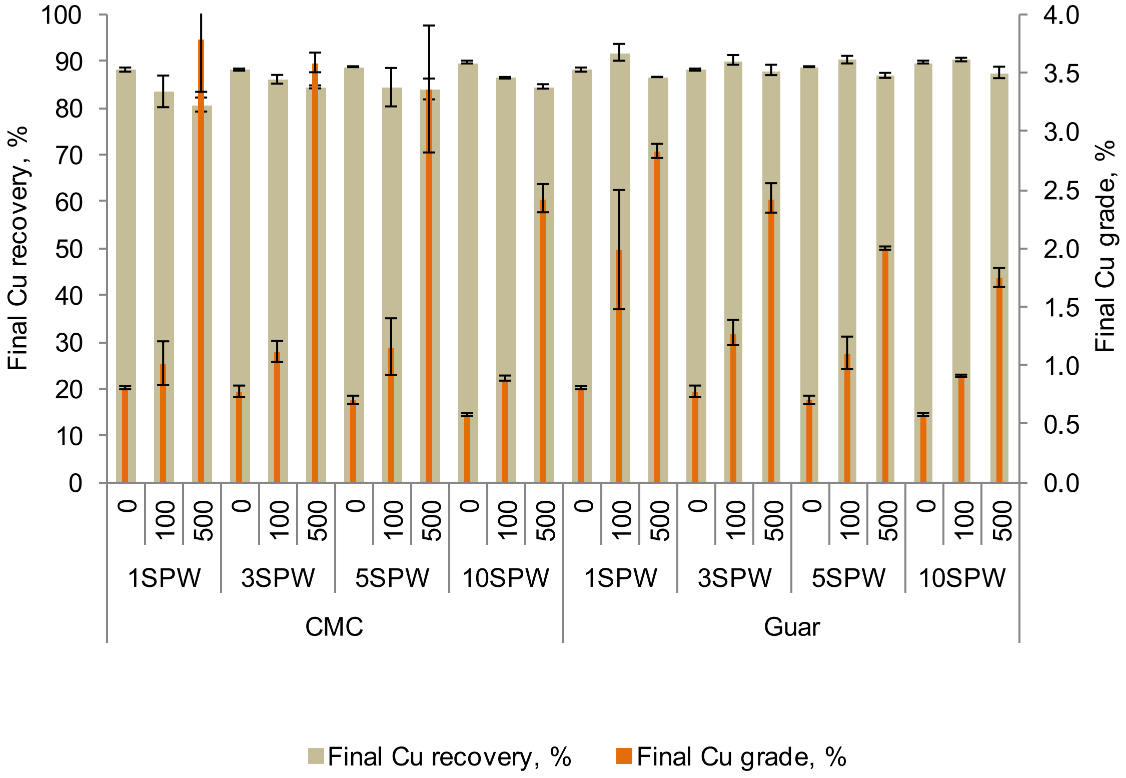


Figure 5.4: Final copper recovery and grade for all synthetic plant water types and depressant dosages.

Figure 5.4 shows the final Cu recovery and grade for all conditions tested. The figure shows that the increase in ionic strength caused an increase in Cu recovery; however the increase in depressant dosage resulted in a decrease in Cu recovery as indicated by the grey bars. Cu grades, indicated by the orange bars, showed slight decreases with increasing ionic strength in the absence of a depressant, and sharp increases when using CMC and guar at 100 g/t and 500 g/t dosages. The highest copper grades were obtained when using CMC at a dosage of 500 g/t and 1SPW. Figure 5.5 to Figure 5.7 makes these findings even more clear by showing the trend of Cu grades vs. Cu recovery.

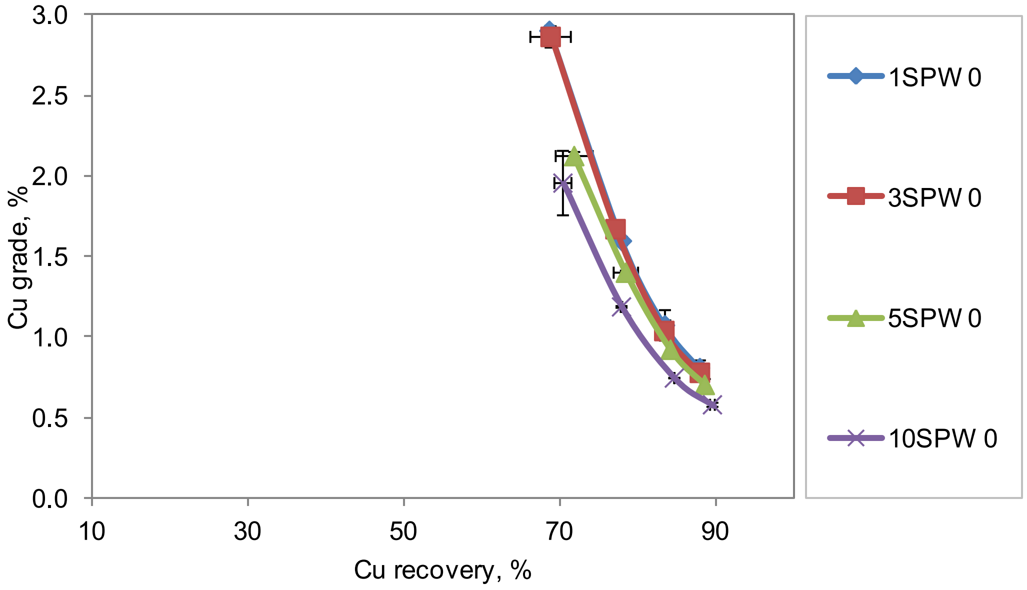


Figure 5.5: Copper grade vs. copper recovery at 0 g/t depressant dosage.

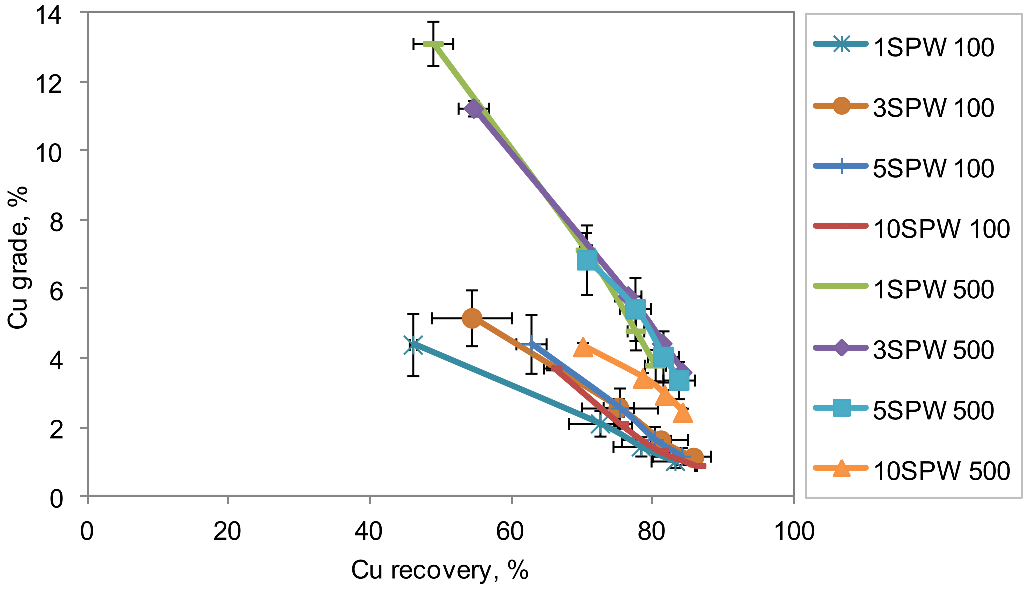


Figure 5.6: Copper grade vs. copper recovery for 100 g/t and 500 g/t CMC.

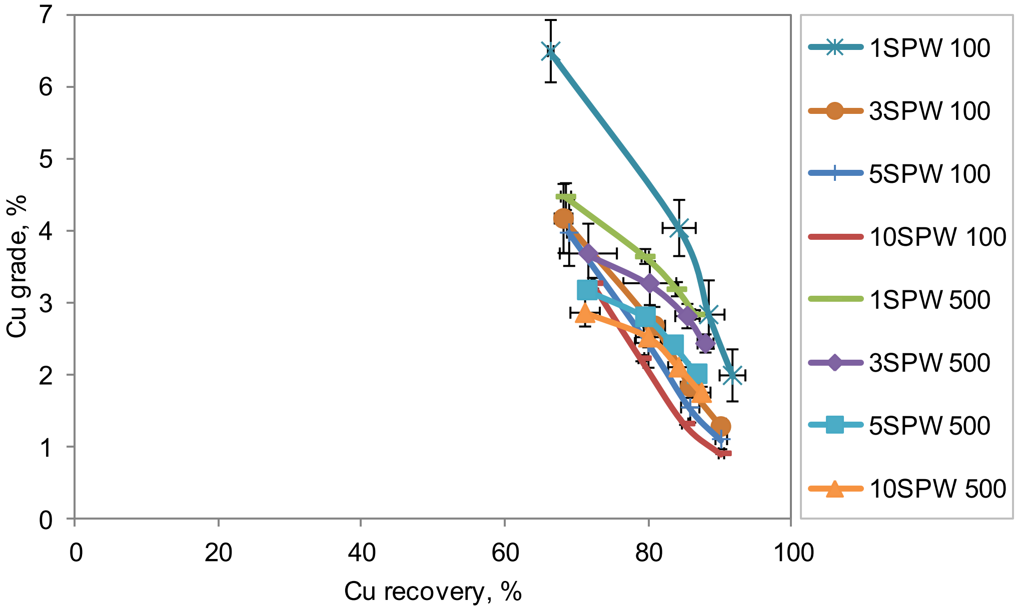


Figure 5.7: Copper grade vs. copper recovery for 100 g/t and 500 g/t guar.

5.2.4.2 Cu Recovery vs. Water at 0 g/t Depressant

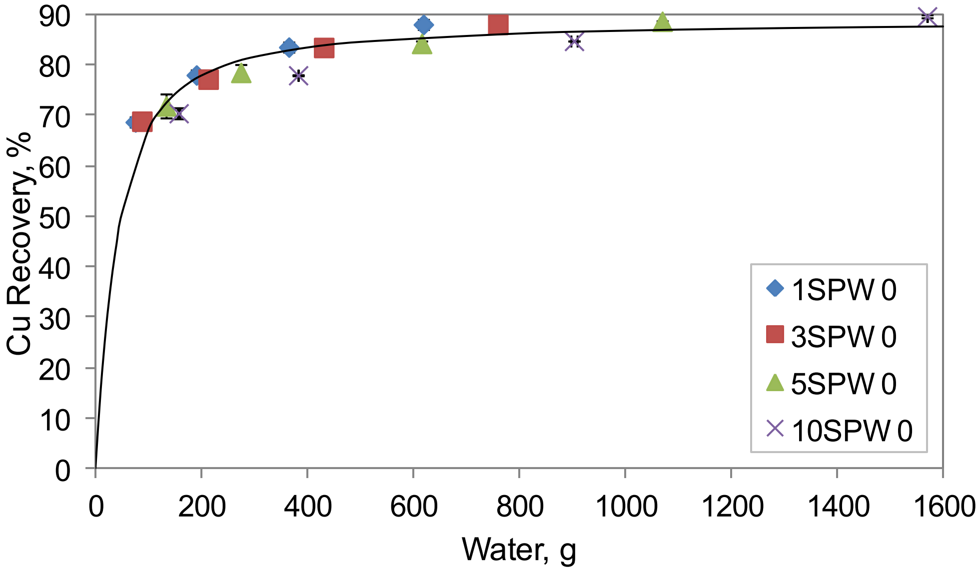


Figure 5.8: Copper recovery vs. water recovery for all synthetic plant water types at 0 g/t depressant.

Figure 5.8 shows Cu recovery vs. water recovered for all synthetic plant water types at 0 g/t depressant dosage. As the ionic strength increased, Cu recovery trend remained unaffected.

5.2.4.3 Cu Recovery vs. Water at 100 g/t and 500 g/t CMC dosages

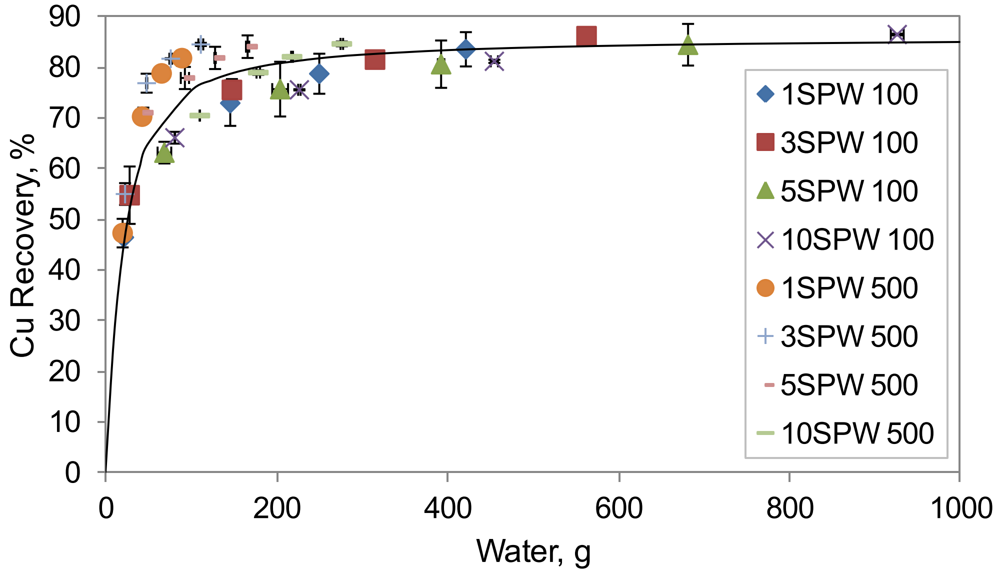


Figure 5.9: Copper recovery vs. water recovery for all synthetic plant water types using CMC at dosages of 100 and 500 g/t.

Figure 5.9 shows the Cu recovery and water recovery results obtained when CMC was tested at 100 and 500 g/t. This figure neither the ionic strength nor depressant dosage affected Cu recovery trend or rate of recovery when using CMC, however the effect of the ionic strength and depressant dosage was seen on the water recovery, that is, the maximum Cu recovery was attained from the higher water recoveries under higher ionic strengths and lower CMC dosages.

5.2.4.4 Cu Recovery vs. Water at 100 g/t and 500 g/t Guar dosages

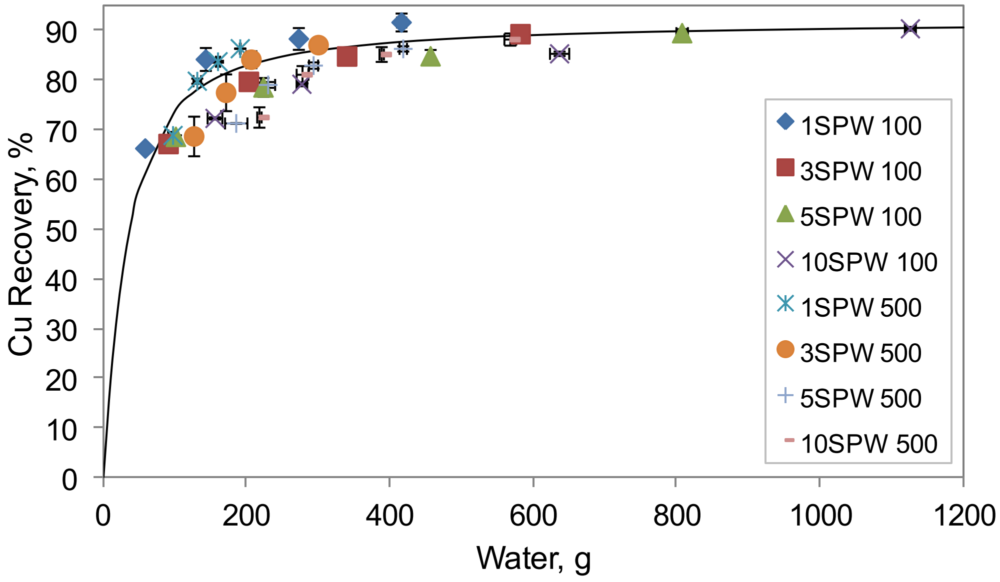


Figure 5.10: Copper recovery vs. water recovery for all synthetic plant water types using guar at dosages of 100 and 500 g/t.

Figure 5.10 shows the trend of Cu recovery vs. water recovery when guar was tested at 100 g/t and 500 g/t dosages. It is illustrated that Cu recovery increased with increasing water recovery; however the increase in ionic strength did not affect Cu recovery trend. It is also evident that the increase in guar dosage had no effect on Cu rate of recovery, although the water recovery was affected by both the increase in ionic strength and guar dosage.

5.2.5 Ni Recovery and Grade

In Section 5.2.5 the effect of ionic strength, depressant type and dosage is evaluated by comparing the nickel recovery and grade.

5.2.5.1 Final Ni Recovery and Grade

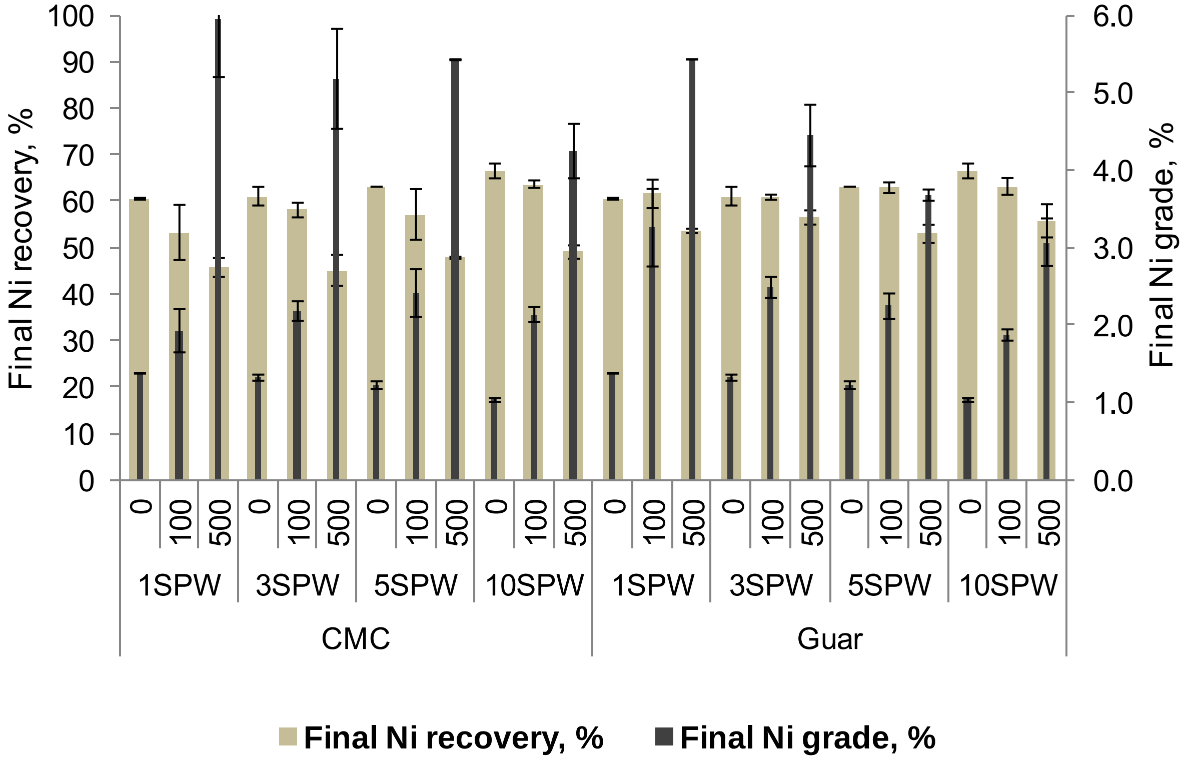


Figure 5.11: Final nickel recovery and grade for all synthetic plant water types and depressant dosages.

Figure 5.11 shows the final Ni recovery and grade for all conditions tested. The highest recoveries of Ni were obtained in the absence of any depressant, and that at 0 g/t depressant the recovery of Ni increased with increasing ionic strength. But as soon as depressants were introduced at 100 g/t dosage, Ni recovery was slightly reduced, and at 500 g/t dosage, Ni recovery showed a dramatic decrease. Ni grade was generally constant for all ionic strengths at no depressant. The results show that Ni grade increased with increasing depressant dosage, it was also observed that Ni grade increased with increasing ionic strength in the presence of any depressant. The highest Ni grades were obtained when using CMC at a dosage of 500 g/t and 1SPW. Figures 5.12 to 5.14 show the trends of Ni grades vs. Ni recovery.

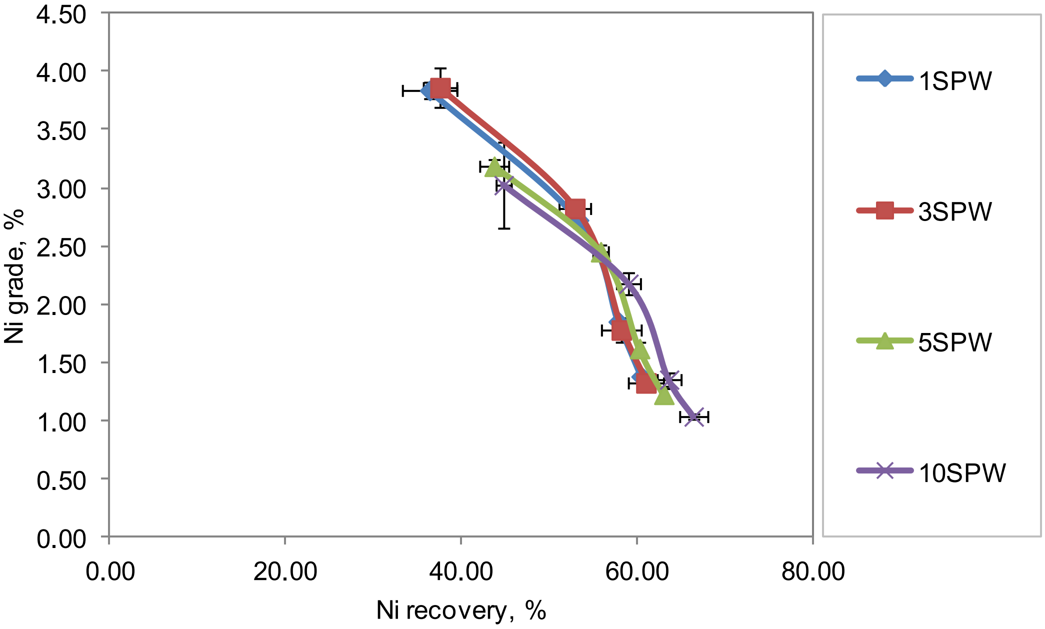


Figure 5.12: Nickel grade vs. nickel recovery at 0 g/t depressant dosage.

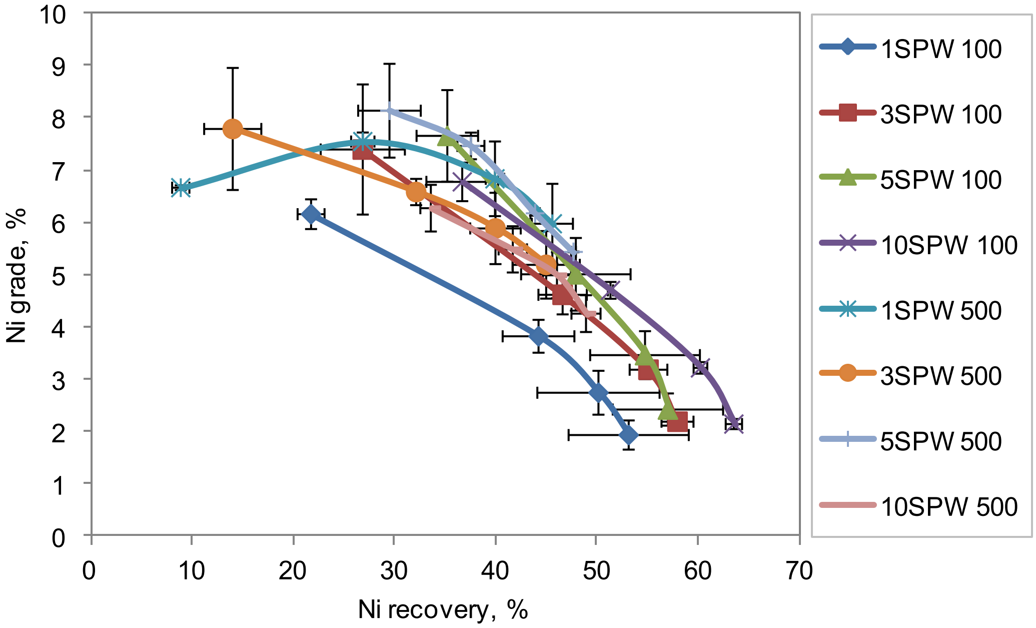


Figure 5.13: Nickel grade vs. nickel recovery for 100 g/t and 500 g/t CMC.

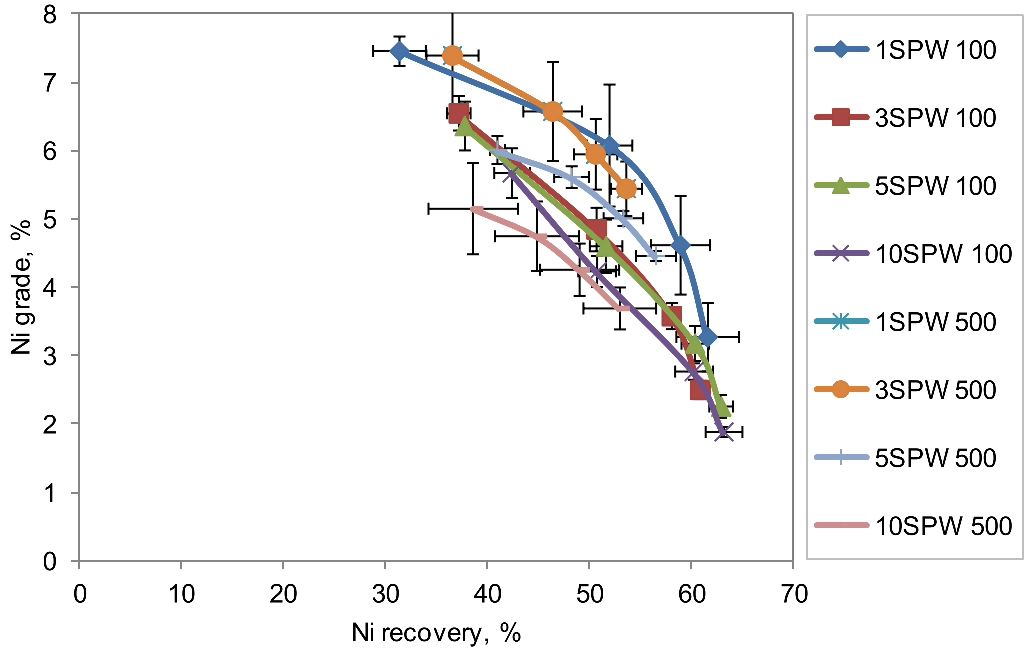


Figure 5.14: Nickel grade vs. recovery for 100 g/t and 500 g/t guar.

5.2.5.2 Ni Recovery vs. Water at no Depressant

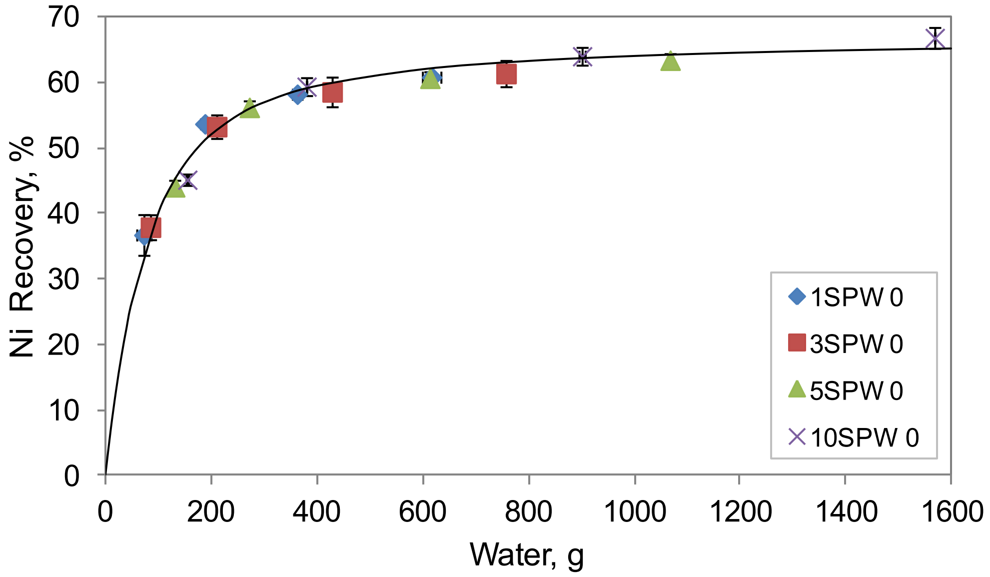


Figure 5.15: Nickel recovery vs. water for all synthetic plant water types at no depressant

Figure 5.15 shows Ni recovery vs. water recovered for all synthetic plant water types at 0 g/t depressant dosage. Ni recovery increased with an increase in the ionic strength of plant water; however the increase in the ionic strength did not show an impact on the rate of Ni recovery. The maximum Ni recovery was attained at higher water recoveries for higher ionic.

5.2.5.3 Ni Recovery vs. Water at 100 g/t and 500 g/t CMC dosages

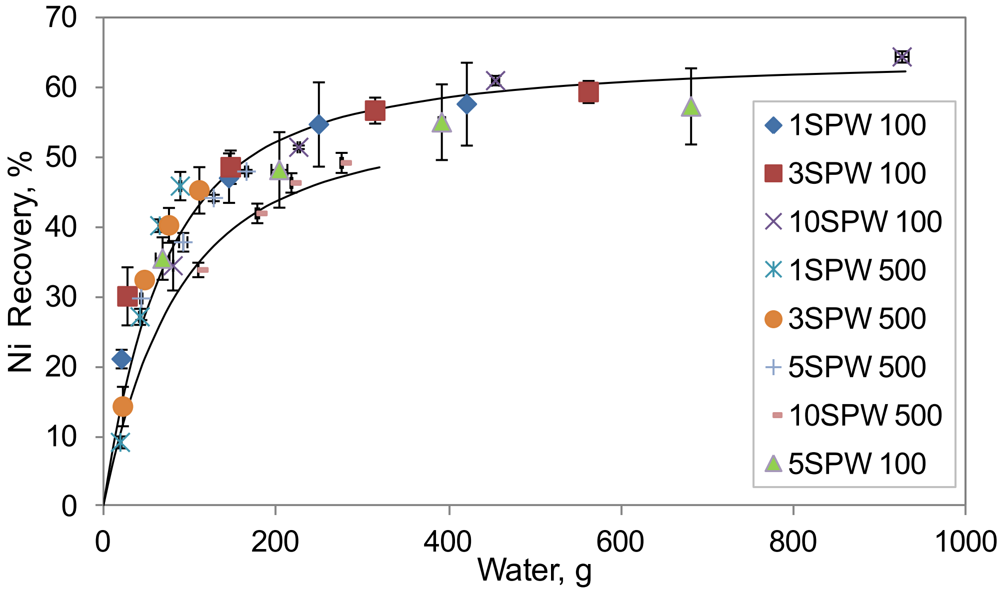


Figure 5.16: Nickel recovery vs. water recovery for all synthetic plant water types using CMC at dosages of 100 and 500 g/t.

Figure 5.16 shows the Ni recovery vs. water recovered obtained when CMC was tested at 100 g/t and 500 g/t. This figure indicates that the rate of Ni recovery was not affected by changes in the ionic strength, but the effect of the depressant dosage was seen on the nickel recovery at 500 g/t CMC, and this depressant dosage effect was prominent at the high ionic strength (i.e. 5 and 10SPW).The maximum Ni recovery was attained at higher water recoveries for higher ionic strengths and lower CMC dosages.

5.2.5.4 Ni Recovery vs. Water at 100 g/t and 500 g/t Guar dosages

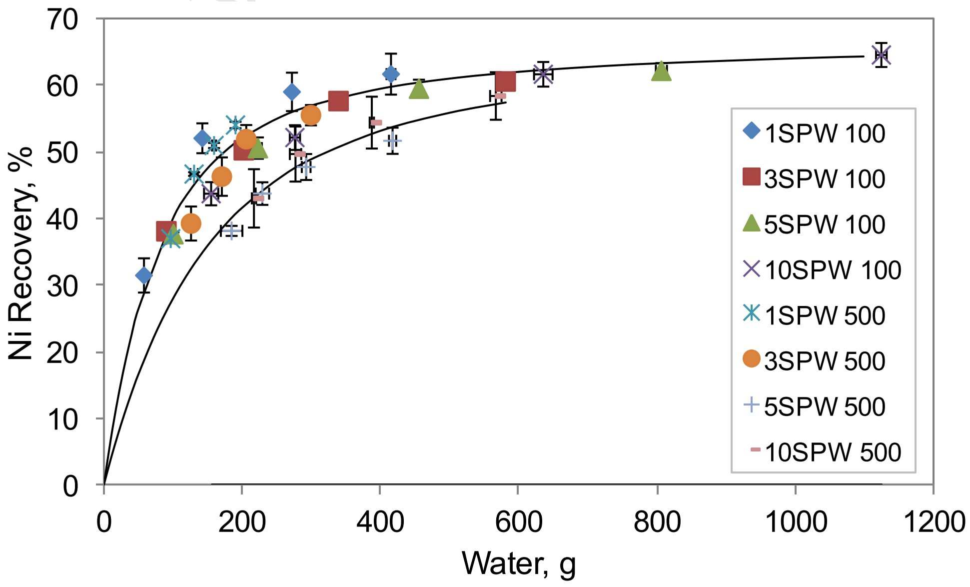


Figure 5.17: Nickel recovery vs. water recovery for all synthetic plant water types using guar at dosages of 100 and 500 g/t.

Figure 5.17 shows the Ni recovery vs. water recovered obtained when guar was tested at 100 g/t and 500 g/t. This figure indicates that the rate of Ni recovery was not affected by changes in the ionic strength. The use of guar at 500 g/t led to a different Ni rate of recovery, and this depressant dosage effect was significantly greater at the high ionic strength (i.e. 5SPW and 10SPW). Maximum Ni recoveries were attained at higher water recoveries for higher ionic strengths and lower guar dosages.

5.2.6 Total Gangue and Floating Gangue

Section 5.2.6 evaluates the effect of ionic strength, depressant type and dosage on the amount of entrained and floating gangue recovered. This was possible by assuming that an increase in the depressant dosage to 500 g/t ensures that no NFG reports to concentrate, allowing the determination of an entrainability factor from the linear nature of the total gangue per unit water curve obtained; the entrainability factor equals the slope of the linear curve as suggested by Wiese et al. (2009).

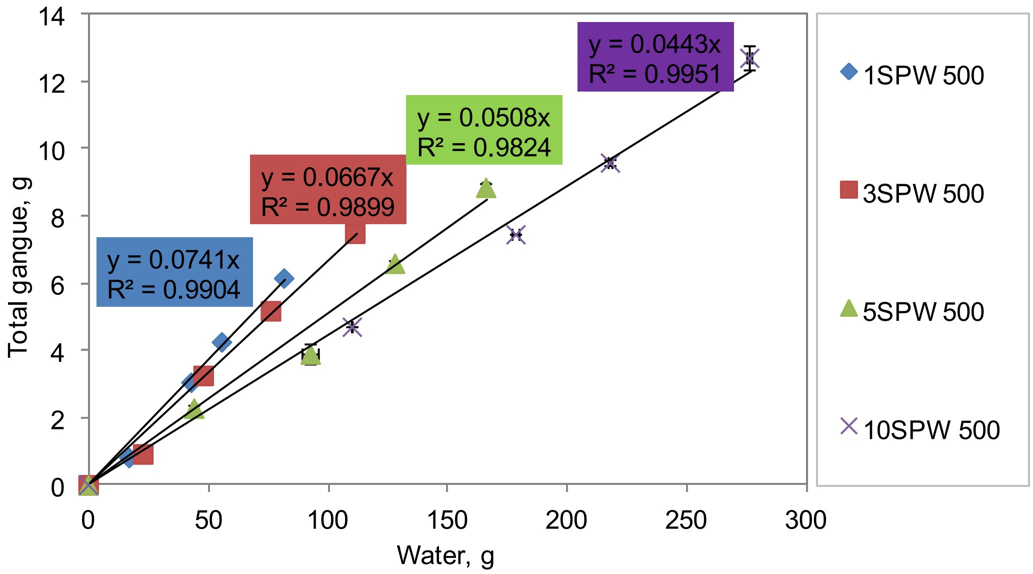


Figure 5.18: Total gangue vs. water recovered when using CMC at 500 g/t. Entrainability factor indicated by the slope of the line.

Figure 5.18 shows the total gangue vs. water recovered when using CMC at 500 g/t. This indicates a significant decrease in the entrainability factor (gradient of the line) for CMC as the ionic strength was increased.

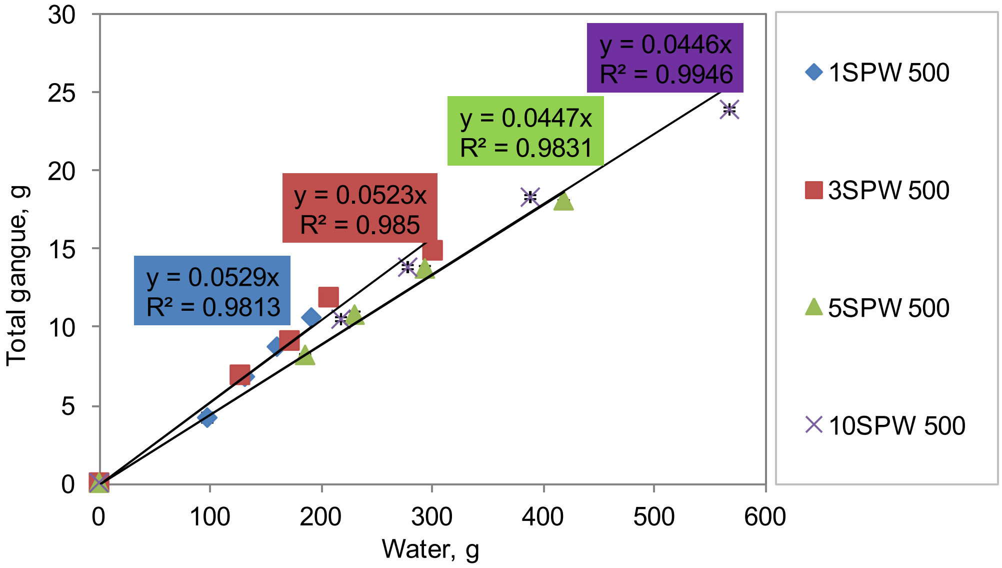


Figure 5.19: Total gangue vs. water recovered when using guar at 500 g/t. Entrainability factor indicated by the slope of the line.

Figure 5.19 shows the total gangue vs. water recovered when using guar at 500 g/t. This indicates a significant decrease in the entrainability factor (gradient of the line) for guar as the ionic strength was increased.

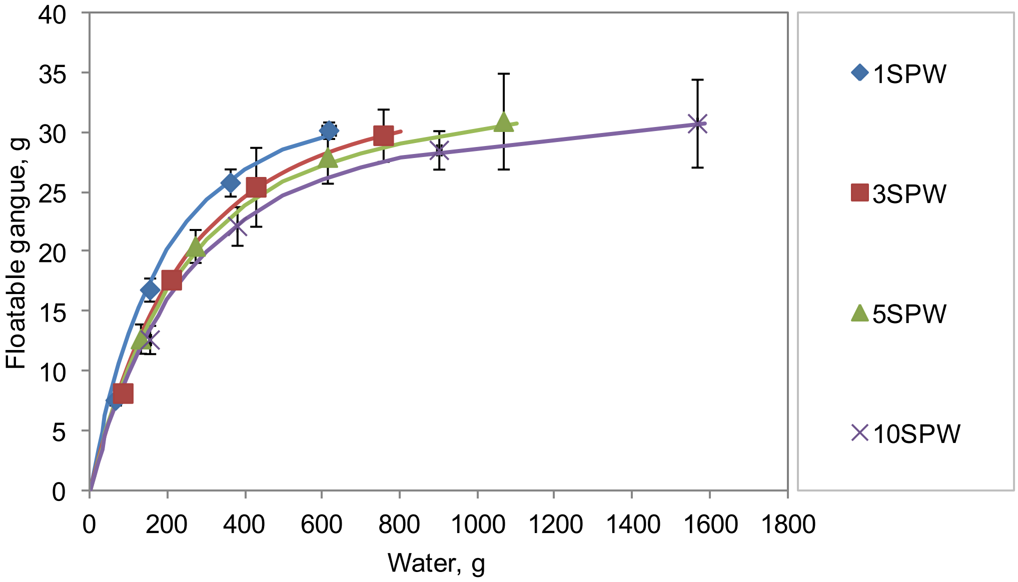


Figure 5.20: NFG vs. water recovered at no depressant.

Figure 5.20 illustrates the amount of floatable gangue recovered vs. water in the absence of any depressant. It is evident from this graph that the rate of recovery of floatable gangue decreased with increasing ionic strength, and that the total amount of floatable gangue reporting to the concentrate increased with increasing ionic strength.

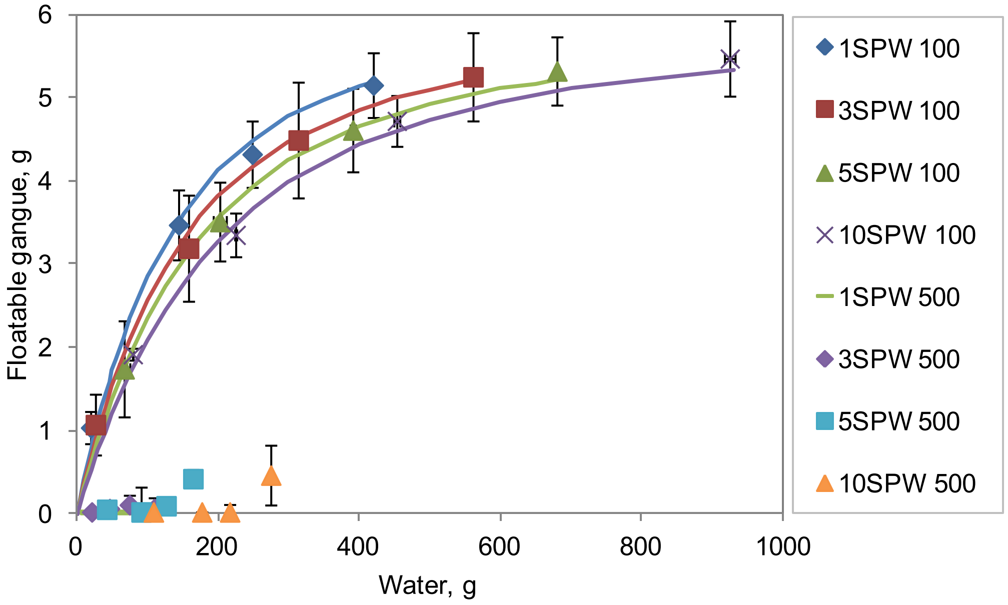


Figure 5.21: NFG vs. water recovered at 100 g/t and 500 g/t CMC.

Figure 5.21 shows the amount of floatable gangue recovered vs. water when CMC was added at a dosage of 100 g/t and 500 g/t. From these results it can be seen that the rate of recovery of floatable gangue decreased with increasing ionic strength, however the total amount of floatable gangue reporting to the concentrate increased with increasing ionic strength. The results of NFG vs. water recovery did not show a definitive trend, so hence these were not fitted to any curve or line. However it is evident that at 500 g/t CMC and 1SPW all NFG had been completely depressed, but it was not so for higher ionic strengths.

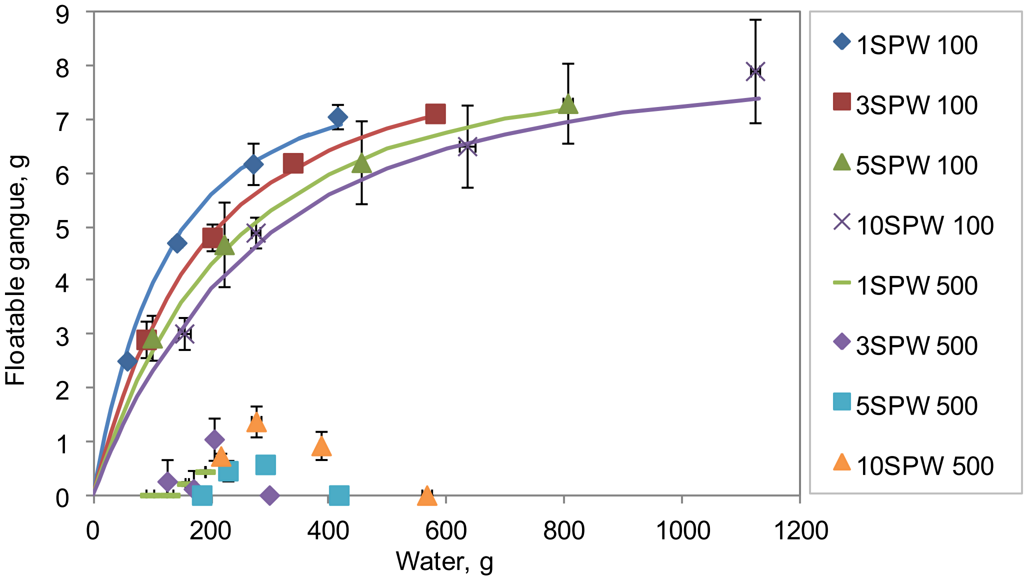


Figure 5.22: NFG vs. water recovered at 100 g/t and 500 g/t guar.

Figure 5.22 shows the amount of floatable gangue recovered vs. water at 100 g/t and 500 g/t guar dosage. These results show that the flotation rate of floatable gangue decreased as the ionic strength increased, but the total amount of floating gangue recovered to the concentrate increased with increasing ionic strength of plant. Again this graph did not show a definitive trend of NFG vs. water recovered at 500 g/t guar, what it did show is that at 1SPW and 500 g/t guar all NFG was prevented from reporting to the concentrate, but not all NFG had been depressed at 500 g/t guar for 3SPW, 5SPW and 10SPW, showing the influence of ionic strength on gangue recovery.

5.2.7 Entrainment using CMC as Depressant

The effect of ionic strength on entrainability when using CMC is shown in Table 5.3. It is very clear that entrainability decreased with increasing ionic strength, which is consistent with an increase in water recovery.

Table 5.3: Entrainment factors and water recovered for varying water types

Water type	Ionic strength [M]	Degree of Entrainment §	Water recovered, g	Frothability
1SPW	0.0213	0.0741	89.48	Low
3SPW	0.0620	0.0667	111.58	Average
5SPW	0.0977	0.0508	166.35	High
10SPW	0.1860	0.0443	276.69	Excessive

§ *Degree of entrainment in units of g of gangue per g of water*

5.2.8 Entrainment using Guar as Depressant

The influence of ionic strength on entrainment when using guar as a floatable gangue depressant is shown in Table 5.4. Entrainability decreased with increasing ionic strength, but the decrease is not as defined as in the case of CMC.

Table 5.4: Entrainment factors and water recovered for varying water types

Water type	Ionic strength [M]	Degree of Entrainment§	Water recovered, g	Frothability
1SPW	0.0213	0.0529	191.29	Low
3SPW	0.0620	0.0523	300.52	Average
5SPW	0.0977	0.0447	418.64	High
10SPW	0.1860	0.0446	568.06	Excessive

§ *Degree of entrainment in units of g of gangue per g of water*

5.3 Key Findings

This section summarises all the major findings of this study in view of the experimental test results obtained.

5.3.1 Effect of Ionic Strength on Solids and Water Recovery

- ✓ The increase in ionic strength resulted in increased amounts of solids and water reporting to concentrates.
- ✓ The increase in ionic strength increased froth stability as indicated by the water recovery.
- ✓ The presence of a depressant was able to decrease the solids and water recovery, but the trend of an increase in solids and water recovery with increasing ionic strength was maintained at all depressant dosages.

5.3.2 Effect of Ionic Strength on Entrainment

- ✓ The degree of entrainment decreased with increasing ionic strength for both CMC and guar.
- ✓ The decrease in the degree of entrainment with increasing ionic strength was more defined when using CMC than guar.
- ✓ Increasing the ionic strength did not show an apparent effect on the degree of entrainment when using guar.
- ✓ The total amount of gangue reporting to concentrate increased with increasing ionic strength.

5.3.3 Effect of Ionic Strength on Floatable Gangue Recovery

- ✓ The amount of NFG recovered per unit of water decreased as the ionic strength was increased.
- ✓ Increasing the ionic strength of plant water led to an increase in the total amount of floatable gangue reporting to the concentrate.
- ✓ The addition of a depressant at a dosage of 100 g/t caused a decrease in the rate of recovery of NFG and the amount of NFG compared to that observed in the absence of any depressant.

5.3.4 Effect of Ionic Strength on Cu and Ni Recovery and Grade

- ✓ The increase in ionic strength resulted in an increase on the final Cu recovery; a maximum Cu recovery of about 90 % was achieved at 10SPW in the absence of a depressant.
- ✓ The recovery of Cu followed the same rate curve throughout the tests conducted showing no ionic strength effect.

- ✓ The increase in ionic strength resulted in a significant increase on the final Ni recovery; the optimum Ni recovery achieved in the absence of any depressant was about 60 %.

- ✓ The flotation rate of Ni was not affected by the changes in ionic strength, however at a depressant dosage of 500 g/t the flotation rate decreased with increasing ionic strength (i.e. at 500 g/t depressant dosage and 5SPW and 10SPW a new rate curve was established).

- ✓ Cu and Ni grades decreased with increasing ionic strength in the absence of any depressant, but the reduction is not as strong as that caused by the addition of a depressant.

5.3.5 Effect of Ionic Strength on Depressant Behaviour

- ✓ For each ionic strength condition it is evident that adding an increased amount of depressant resulted in a significant decrease in the amount of solids and water reporting to the concentrate, and therefore a decrease in froth stability.

- ✓ Depressant addition to the system had a strong influence on the amount of NFG reporting to the concentrate; the rate of NFG recovery decreased with increasing ionic strength and the total amount of NFG reporting to the concentrate decreased with increasing depressant dosage.

- ✓ The decrease in the water recovery, therefore froth stability, when a depressant was charged into the system at a dosage of 100 g/t suggested that this was as a result of the removal of the froth stabilising NFG from the concentrate.

- ✓ An increase in depressant dosage showed a decrease in the total/final Cu recovery, and the rate of Cu recovery remained the same. The increase in depressant dosage increased both Cu and Ni grades dramatically.

- ✓ Depressant type showed a slight impact on the final recoveries of Cu and Ni recoveries.

- ✓ The increase in the ionic strength of plant water (5SPW and 10SPW) in the presence of a depressant at 500 g/t led to a significant decrease in Ni recovery, and the rate of Ni recovery was significantly lower than the rate obtained at 0 g/t and 100 g/t.

- ✓ The highest base metal sulphide grades were obtained at the highest depressant dosage and the lowest ionic strength. CMC performed better than guar in depressing the gangue and increasing Cu and Ni grades.

6. EFFECT OF INCREASING IONIC STRENGTH OF PLANT WATER ON FOAMABILITY

6.1 Effect of Ionic Strength on Water Recovery

A series of 2-phase (i.e. no solids) flotation tests were carried out at a fixed DOW 200 concentration of 40 g/t, the mass of water recovered was determined as a function of time for the four synthetic plant waters as shown in Figure 6.1.

6.1.1 Test Conditions

The test conditions which were used in ‘mineral-less’ batch flotation are shown in Table 6.1.

Table 6.1: Tests conditions to evaluate the effect of ionic strength water recovery in a 2-phase batch float.

Description	Condition
Water type and ionic strength	1SPW
	3SPW
	5SPW
	10SPW
Frother type and dosage	DOW 200 at 40 g/t

6.1.2 Results

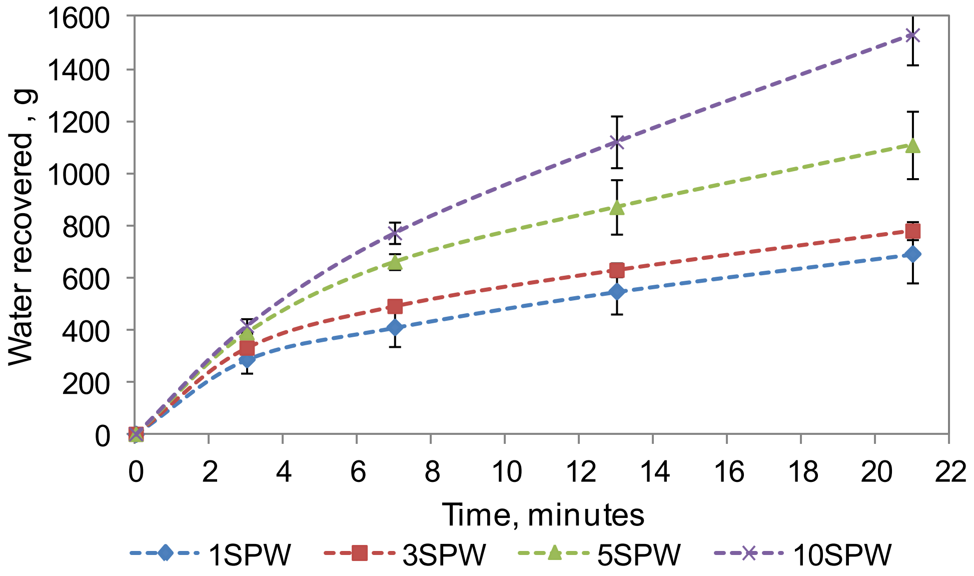


Figure 6.1: Water recovered vs. time for the 2-phase flotation tests with increasing ionic strength of plant water at no depressant.

Figure 6.1 illustrates that the amount of water reporting to concentrate increased with increasing ionic strength in the absence of any mineral. This suggests that high ionic strength conditions led to more mobile and stable foam.

6.2 Effect of Ionic Strength on Foam Height

An investigation of the effect of ionic strength of plant water on foam height was initiated, and a number of 2-phase foam column tests were carried out at a frother dosage of 5 g/t DOW 200; the foam height and the pulp-foam (solution-air) interface measurements were obtained for the four synthetic plant waters as shown in Figure 6.2 to Figure 6.4.

6.2.1 Test Conditions

The test conditions which were used to evaluate the effect of ionic strength on 'mineral-less' column flotation studies are shown in Table 6.2., this work was deemed vital as further results from different techniques were needed to predict and support arguments around the role that ions play in the foam stability of a flotation system.

Table 6.2: Tests conditions to evaluate the effect of ionic strength on foam height and bubble size in a 2-phase batch foam flotation column.

Description	Condition
Water type	1SPW 3SPW 5SPW 10SPW
Frother type and dosage	DOW 200 at 5 g/t

6.2.2 Results

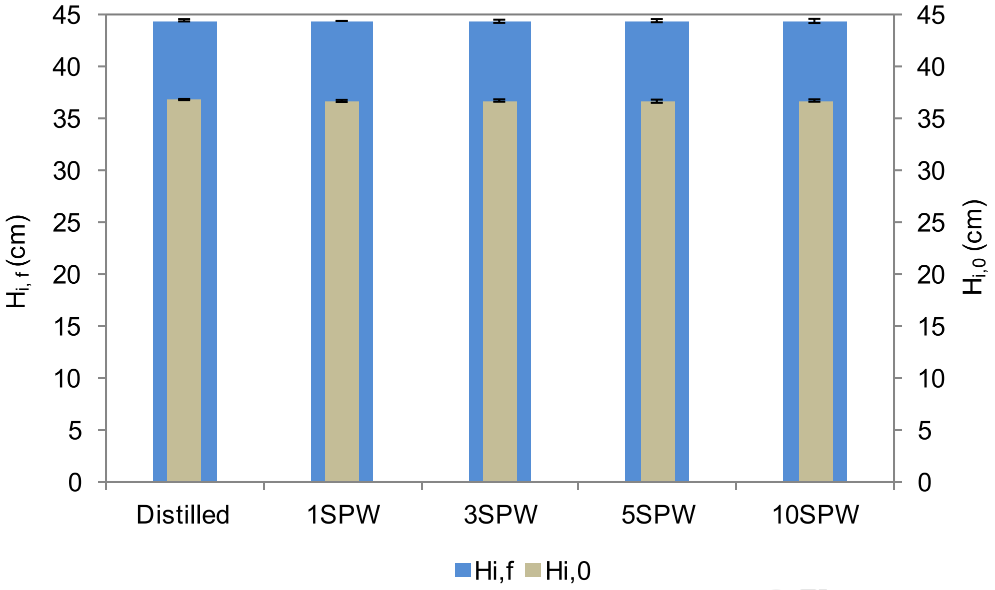


Figure 6.2: Effect of ionic strength on the initial solution-air ($H_{i,0}$) and the final solution-air interface ($H_{i,f}$).

Figure 6.2 illustrates the initial height of the solution-air interface at no air flow rate (as indicated by the grey colour on the bar graph) and the final height of the solution-air/froth interface (indicated by the blue colour) at a constant air flow rate of 2 L/min. The pulp-foam interfaces remained unchanged with increasing ionic strength. Figure 6.3 shows the effect of ionic strength on the change in solution-air interface or pulp-air interface level.

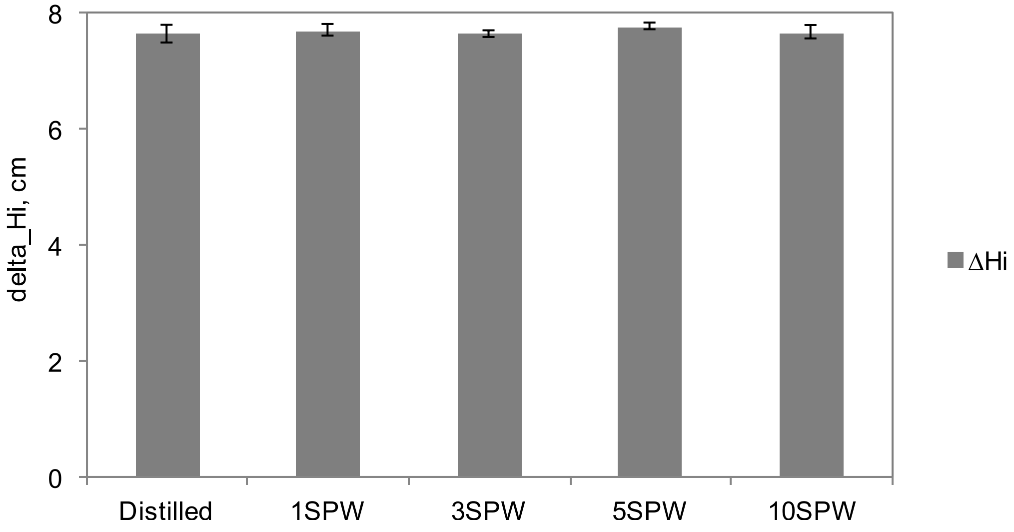


Figure 6.3: Effect of Ionic strength of plant water on the change in the solution-air interface (ΔH_i).

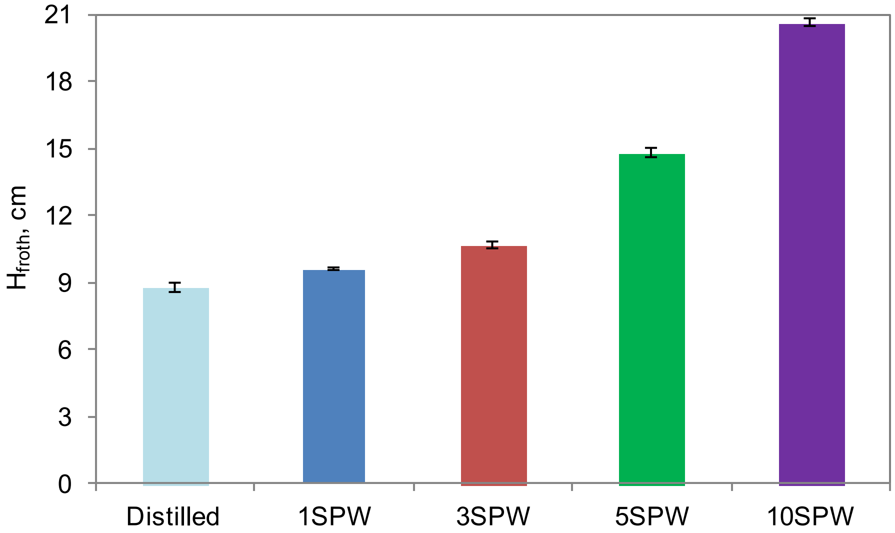


Figure 6.4: Effect of increasing ionic strength of plant water on froth height

Figure 6.4 shows the foam height and pulp-foam interface for the four synthetic plant water types tested at 5 g/t DOW 200 dosage, together with results obtained for distilled water tested at the same frother dosage. The results showed that foam height increased with increasing ionic strength, that is, $\mathbf{H_{foam,\ 10SPW} > H_{foam,\ 5SPW} > H_{foam,\ 3SPW} > H_{foam,\ 1SPW} > H_{foam,\ Distilled}}$.

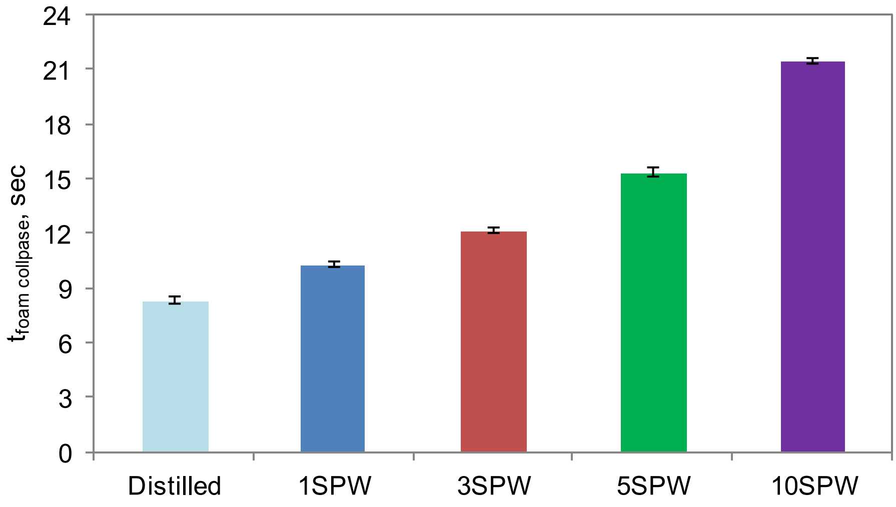


Figure 6.5: Effect of ionic strength of plant water on foam collapse time

Figure 6.5 shows the time that it took for the foam to collapse to its initial height (the initial height being the height which was attained when no air was charged into the system as a function of ionic strength). These results show that the foam collapse time increased with increasing ionic strength.

6.3 Effect of Ionic Strength on Bubble Size

6.3.1 Results

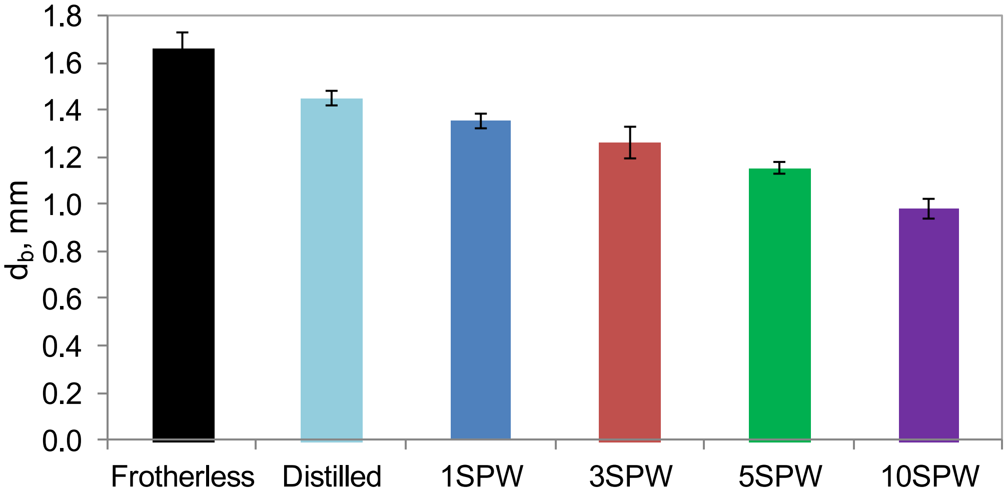


Figure 6.6: Effect of increasing ionic strength of plant water on bubble size

Figure 6.6 shows mean bubble diameters for the four synthetic plant waters tested, together with results obtained for distilled water without and with a foam (foamless and distilled on the bar graph). The results showed that bubble size decreased with increasing ionic strength, that is, $\mathbf{d_{10SPW}<d_{5SPW}<d_{3SPW}<d_{1SPW}<d_{distilled}<d_{frotherless}}$. The error bars shown are within each other's error even though the bubble size decreased with increased ionic strength. Figure 6.7 to Figure 6.8 show the bubble size distribution for all tested conditions.

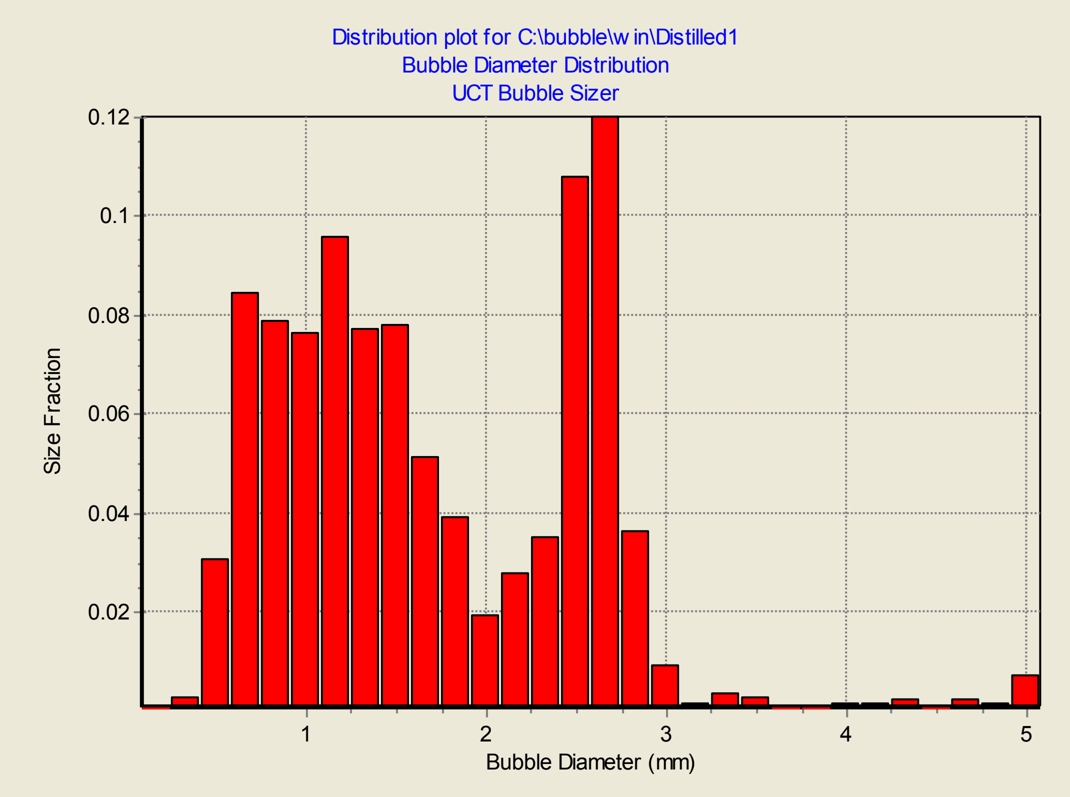


Figure 6.7: Frotherless bubble size distribution.

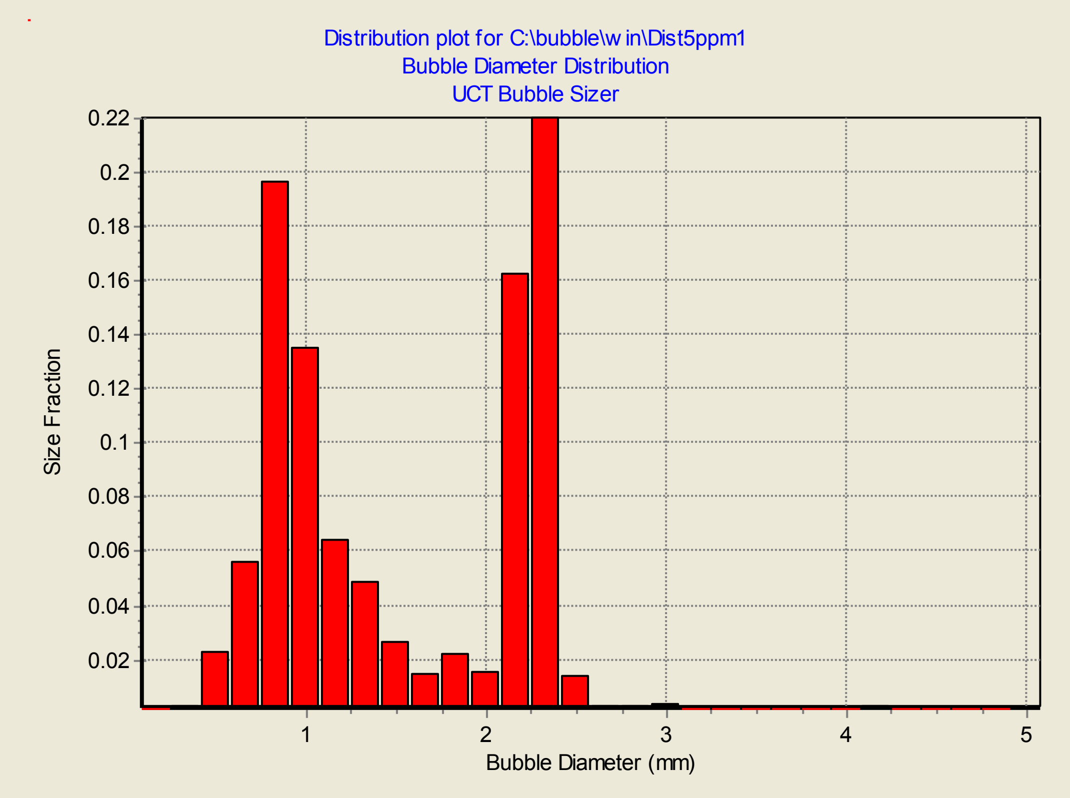


Figure 6.8: Bubble size distribution for distilled water.

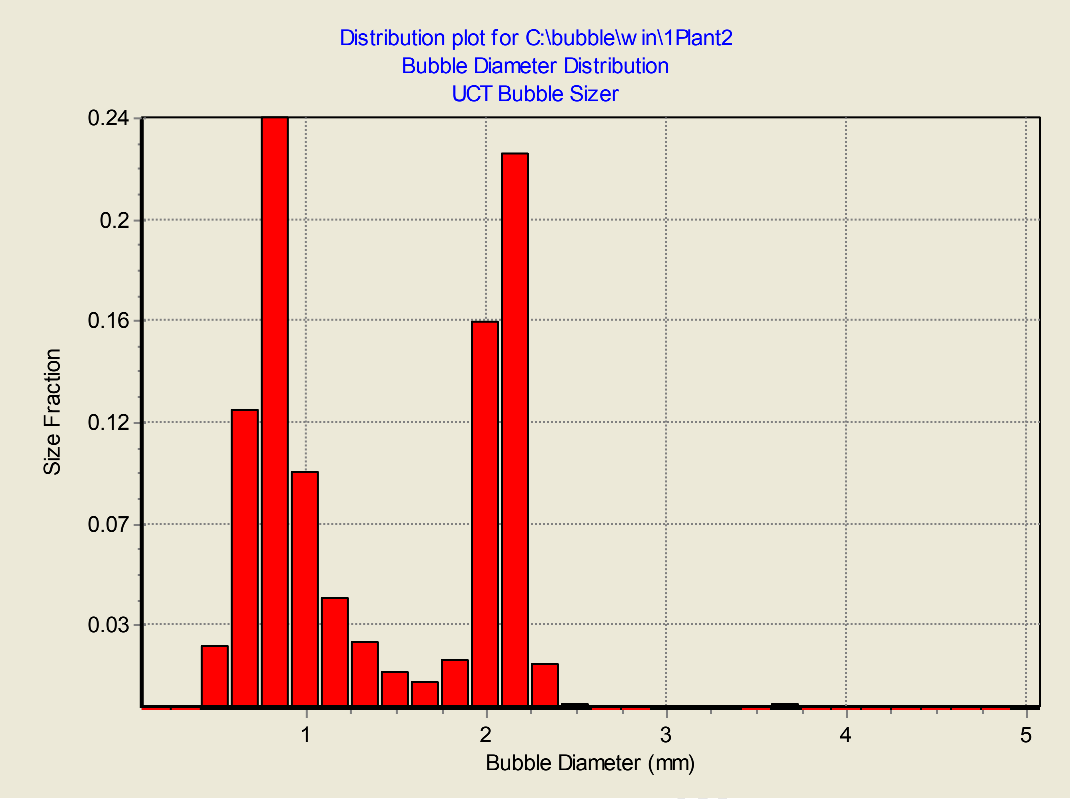


Figure 6.9: Bubble size distribution of 1SPW.

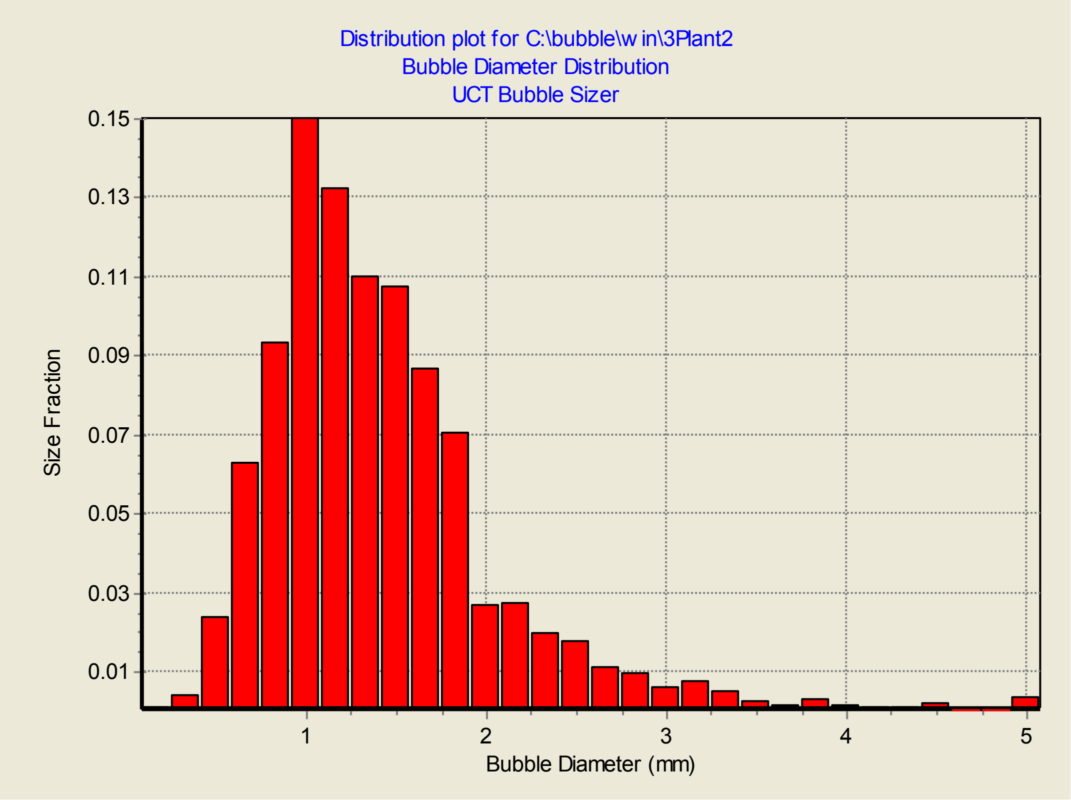


Figure 6.10: Bubble size distribution of 3SPW.

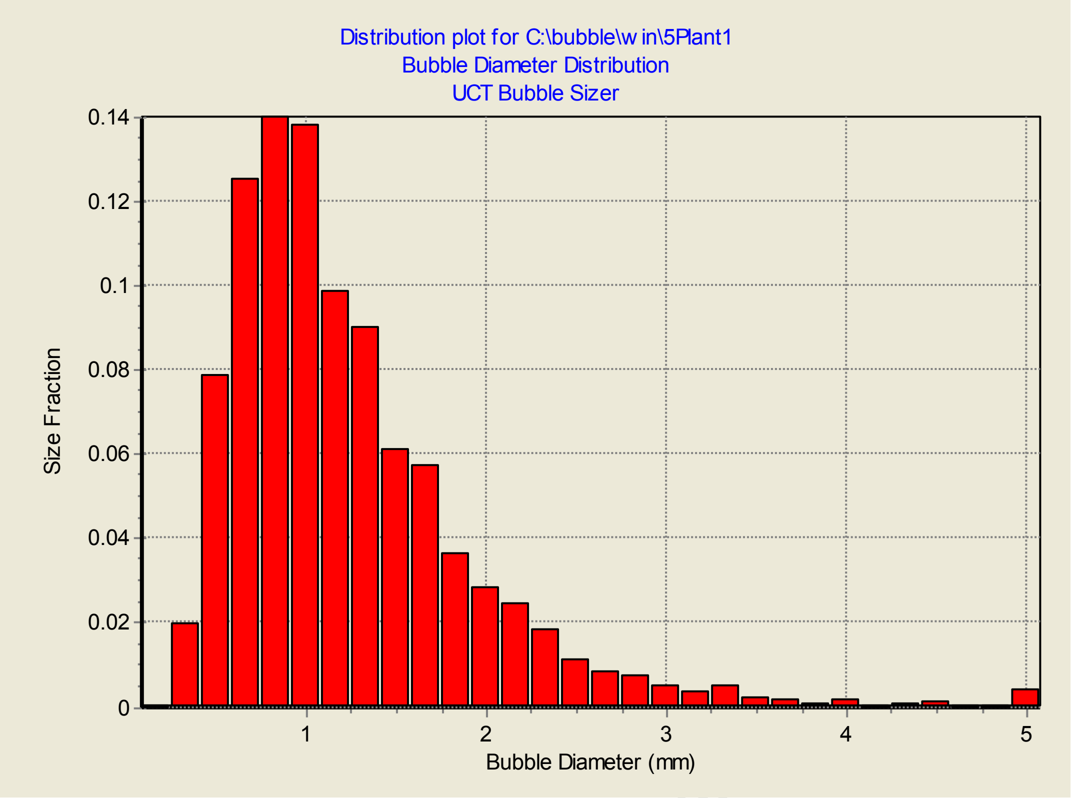


Figure 6.11: Bubble size distribution of 5SPW.

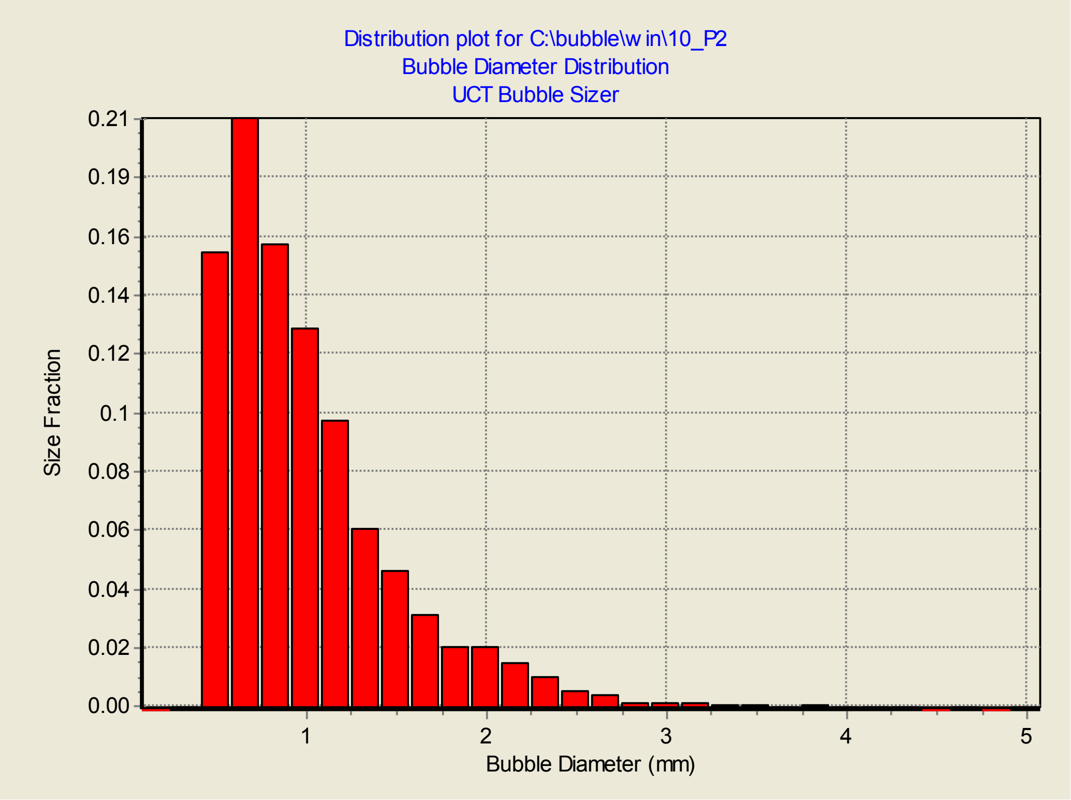


Figure 6.12: Bubble size distribution of 10SPW.

6.1 Key Findings

The effect of ions in the 2-phase batch flotation column was investigated by conducting tests on the foam/water recovery and gas dispersion properties (such as the bubble size diameter and bubble size distribution, foam height and foam collapse rate).

- ✓ An increase in the ionic strength of plant water caused a significant increase in foam or water recovery.
- ✓ The increase in ionic strength led to an increase in the foam height.
- ✓ Pulp-foam interface remained constant with increasing ionic strength.
- ✓ The foam collapse time increased with increasing ionic strength of plant water.
- ✓ The increase in ionic strength caused a decrease in the bubble size

This study has allowed the demonstration of the interactions between ions and air bubbles in the flotation system as well as the impact that ions could have on foamability which may affect the flotation performance of a Merensky ore as foamability and foam stability are critical factors in froth flotation.

7. EFFECT OF SINGLE SALT SOLUTIONS ON THE FLOTATION BEHAVIOUR OF VALUABLE MINERALS IN A MERENSKY ORE

7.1 Effect of Single Salt Solutions at the 1SPW Ionic Strength on Floatability

7.1.1 Test Conditions

The conditions used to elucidate the effect of single salt solutions at 1Plant ionic strength on the flotation behaviour of sulphide minerals in a Merensky ore in the absence of a depressant are shown in Table 7.1.

Table 7.1: Test conditions for the investigating the effect of single salt solutions at 1Plant ionic strength

Description	*Condition*
Water type and ionic strength	1SPW Single salt solutions at 0.0213 mol/L (Table 4.3)
Collector and dosage	SIBX at 150 g/t
Frother and dosage	Dow 200 at 40 g/t

7.1.2 Summary of Mass Balancing

Table 7.2: Summary of results obtained for single salt solutions at 1Plant ionic strength

Flotation Condition	Mass (g)	Water (g)	Cu rec (%)	Cu grade (%)	Ni rec (%)	Ni grade (%)
1Plant	85.49	759.77	87.60	0.61	56.13	1.03
NaCl	91.88	727.88	88.30	0.55	59.70	1.10
$NaNO_3$	95.06	757.94	89.21	0.60	59.93	1.09
Na_2SO_4	90.86	605.64	87.42	0.55	58.34	1.08
$CaCl_2$	82.34	831.02	88.73	0.58	59.26	1.15
$Ca(NO_3)_2$	78.82	768.93	86.93	0.63	59.72	1.26
$CaSO_4$	88.36	851.96	87.60	0.57	55.73	1.00
$MgCl_2$	87.93	828.03	88.46	0.60	59.69	1.19
$Mg(NO_3)_2$	88.04	794.39	87.66	0.62	60.17	1.25
$MgSO_4$	90.60	884.30	88.68	0.60	60.64	1.14

The results obtained for final solids and water recovery are shown in Figure 7.1 and Figure 7.5 such that Figure 7.1 gives a clear indication of the cation effect and Figure 7.5 showing the anion effect. In Figure 7.1 the behaviour of the selected ions is also compared to that of 1SPW on the selected Merensky ore.

7.1.3 Final Solids and Water Recovery

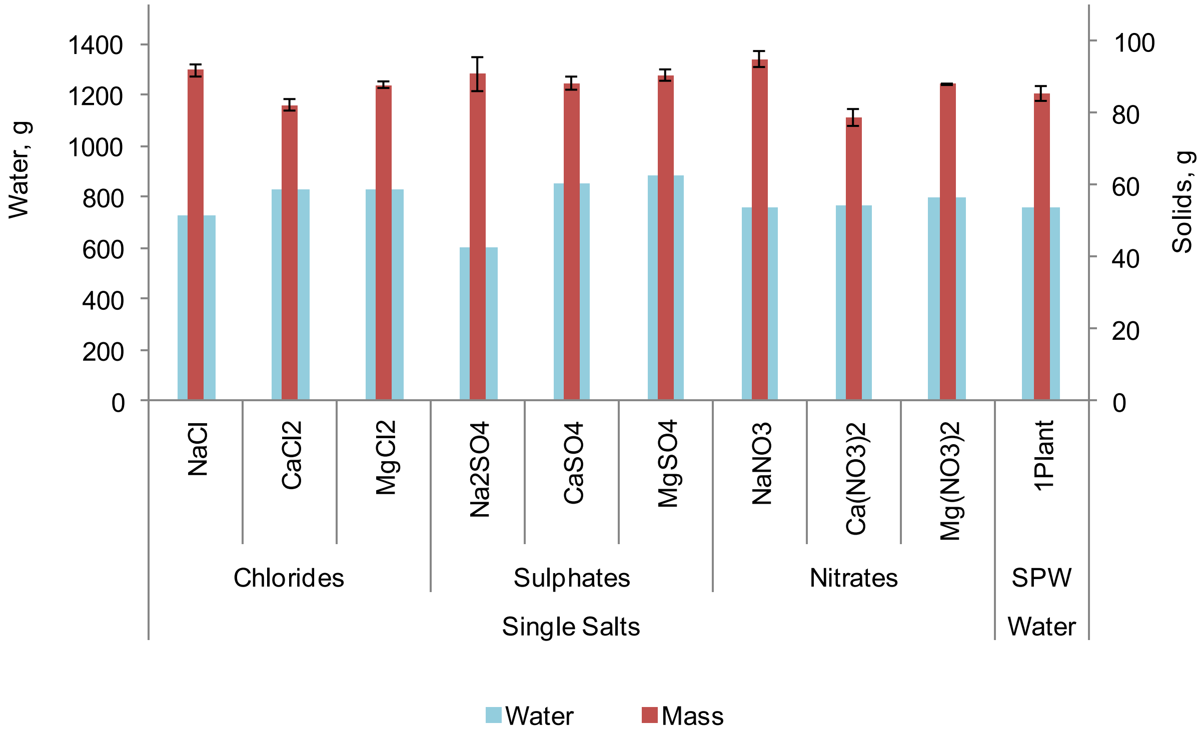


Figure 7.1: Final solids and water recovery for all single salt solutions - the cation effect, in comparison to 1SPW

Figure 7.1 shows the final amount of solids and water recovered for all tested single salt conditions. The results depicted in this figure illustrate the cation effect, and these are compared to those of 1SPW. It is evident that the amount of water recovered with each tested did not deviate from that which was found when normal synthetic plant water was used, however significant differences were observed in the amount of mass recovered with different ions in water. A finding that stood out is that the salts of sodium gave much higher solids recoveries with all anions than the divalent calcium and magnesium. It is also clear that the solids recoveries for salts of calcium and magnesium were comparable to each other. Figures 7.2 through 7.4 show graphs of the solids recovery vs. water recovery for all single salts as a function of their cation.

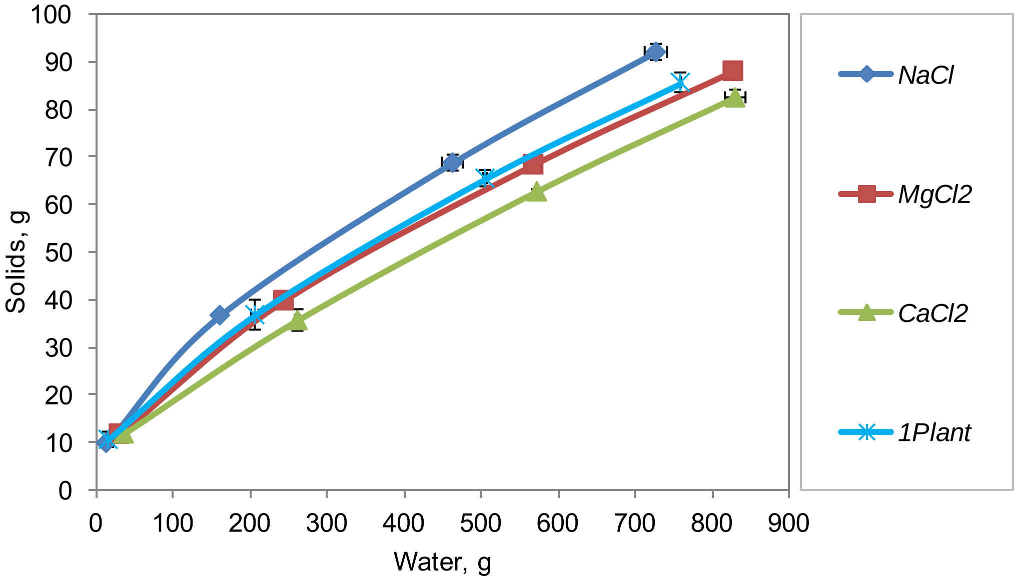


Figure 7.2: Solids recovered vs. water for chlorides and 1Plant.

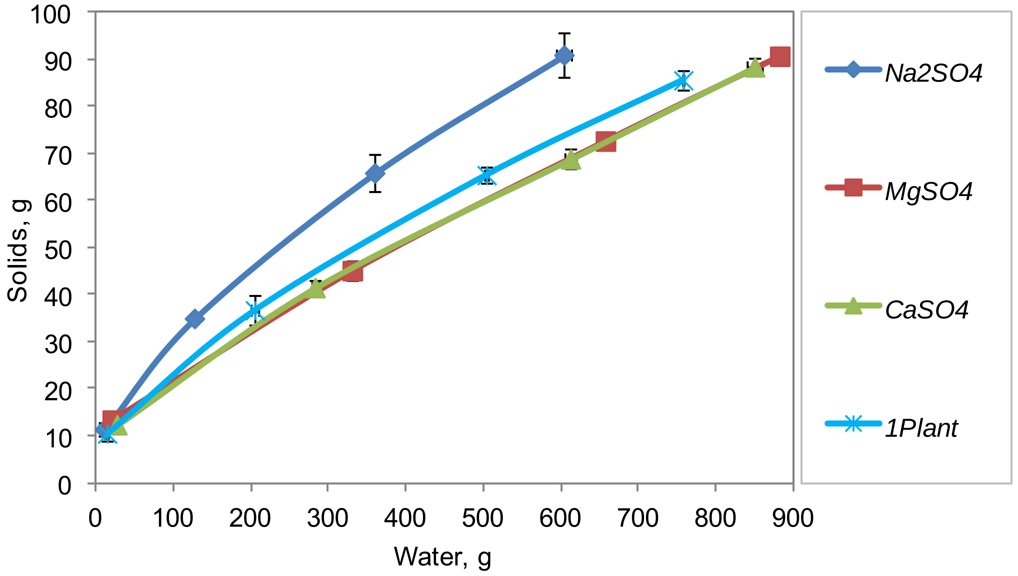


Figure 7.3: Solids recovered vs. water for sulphates and 1Plant.

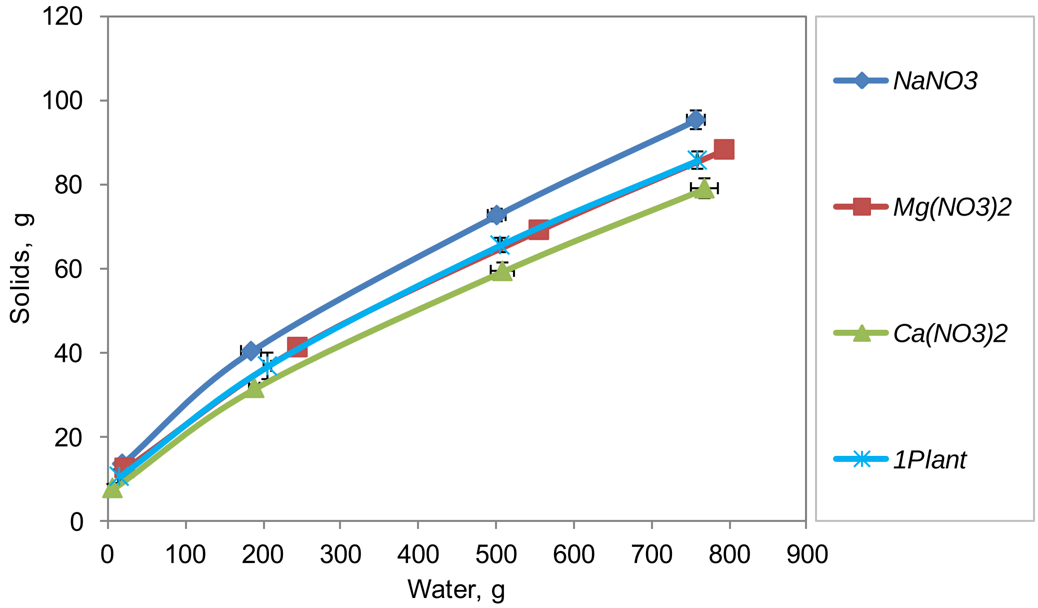


Figure 7.4: Solids recovered vs. water for nitrates and 1Plant.

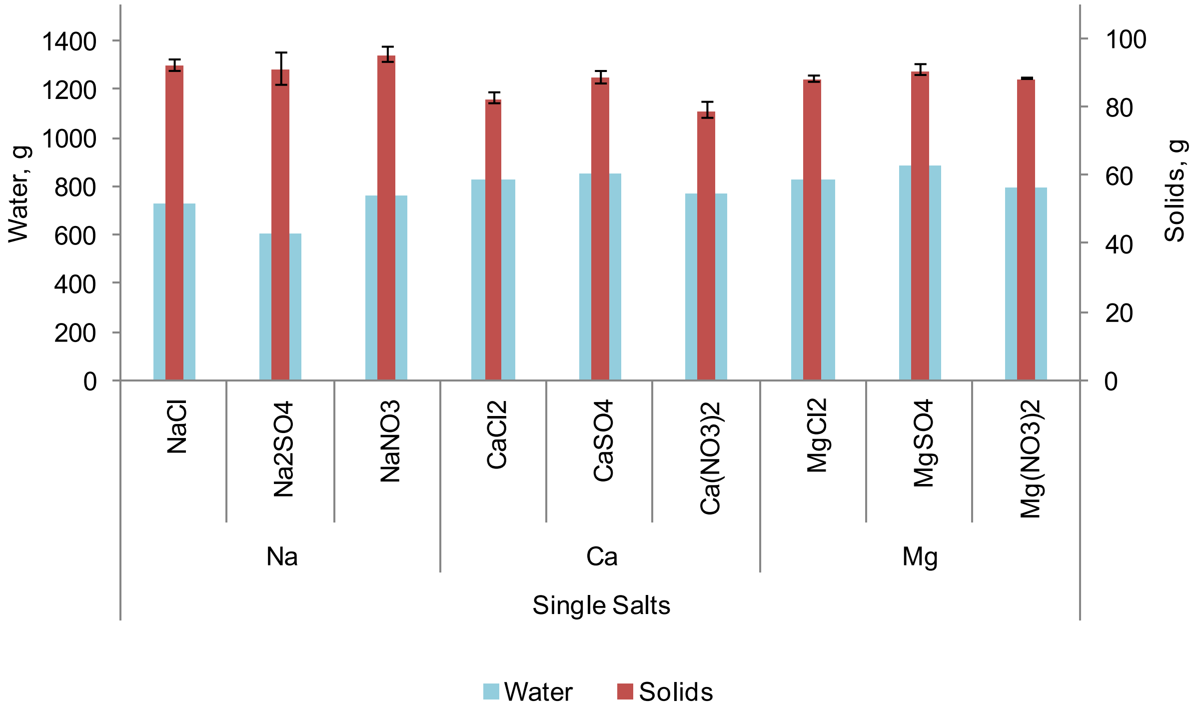


Figure 7.5: Final solids and water recovery for all single salt solutions – the anion effect

Figure 7.5 shows the anion effect for the same results shown in Figure 7.1. If the results on the sodium salts are inspected carefully it can be seen that the change in anion type did not have any effect on the amount of solids and water recovered; the same findings were obtained for calcium and magnesium. Calcium and magnesium, both being divalent cations, did not show significant differences in the final amount of solids and water recovered with all tested anions. This figure demonstrates that the change in anion type had no effect on the amount of solids and water recovered. Figures 7.6 through 7.8 show the solids recovery vs. water recovery for all tested salts as a function of their anion.

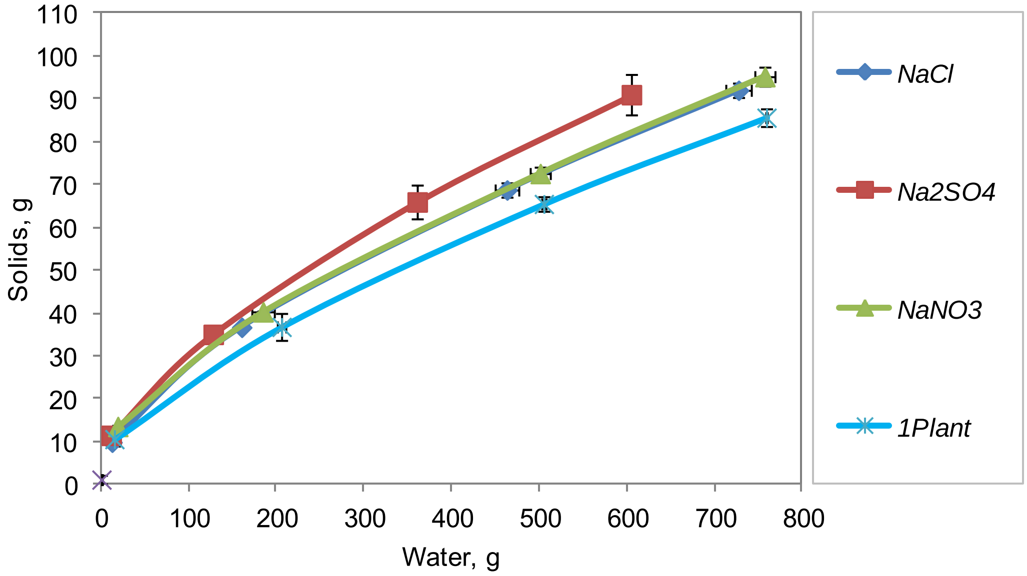


Figure 7.6: Solids recovered vs. water for all Na$^+$ compared to 1Plant.

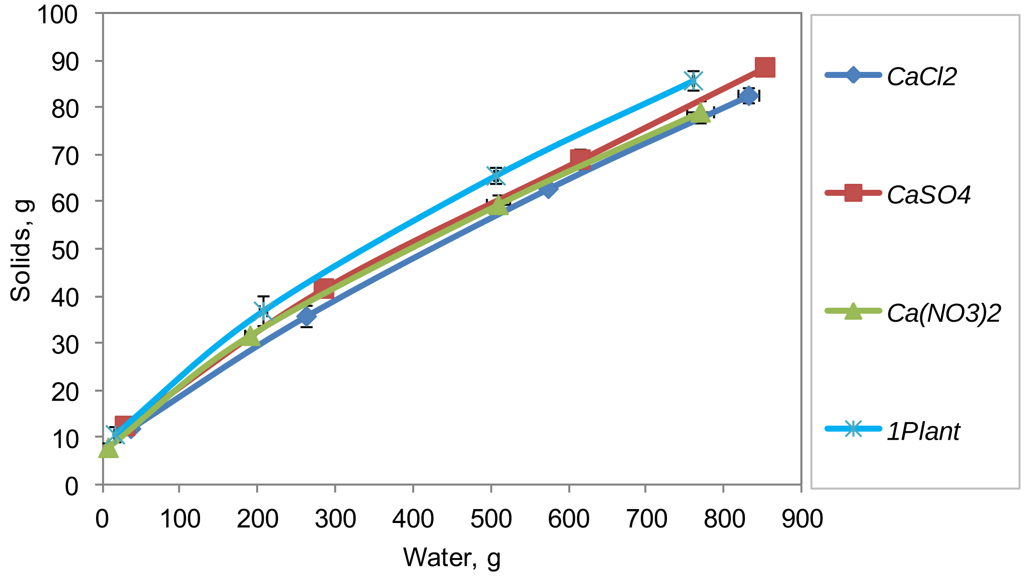


Figure 7.7: Solids recovered vs. water for all Ca^{2+} compared to 1Plant.

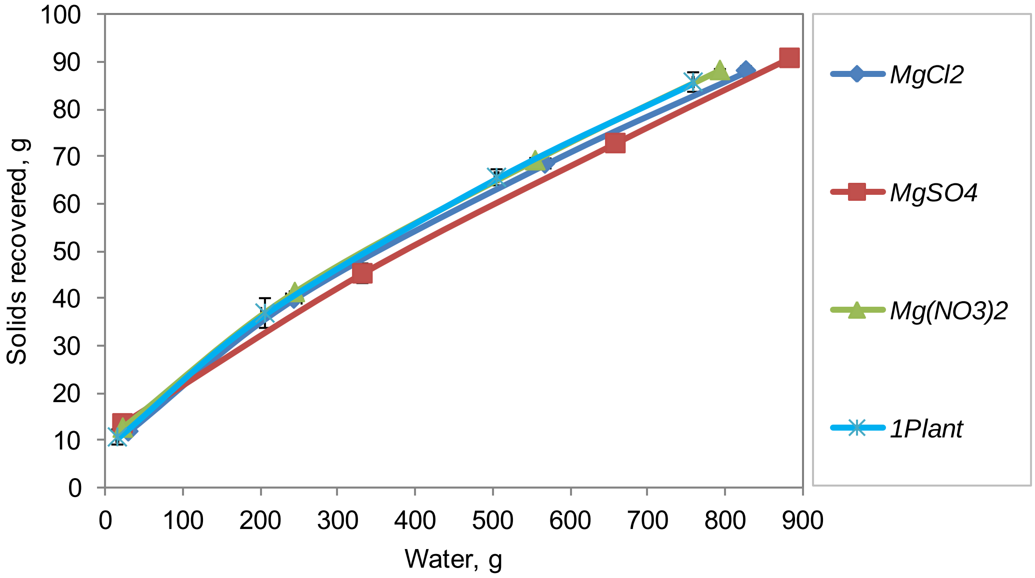


Figure 7.8: Solids recovered vs. water for all Mg^{2+} compared to 1Plant.

7.1.4 Cu Recovery and Grade

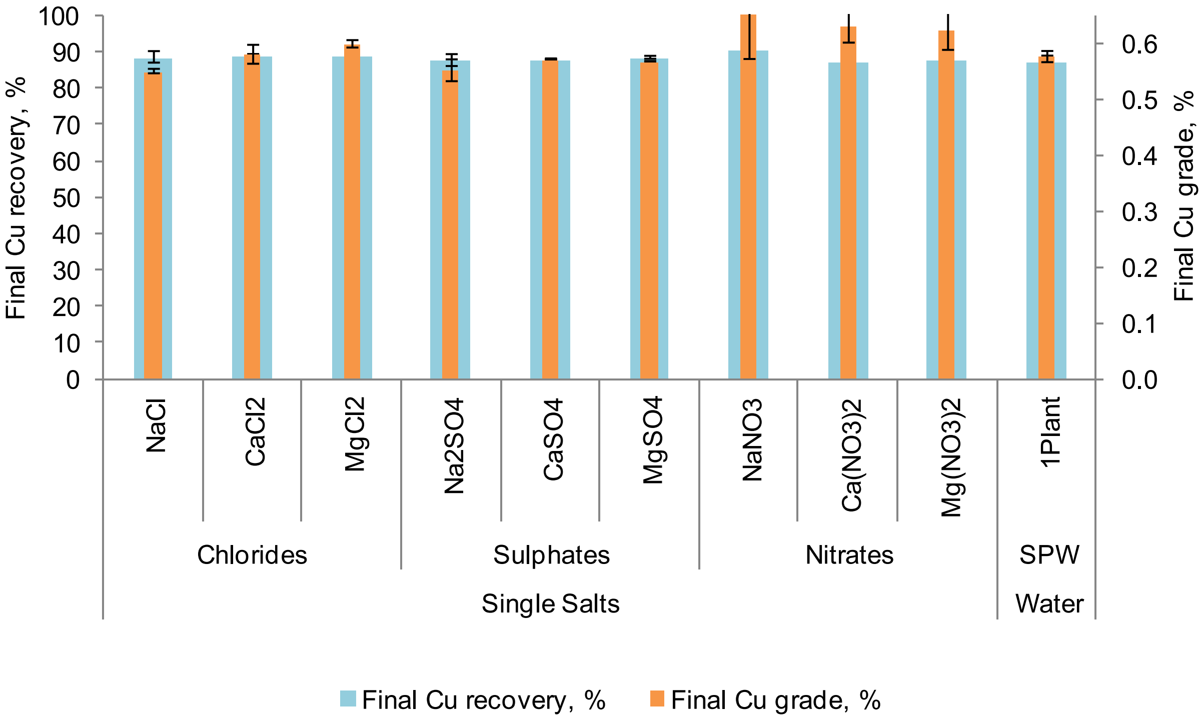


Figure 7.9: Final copper recovery and grade for all single salt solutions – the cation effect, and compared to 1SPW.

Figure 7.9 illustrates the findings obtained for the final Cu recovery and grade for all single salt conditions tested; the cation effect is also shown, i.e. the change in the final Cu recovery and grade with cation type (monovalent or divalent). These results are plotted together with those of 1SPW as a means to detect any ions that deviate from the results obtained when 1SPW was used. As can be seen from the figure, the copper recovery remained the same irrespective of cation or anion type. Cu grade remained unaffected by cation type as the results for sodium, calcium and magnesium were fairly comparable. Cu grades showed a significant increase for the nitrates, but even then, these grades did not show differences with respect to cation type, showing that there was no cation effect on the final Cu recovery and grade. Figures 7.10 through 7.12 show Cu grades vs. Cu recovery for all tested salts as a function of their cation.

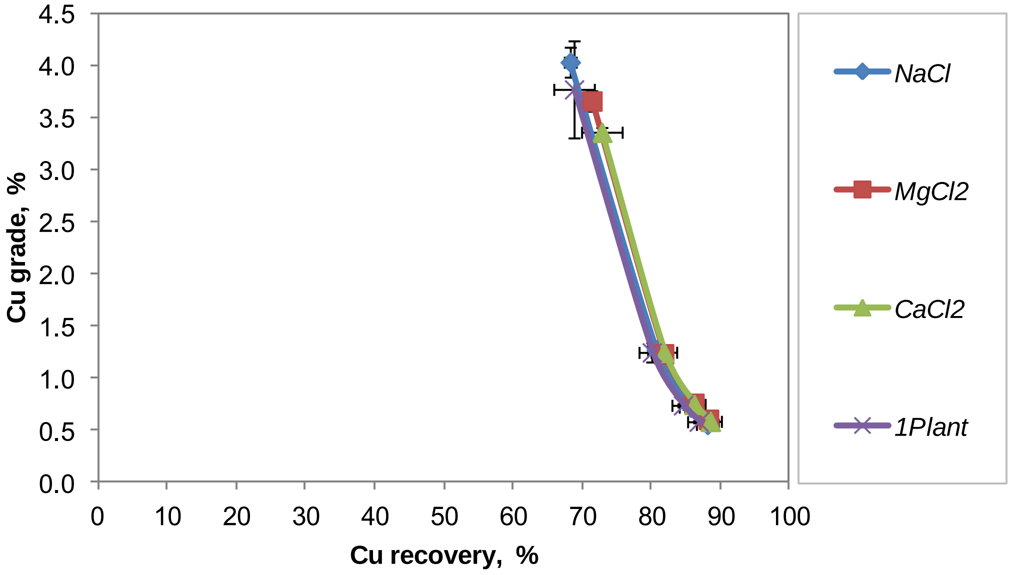


Figure 7.10: Copper grade vs. copper recovery for chlorides and 1Plant.

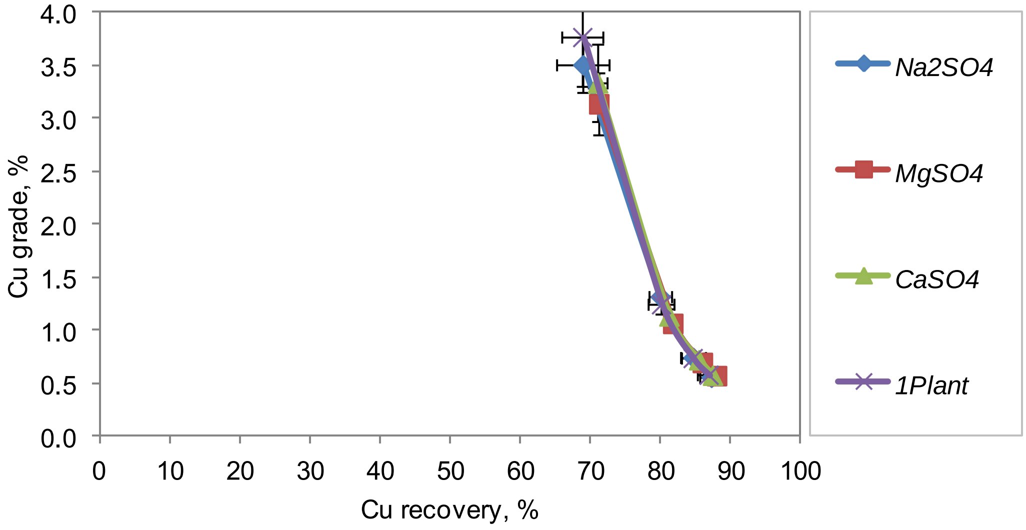


Figure 7.11: Copper grade vs. copper recovery for sulphates and 1Plant.

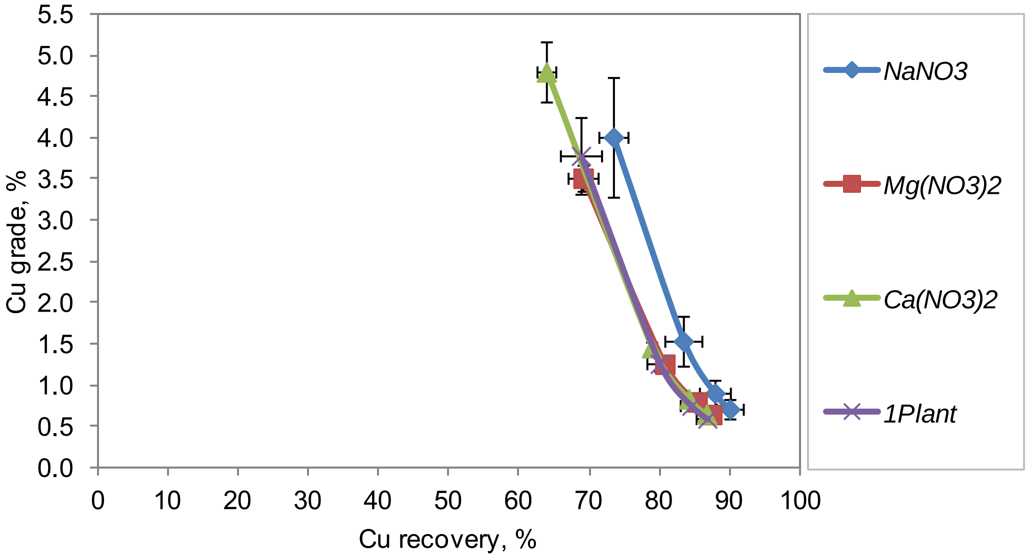


Figure 7.12: Copper grade vs. copper recovery for nitrates and 1Plant.

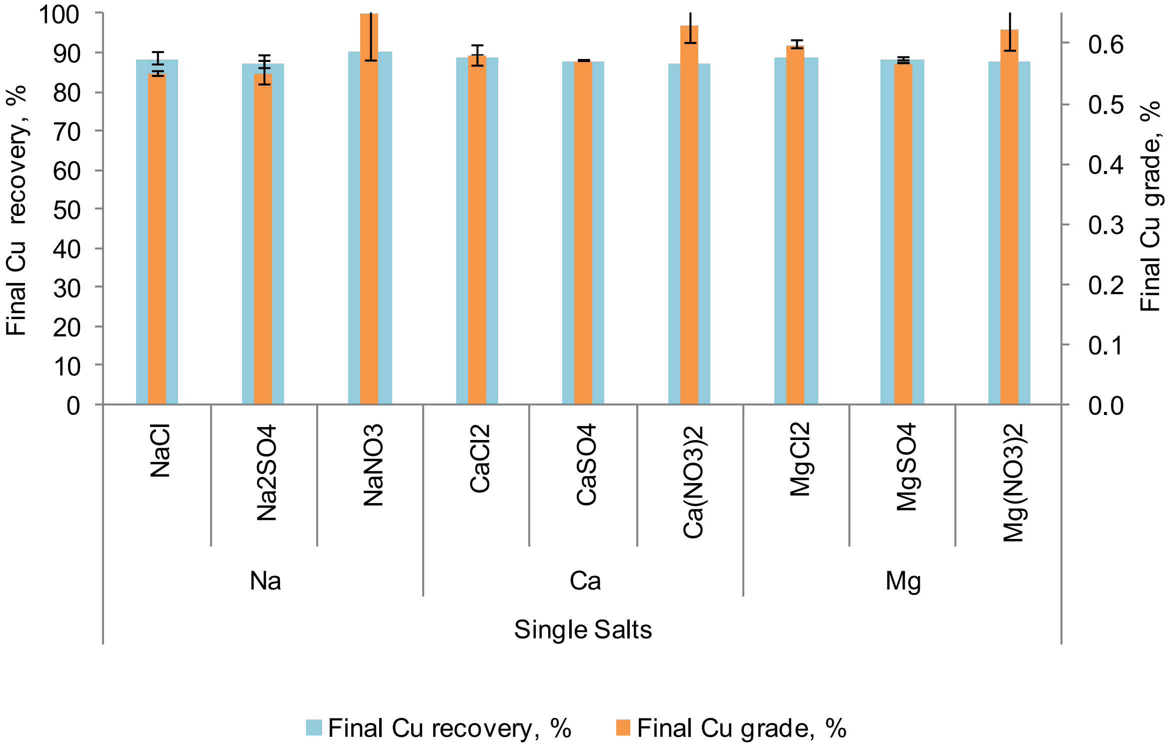


Figure 7.13: Final copper recovery and grade for all single salt solutions – the anion effect

Figure 7.13 illustrates the results obtained for the final Cu recovery and grade showing the anion effect. It is shown that the final copper recovered remained unaffected by changes in the anion type; the final Cu recovery remained in the region of 90 % for all tested conditions. The type of the anion used is however shown to have an impact on the final Cu grade obtained; the nitrates show an increase in the final Cu recovery, whereas the chlorides, sulphates, and carbonates gave similar Cu grades for each cation type. Figures 7.14 through 7.16 show Cu grades vs. Cu recovery for all single salts as a function of their anion.

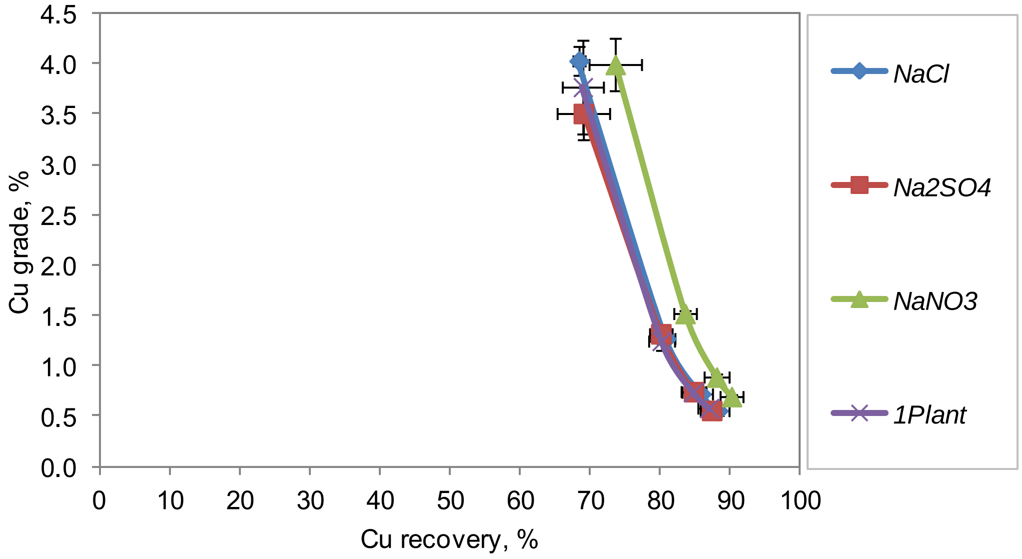


Figure 7.14: Copper grade vs. copper recovery for all Na$^+$ compared to 1Plant.

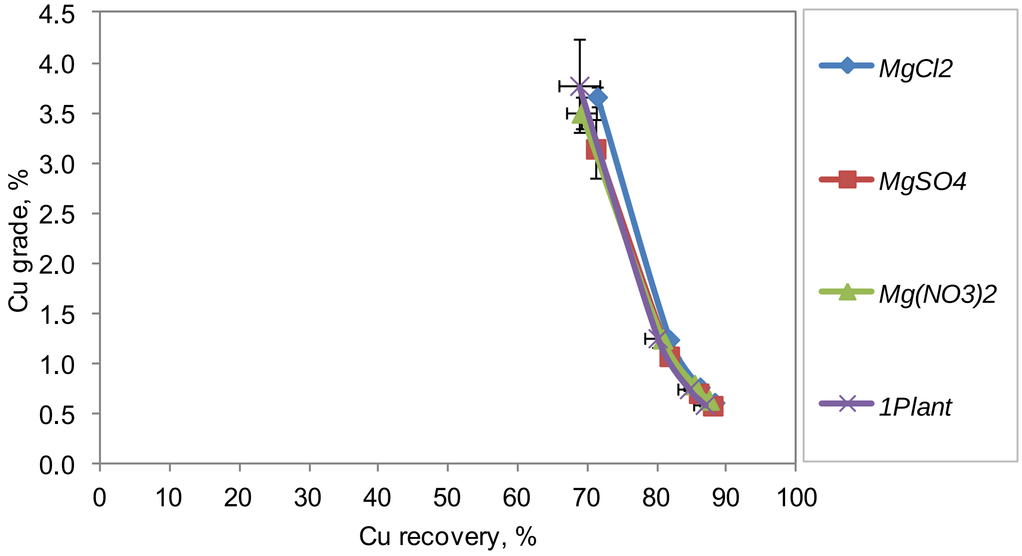


Figure 7.15: Copper grade vs. copper recovery for all Mg^{2+} compared to 1Plant.

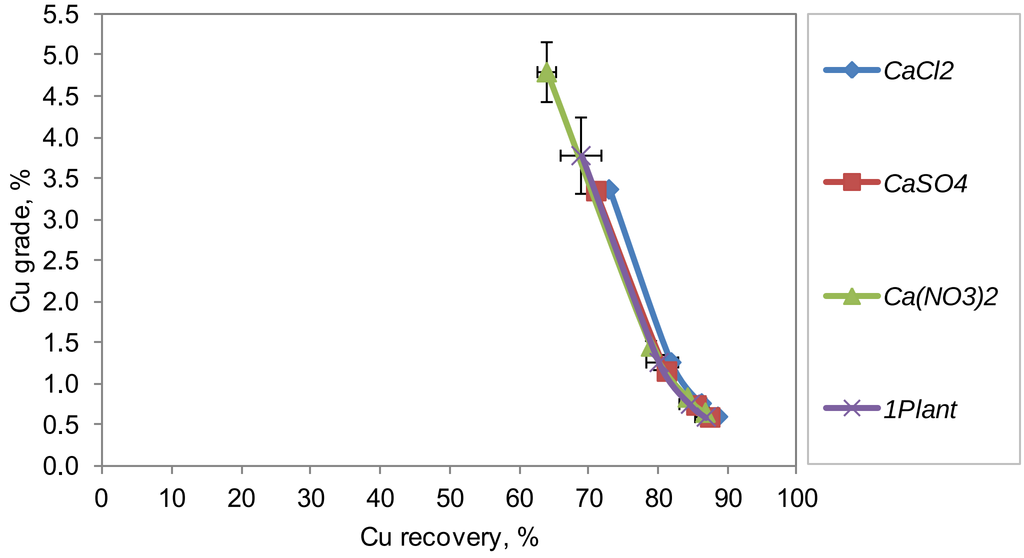


Figure 7.16: Copper grade vs. copper recovery for all Ca^{2+} compared to 1Plant.

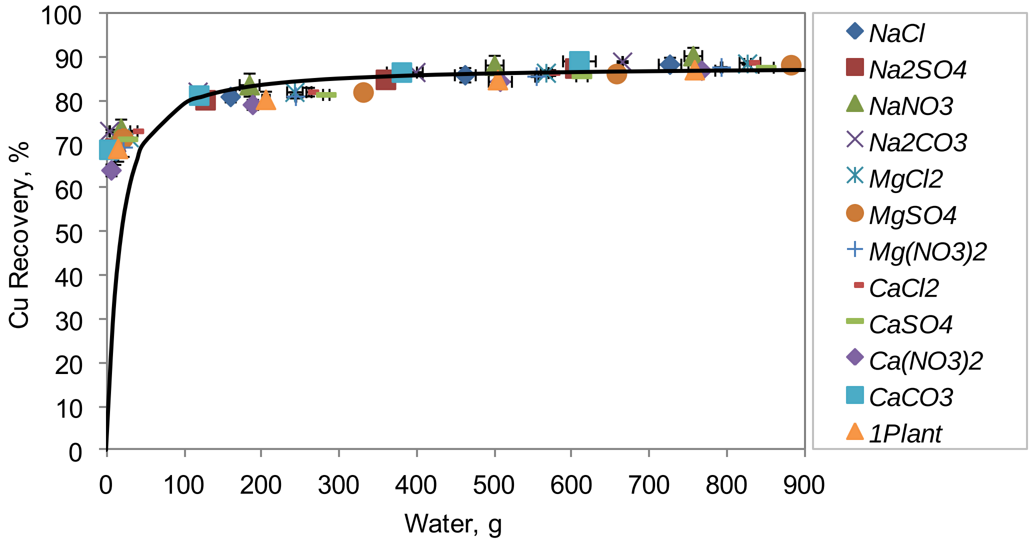


Figure 7.17: Copper recovery versus water recovered for all single salt solutions

The recovery of Cu followed a similar trend for all tested single salts, and this result was to the same as that which was obtained when synthetic plant water was tested at the same ionic strength of 0.0213 mol/L. This is demonstrated in Figure 7.17, which shows the recovery of Cu vs. water recovered. All salts tested yielded the same final Cu recovery as with 1SPW. The maximum Cu recovery attained was about 90 % as illustrated in this figure.

7.1.5 Ni Recovery and Grade

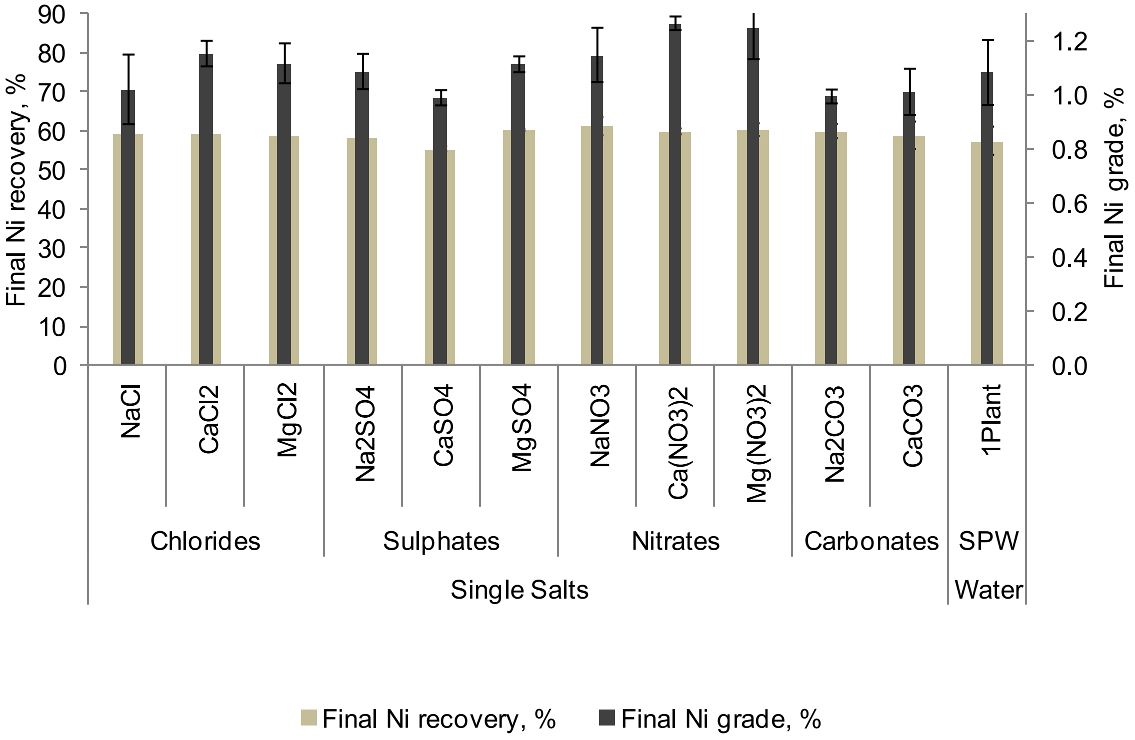


Figure 7.18: Final nickel recovery and grade for all single salt solutions – the cation effect, and compared to 1SPW

The results for the final Ni recovery and grade are shown in Figure 7.18. The results indicate similar Ni recoveries were obtained from the Merensky ore regardless of the salt type; and these results were comparable to those obtained when synthetic plant water was used, maximum Ni recoveries obtained were around 60 %. According to this figure it is evident that changing the cation type did not lead to a significant difference in the final Ni grade. However a significant difference in the final Ni grade was observed when changing the anion type, particularly the nitrates, which gave significantly higher final Ni grades than the other anions investigated. An average final Ni grade of 1.1 % was achieved in the concentrate. Figures 7.19 through 7.21 show Ni grades vs. Ni recovery for all single salts comparing cation effect.

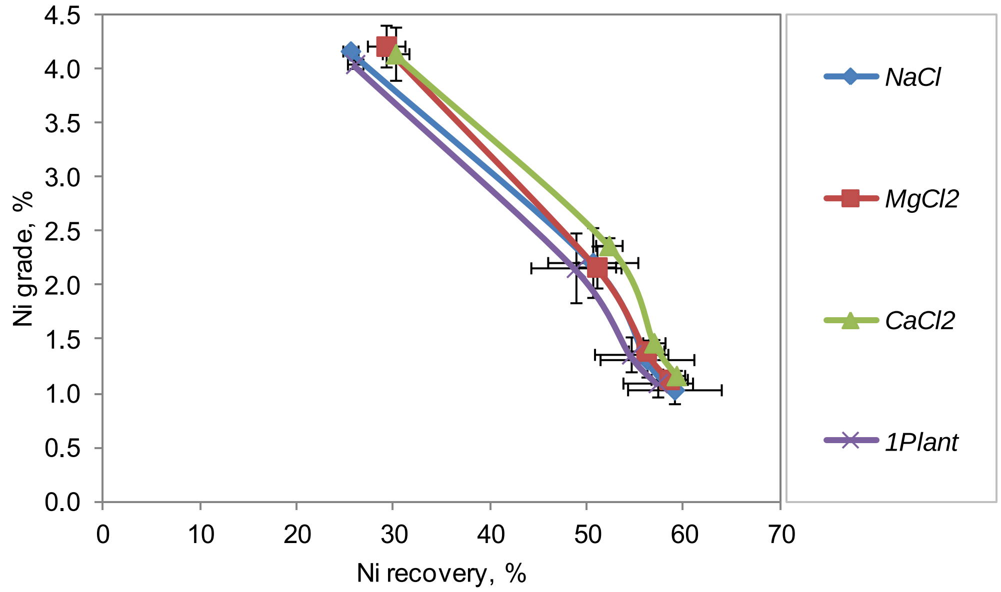


Figure 7.19: Nickel grade vs. nickel recovery for chlorides and 1Plant.

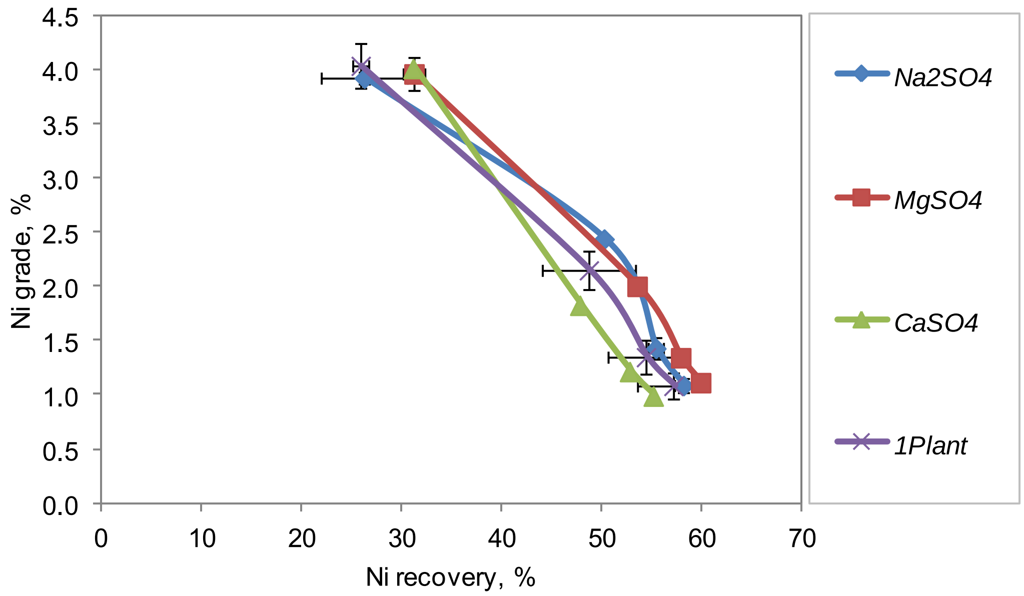


Figure 7.20: Nickel grade vs. nickel recovery for sulphates and 1Plant.

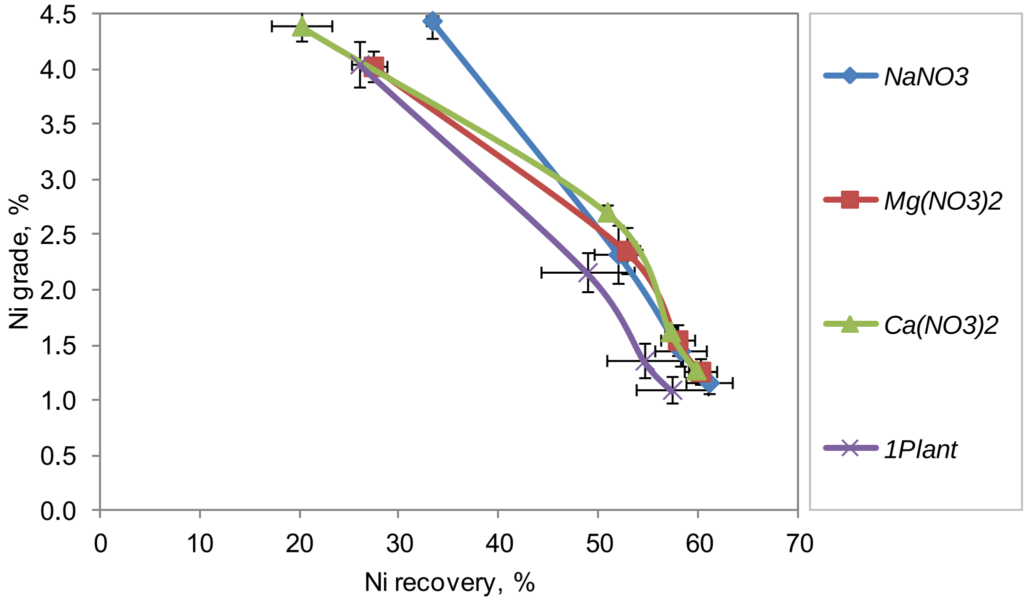


Figure 7.21: Nickel grade vs. nickel recovery for nitrates and 1Plant.

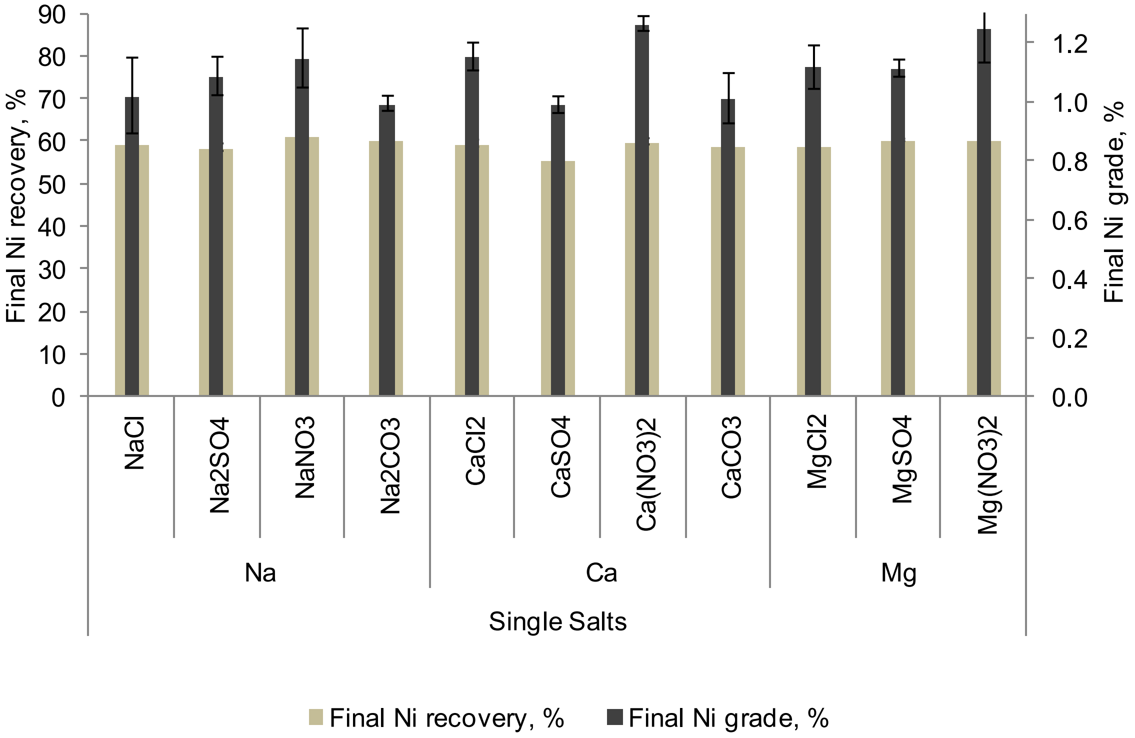


Figure 7.22: Final nickel recovery and grade for all single salt solutions – the anion effect

Figure 7.22 shows the results for the final Ni recovery and grade for all single salts, the anion effect is illustrated in this figure. It can be seen that the deviations in Ni grade between the chlorides, sulphates, and carbonates are insignificant; however the nitrates showed significantly higher Ni grades compared to the other anions. The maximum Ni concentrate grade achieved in the presence of nitrates was around 1.3 %. Figures 7.23 through 7.25 show Ni grades vs. Ni recovery for all tested salts showing the anion effect.

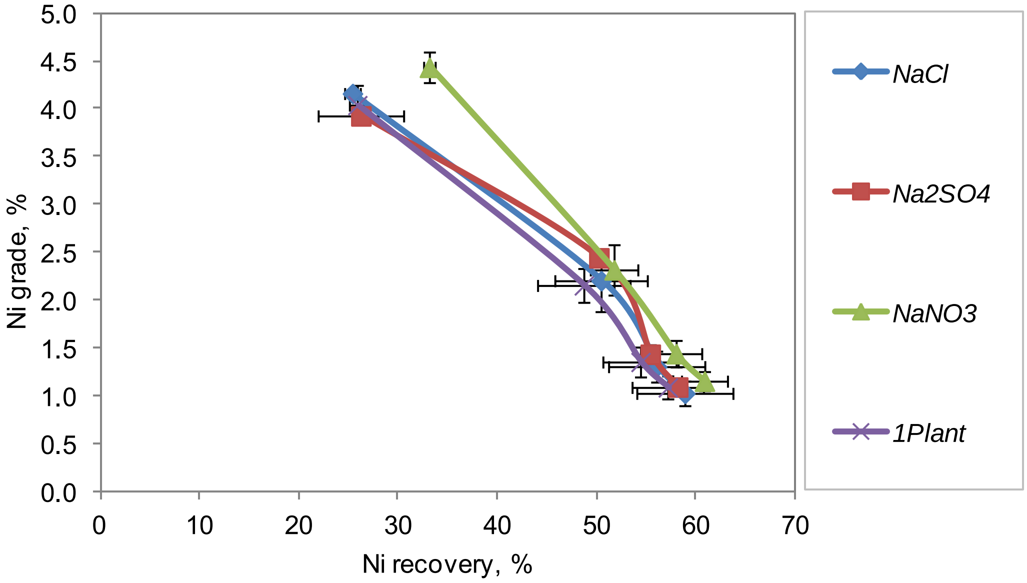


Figure 7.23: Nickel grade vs. nickel recovery for all Na^+ compared to 1Plant.

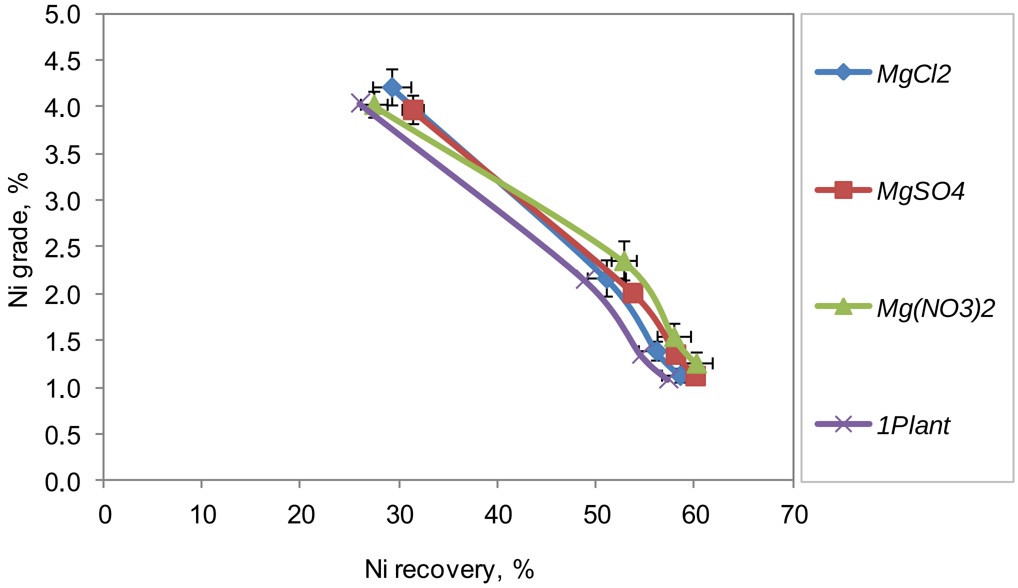


Figure 7.24: Nickel grade vs. nickel recovery for all Mg^{2+} compared to 1Plant.

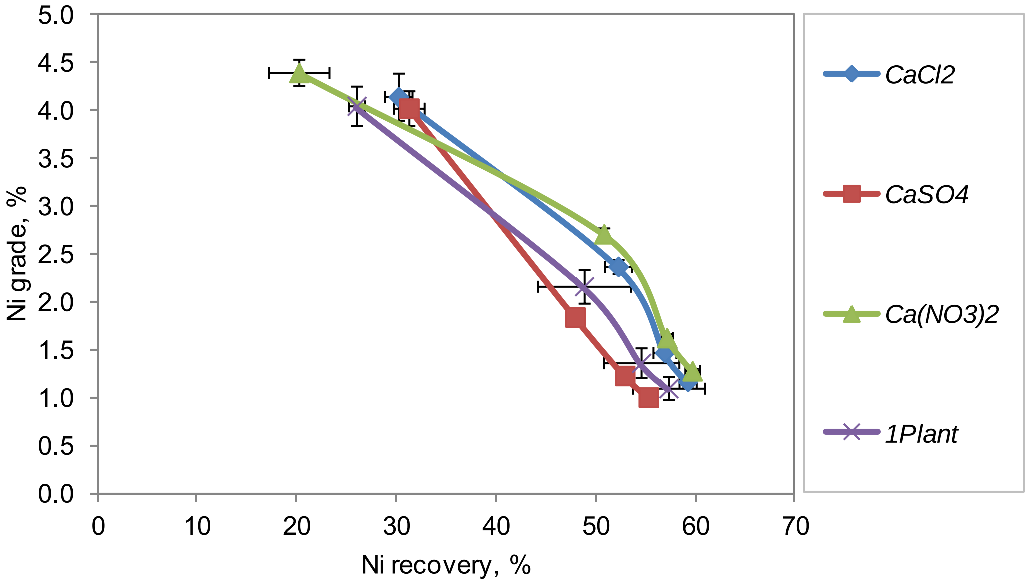


Figure 7.25: Nickel grade vs. nickel recovery for all Ca^{2+} compared to 1Plant.

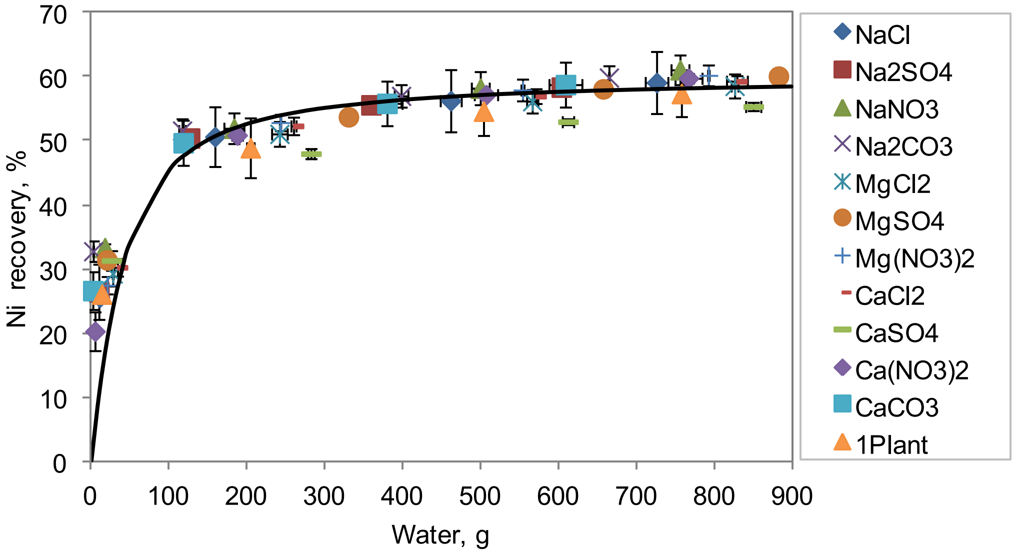


Figure 7.26: Nickel recovery versus water recovered for all single salt solutions

Figure 7.26 shows Ni recoveries vs. water recovered for all tested single salts, and these results are compared to that obtained when using 1SPW. These results illustrate that the change in single salt type resulted in insignificant deviation in the Ni recovery trend obtained with each salt. Thus the use of different single salts at an ionic strength of 0.0213 mol/L was not detrimental to the recovery of Ni since the trends obtained were similar to that obtained when using synthetic plant water at the same ionic strength, and that the rate of flotation of Ni remained unchanged.

7.2 Key Findings

The results have shown that;

- ✓ Higher amounts of solids report to the concentrate in the presence of sodium salts, these recoveries exceeded those obtained with calcium and magnesium salts.
- ✓ Magnesium and calcium salts led to similar solids recoveries, and that all single salts showed similar water recoveries.
- ✓ The change in the anion type had no effect on solids and water recoveries, but it needs to be stated that the nitrates gave slightly lower mass pulls in each cation type.
- ✓ A cation effect was observed as sodium being a monovalent cation led to increased mass pull than the divalent Ca^{2+} and Mg^{2+} ions.

The change in ion type had no effect on Cu and Ni recoveries. The final Cu recovery achieved was about 90 %, whilst that of Ni reached a maximum of about 60 %. These findings were similar those obtained when 1SPW was tested at 0 g/t depressant.

A cation effect was observed on the Cu and Ni grades with Na^{+} giving slightly lower grades owing to the increased solids recovery; however an anion effect became evident as the nitrate salts resulted in higher Cu and Ni grades of 0.65 % and 1.3 % respectively. Whereas the rest of the anions gave similar Cu and Ni grades of about 0.58 % and 1.1 % respectively, these findings were very similar to those obtained when using 1SPW.

8. EFFECT OF SINGLE SALT SOLUTIONS AT 1SPW IONIC STRENGTH ON FOAMABILITY

8.1 Effect of Single Salt on Water Recovery

8.1.1 Test Conditions

The test conditions which were used in 'mineral-less' batch flotation are shown in Table 8.1.

Table 8.1: Tests conditions to evaluate the effect of ionic strength water recovery in a 2-phase batch float.

Description	Condition
Water type and ionic strength	1SPW Single Salts
Frother type and dosage	DOW 200 at 5 g/t

8.1.2 Results

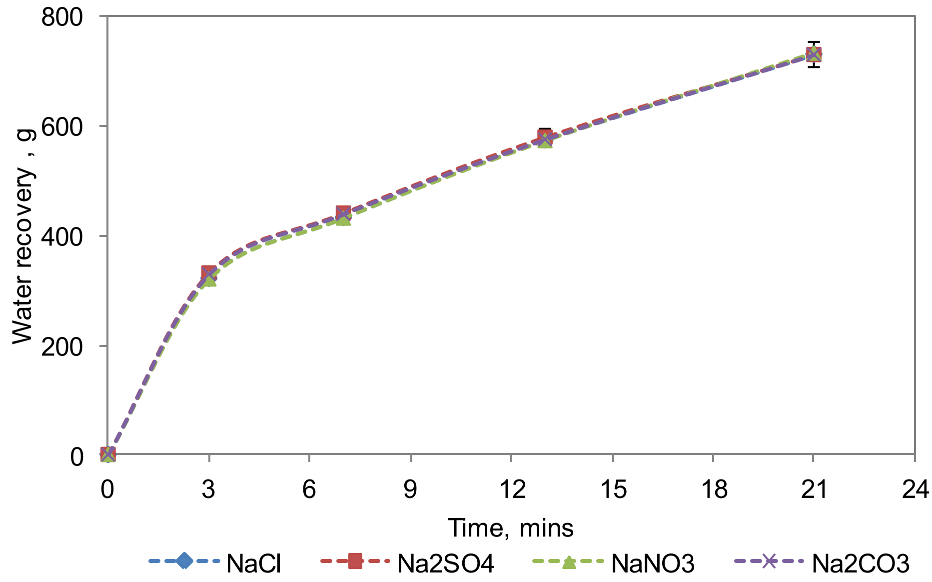


Figure 8.1: Effect of sodium salts on water recovery.

Figure 8.1 illustrates the effect of sodium salts of the four selected anions found in synthetic plant water on the water recovery of a 2-phase batch float system. These results showed that water/foam recovery remained unchanged with all conditions, showing that anion type did not have an impact on foamability or foam mobility.

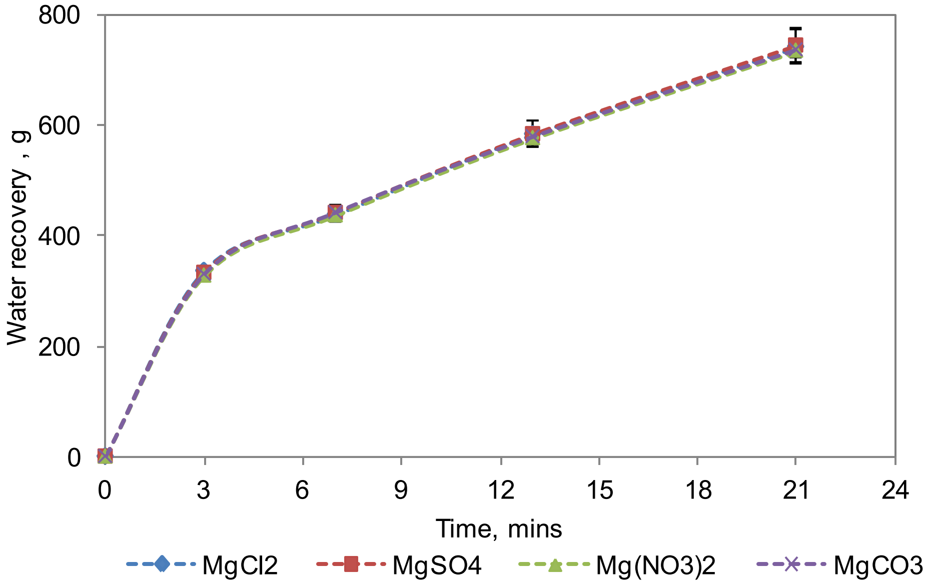


Figure 8.2: Effect of magnesium salts on the water recovery.

Figure 8.2 shows the results of water recovery obtained when using magnesium salts at various anions. Findings show that the water recovery remained constant, indicating that anion type did not have an impact on foam recovery.

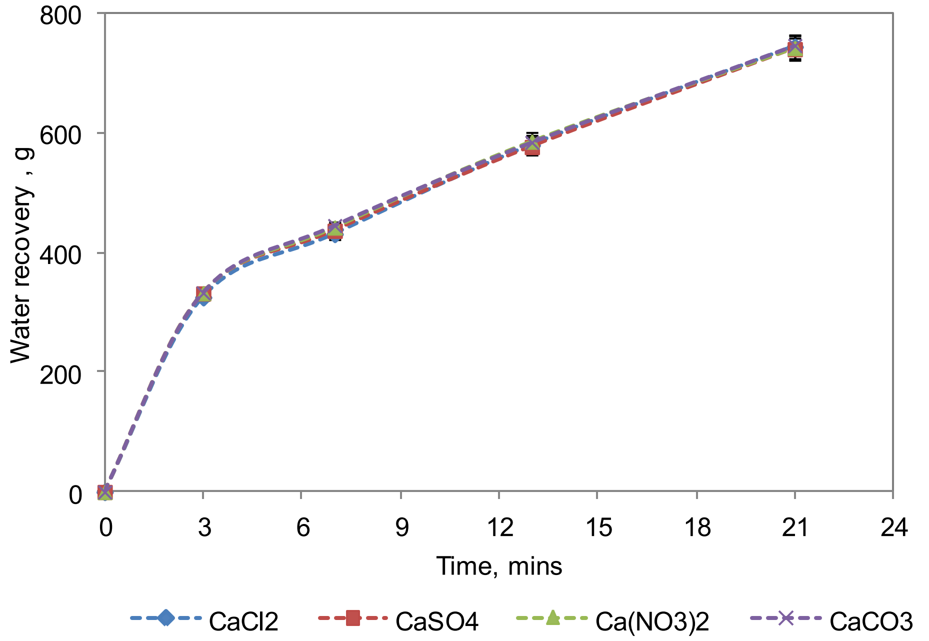


Figure 8.3: Effect of calcium salts on the water recovery.

The effect of anion type of calcium salts on the recovery of water is illustrated in Figure 8.3. Results of water recovery showed a constant trend with anion type. It is demonstrated on this graph that the anion type had no significant impact on the water recovery.

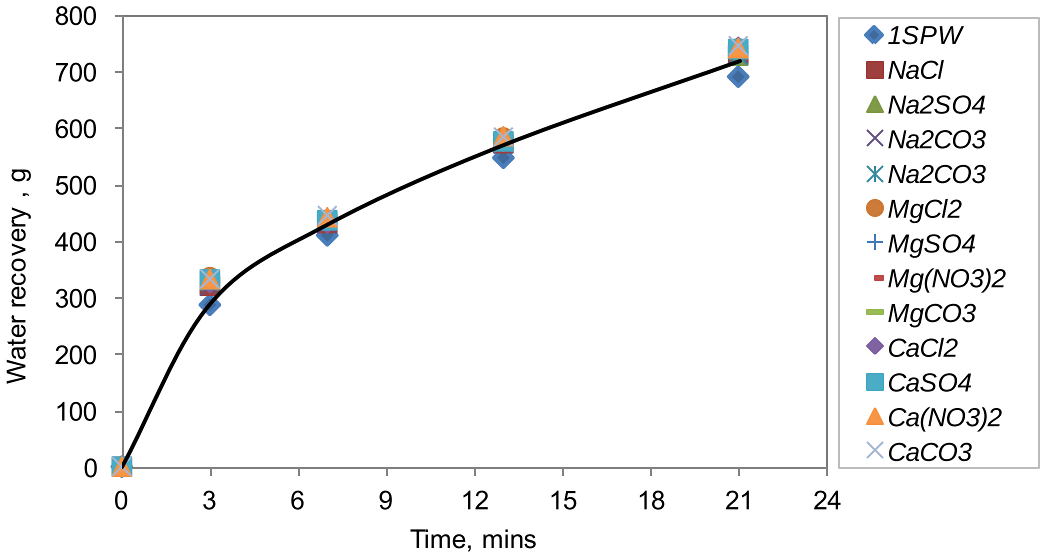


Figure 8.4: Effect of ion type on the water recovery –compared to 1SPW.

Figure 8.4 illustrates the water recovery results obtained for all single salts tests, and these results are compared to 1SPW. According to the graph all single salts followed the same trend as that of 1Plant, thus showing no ion type effect on water recovery.

8.2 Effect of Single Salt on Bubble Size

An investigation of the effect of various ions in plant water on the bubble size and foamability was initiated to complement the 3-phase study carried out on the single salts as shown in Chapter 7. A series of tests was carried out using the UCT Bubble Size Analyser where various single salt solutions were used with DOW 200 added to the flotation column at 5 g/t; the mean bubble diameter and bubble size distribution measurements were obtained from the technique for all tested single ions.

8.2.1 Test Conditions

The test conditions which were used for the investigation of the effect of single ions, cation and anion type on 2-phase pulp bubble size measurements are shown in Table 8.2., this study is very critical as it should provide a better understanding of the impact that various ions could have on foam stability.

Table 8.2: Tests conditions to evaluate the effect of various ions on bubble size in a 2-phase batch flotation column.

Description	Condition
Water type and ionic strength	Single salts
Frother type and dosage	DOW 200 at 5 g/t

8.2.2 Results

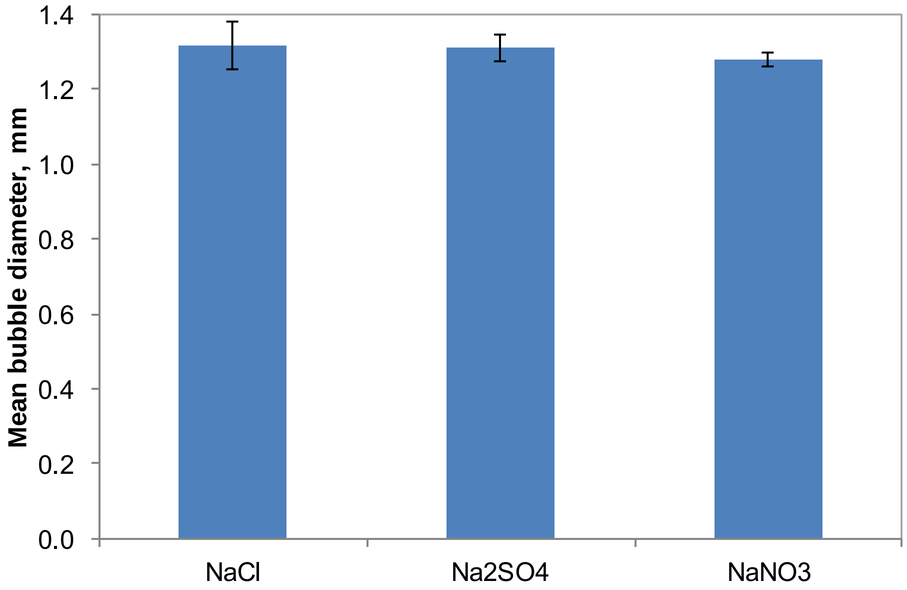


Figure 8.5: Effect of sodium salts on the bubble size.

Figure 8.5 shows the effect of anion type of sodium on the bubble size. The findings illustrate that the anion type had no impact on the bubble size in that the mean bubble diameter remained constant at around 1.3 mm.

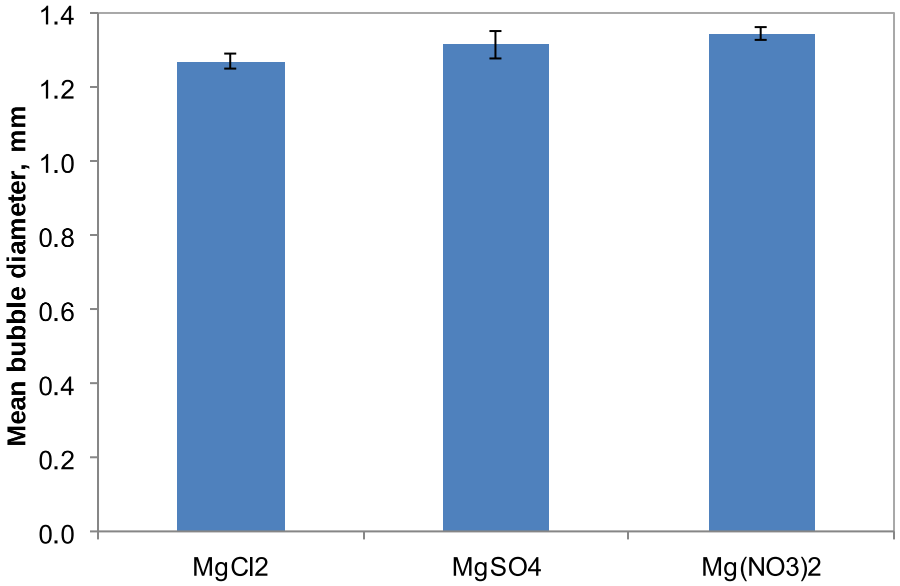


Figure 8.6: Effect of magnesium salts on bubble size.

The results in Figure 8.6 show the bubble size as a function of the anion type of magnesium salts. From this graph it can be seen that the mean bubble diameter remained fairly constant at 1.3 mm. These results (from Figure 8.5 and Figure 8.6) showed that the bubble diameter was unaffected by either anion type or cation type. Sodium being a monovalent cation yielded the same bubble size results as a divalent cation (magnesium) at the 1SPW ionic strength.

8.3 Key Findings

Based on the experimental results of this study the key findings are:

- ✓ The water recovery trend was the same for all single salts tested.
- ✓ There was neither an anion effect nor cation effect on the foam recovery.
- ✓ Foam recovery results were similar to those obtained with 1SPW.
- ✓ Results revealed that for the single salts at 1SPW ionic strength, bubble size measurements did not deviate from those obtained when using 1SPW, in that the extent to which the single salts reduced bubble diameter was the same as that of 1SPW.

9. DISCUSSION

9.1 Introduction

The aim of this study was to investigate the effect of ionic strength of plant water on copper, nickel and NFG recovery from a platinum bearing ore of the Merensky reef. Two Different polymeric depressants at low and high dosages were investigated in the presence of SIBX and a polyglycol ether frother. This study was conducted in order to better understand the impact that the presence of high amounts of ions in plant water could have on the flotation performance of a selected Merensky ore. It was deemed useful to evaluate the impact of increasing ionic strength of plant water on depressant behaviour by considering the response of solids and water recovery; copper and nickel recovery and grade; the recovery of NFG; entrainability; and froth stability.

The understanding of these responses to water quality, ionic strength in particular, could provide solutions by which the use of recycled water could be combated so as to maintain an effective and efficient flotation process that does not contradict environmental laws and profitability standards.

In order to fulfil the objective of the study, a number of experiments were conducted under a series of solution conditions, which were described in detail in Chapter 4. This chapter presents a critical discussion of the key findings of this thesis in the context of available literature, and the key findings will be discussed with a view to ascertain whether the results of this study are in line with the objectives and hypotheses:

- ✓ *The increase in the ionic strength of plant water causes an increase in the solids and water recovery with a consequent decrease in the concentrate grade because the presence of ions increases frothability.*
- ✓ *The increase in ionic strength in the 2-phase system will cause a decrease in the pulp bubble size; consequently the foam height will increase because the presence of the ions improves foamability due to the froth-like properties of the electrolyte solutions..*
- ✓ *Ion type in synthetic plant water may yield different flotation results due to differences in frothing properties.*

This chapter begins with a discussion of the results obtained in investigating, firstly, **the effect of ionic strength on floatability** in a 3-phase system using CMC and guar at low and high dosages. This is followed by a discussion on **the effect of ionic strength on foamability or gas dispersion properties**. This investigation was carried out as it was important to establish whether the ionic strength had any impact on frothability and to confirm the findings of Corin *et al.*, (2011) regarding the impact of ionic strength on 3-phase studies being linked to 2-phase effects. **The**

effect of single salt ions or ion type on floatability is discussed next, and finally **the effect of ion type on foamability**.

9.2 Effect of Ionic strength on Floatability

9.2.1 Effect of Ionic strength on Solids and Water Recovery

The findings of this study showed that as the ionic strength increased, the amount of solids and water reporting to concentrate increased at all depressant dosages. This effect was a result of the enhanced frothability in the presence of high amounts of ions in the water system which possibly led to gangue particle activation, and hence increased the amount of solids as well as water being recovered to the concentrate. It has been postulated that water recovery is a good indication of froth stability (Wiese, 2011; Harris, 2009; Wiese, 2009), therefore it can be said that the increase in the amount of ions and hence the ionic strength stabilised the froth, and thereby increased frothability. This ionic strength froth stabilising effect can be attributed to the fact that inorganic electrolytes reduce the surface hydration of the naturally hydrophobic minerals, which provides attractive forces between the air bubbles and the particles, and it is suspected that the adsorption of salt ions disrupts the hydration layers surrounding mineral particles (Klassen and Mokrousov, 1963). This disruption is known to primarily occur at high ionic strength, where specific adsorption of cations may change the surface charge of the particles and cause strong attraction between the particles (Dishon *et al.*, 2009) however this theory is limited in that it does not account for the minerals that are not naturally hydrophobic. The phenomenon of an increased froth stability could also be explained by the fact that inorganic electrolytes at high ionic strength tend to reduce the zeta potential of bubbles and particles, and compress the electrical double layers and hence reduce the repulsive forces present thereby leaving the hydrophobic force as the only dominant force in the flotation system resulting in increased solids and water recovery and a more stable froth (Yoon and Sabey, 1989; Paulson and Pugh, 1996). It was also illustrated that the increase in depressant dosage (both CMC and guar) decreased the recovery of solids and water at all ionic strengths evaluated, however the decrease varied with ionic strength, showing that the degree to which the depressants depressed floating gangue was affected by the amount of ions present in the system, this result was expected as the primary use of a depressant is to depress the amount of naturally floatable gangue reporting to the concentrate so as to prevent dilution of the flotation concentrate where valuable minerals are collected for further treatment, these findings are in agreement with previous studies (Corin *et al.*, 2011; Mooruth and Booley, 2009).

The increase in depressant dosage not only led to a decrease in floatable gangue recovery, but also indirectly destabilised the froth, because of the removal of froth stabilising gangue such as talc (Bradshaw *et al.*, 2004; Shortridge *et al.*, 2003; Steenberg and Harris, 1984). The tremendous drop in water recovery at a depressant dosage of 500 g/t in comparison to a dosage of 100 g/t is evidence of the impact of depressant dosage on froth stability, and it shows that at 100 g/t dosage the froth stabilising gangue were present in reasonable amounts as can be seen in Figure 5.21 and Figure 5.22. This trend was observed for all ionic strength conditions. It is thus postulated that an increase in the amount of ions or the ionic strength increased the amount of gangue present in the froth phase and therefore stabilised the froth. This is attributed to the reduction in the repulsive force between the bubble and the mineral particles at increased ionic strength (Ozdemir *et al.*, 2009).

The findings suggest that the ions could have promoted frothability as well as froth stability in the 3-phase system, as in the manner of the 2-phase system by altering the surface chemistry of the system as well as gas dispersion properties such as the reduction in bubble size, creating an increased bubble surface area and promoting the attachment of mineral particles, and hence the increase in solids and water recovery.

It has been illustrated that at 100 g/t and 500 g/t dosages, CMC resulted in lower solids and water recovery than guar, this is primarily due to the greater froth destabilising effect of CMC, this result agrees with the study on indirect effects on froth stability conducted by Wiese, (2011). The presence of ions such as Mg^{2+} and Ca^{2+} have been proven to enhance the ability of CMC to depress naturally floatable gangue (Shortridge *et al.*, 1999).

It is important to stress the point that the trend of increasing solids and water recovery in increasing ionic strength is in agreement with the 2-phase batch flotation results, where it was observed that the water recovery increased with increasing ionic strength, showing that the effects observed in the 3-phase study could be directly linked to the frothability effect of the ions, and the impact on depressant ability which also indirectly affects froth stability.

Thus it can be postulated that the impact of ionic strength on floatability depends largely on the influence that the ions have on frothability, both the direct and indirect effects on froth stability are critical factors.

9.2.2 Effect of Ionic strength on Entrainment

The technique developed in the CMR at UCT for decoupling floating gangue and entrained gangue was used in this study (Wiese, 2009). The entrainment factors were obtained for both depressants under all tested water types.

The results presented in Table 5.3 and Table 5.4 illustrate that entrainment is influenced by the ionic strength of plant water. The increase in ionic strength decreased the degree of entrainment as seen in the studies by Corin *et al.* (2011) and Mooruth and Booley (2009). The results showed that CMC resulted in larger entrainment factors than guar under all ionic strengths except for 10SPW, and the trend of a decrease in entrainment with increasing ionic strength was more apparent with CMC than with guar. The possible explanation for this result is that the presence of ions in water created a much more dispersed system, and that the dispersion was even greater for CMC due to its strong negative charge density.

Findings showed that the presence of ions in the flotation system had a strong impact on the performance of these depressants due to interactions between naturally floatable gangue and the depressant in the pulp zone. This indicates that as the ionic strength increased, the coagulation of unwanted gangue within the system possibly increased, and thus particles could exhibit an increased settling behaviour at higher ionic strength as seen by the decrease in entrainment. The vast difference in the coagulative nature of CMC and guar is possibly due to stronger interactions of the ions with CMC, as CMC is a charged molecule with a strong negative charge density. The findings showed that recovery by entrainment decreased with increasing ionic strength for both depressants. It has been shown that entrainment is strongly related to the water recovery (Engelbrecht and Woodburn, 1975; Warren, 1985), and postulated that a decrease in water recovery also decreases the entrainment of particles (Dhliwayo, 2005). However the findings of this study are counter-intuitive in that the degree of entrainment decreased with increasing ionic strength, and thus showing a decrease with increasing water recovery, this behaviour was also confirmed by the comparison between CMC and guar entrainment findings, because CMC resulted in a greater decrease in water recovery than guar yet its entrainment factors were higher than when using guar for all water types. These findings suggest that in the flotation of the selected Merensky ore, the weaker the froth stability the stronger the degree of entrainment and thus more material was recovered by entrainment. These findings show that there was a decrease in the amount of entrained material per unit water as the ionic strength increased, thus suggesting that there was an increase in the coagulative nature of the ore due to the increase in ionic strength probably by the adsorption of Ca^{2+} and Mg^{2+} onto the particle surfaces resulting in a decrease in the surface charge and causing reduction in the entrained mass.

The results showed that entrainment was not significantly influenced by the increase in ionic strength when using guar. The entrainment factors as shown in Table 5.4 were not largely different in guar, whereas with CMC there were significant reductions as the ionic strength increased due to the larger changes in the recovery of naturally floatable gangue, water recovery and froth stability. The results indicate that the use of plant water at high ionic strength in the presence of a depressant at 500 g/t gave rise to less gangue reporting to the concentrate. This occurred even though frothability had increased with the increase in ionic strength, showing that the inadvertent enhancement in froth stability which led to increased NFG recovery can be mitigated by use of an appropriate depressant.

9.2.3 Effect of Ionic strength on Floatable Gangue Recovery

It is known that platinum bearing ore bodies contain a significant amount of naturally floatable gangue minerals such as talc. The recovery of gangue to the concentrates is undesirable as this leads to poor concentrate grades. Therefore polysaccharides such as CMC and guar have been used to effectively depress NFG, and thus improve the concentrate grades (Jenkins and Ralston, 1997; Mackenzie, 1980). It has been speculated that many parameters; one being the ionic strength, can affect the performance of polysaccharides in depressing floatable gangue, therefore understanding the impact of ions on depressant behaviour in NFG recovery mitigation is of fundamental importance.

The study has shown that the ionic strength had an effect on froth stability, because the total amount of floatable gangue reporting to the concentrate increased quite significantly with increasing ionic strength as shown in Figure 5.22; however there was a decrease in the amount of NFG per unit water reporting to concentrate as the ionic strength increased. The results showed that the presence of ions led to an enhanced froth stability evident by the increase in solids and water recovery, whilst simultaneously promoting coagulation thus resulting in a decrease in gangue recovery per unit water.

The trend of a decrease in floatable gangue recovery with increasing ionic strength was observed at depressant dosages of 0 g/t and 100 g/t as shown in Figure 5.20 to Figure 5.22. This was the case for both depressants, although CMC resulted in a greater decrease in the amount of gangue reporting to concentrate than guar, this was expected because guar did not show significant reduction in entrainment and its effect on froth stability was not as pronounced as that of CMC as the ionic strength increased. Shortridge *et al.* (1999) showed that at high ionic strength CMC had a greater depressing effect on talc than did guar; with talc being the main constituent of NFG.

The insignificant decrease in the amount of NFG recovered when using guar is linked to viscosity properties of guar which affects the depressing ability on talc, which agrees with the findings of Shortridge *et al.* (2002) that the influence of ionic strength and ion type is greatly enhanced when using CMC, whereas the depressing ability of guar would not change. It has been shown that the use of high depressant dosages (i.e. 500 g/t) can effectively depress all naturally floatable gangue for both depressants, and this is confirmed in a study on depressant behaviour by Wiese (2009).

It was observed that a depressant dosage of 100 g/t had a major influence on the rate of recovery of NFG as it reduced both the amount and the rate of recovery by more than 60 %. Also the increase in the ionic strength of plant water caused a definite reduction in the rate of recovery of NFG (as indicated by the slopes of the curves in Figure 5.20 to Figure 5.22). This result suggesting that the increase in ionic strength increased the coagulative nature of the NFG particles and also the depressant ability seemed to have been improved as the ionic strength increased, this reduction in the rate of NFG was greater in the case of CMC than guar. This phenomenon was expected because of strong negative charge density on the CMC molecules, it is possible that during this process the presence of Ca^{2+} and Mg^{2+} enhanced the adsorption of CMC onto the NFG surfaces, resulting in the slower flotation rates.

However the assumption that all NFG is completely depressed at 500 g/t and only reports to the concentrates by entrainment was based on the use of standard synthetic plant water (1SPW) which is at the lowest ionic strength. If higher ionic strength conditions such as 10SPW are to be considered and their froth stabilising effect then not all NFG would be depressed at 500 g/t depressant dosage as shown in this study, as the system would need a higher depressant dosage to ensure an effective counter action on the froth stabilising action of the ions which leads into higher solids and water recovery, and therefore slightly increased total NFG reporting into concentrates.

9.2.4 Effect of Ionic strength on Cu and Ni Recovery and Grade

The mass percentages of copper and nickel contained in the Merensky ore used in this study were about 0.048 %, and 0.135 % respectively. Performing batch floats under low and high depressant dosages enabled the determination of maximum NFG recoveries to the concentrates, and thus the estimation of the amount of NFG present in the ore. The ore contained about 4-6 % NFG.

Increasing the ionic strength of the water system led to higher amount of solids and water being recovered to the concentrates. This highlights the impact that ions have on the froth stability of the flotation system as both solids and water recovered increased quite significantly with increasing ionic strength. The presence of high amounts of ions in the flotation system resulted in increased froth mobility which increased the rate at which both the mass and water is recovered. This behaviour is attributed to the ions and ionic strength effect on the effective viscosity(Examiners' report), other authors (Quinn *et al.*, 2007; Crozier, 1992; Iwasaki et al., 1980; Viviers, 1979) have shown that the presence of ions such as Ca^{2+}, Mg^{2+}, Na^{+} and Cl^{-} in the water systems tends to decrease the bubble size, and reductions in the bubble size are known to improve froth stability because of a reduction in the repulsive force between the mineral particles and the air bubbles, so essentially these ions act as frothers in froth flotation due to their effect on the surface tension.

The use of a depressant counter-acted the frothability action caused by an increase in ionic strength. At 100 g/t depressant dosage the mass and water recovery trends were significantly reduced, but a depressant dosage of 500 g/t led to further decreases in the solids and water reporting to concentrates. This result was observed for both depressants, and these findings were as expected because the depressants simply performed their action in the flotation system, which is to depress all unwanted gangue and prevent them from diluting the concentrates. Thus the depressant action was influenced by a change in ionic strength.

An increase in the ionic strength resulted in a decrease on the Cu recovery. The highest Cu recovery achieved was 91.73 %; this is an indication of the fast floating nature of chalcopyrite which is the major Cu containing mineral in Merensky ores. Ni recovery increased with increasing ionic strength, these findings are indicative of the ionic strength effect on pentlandite recovery as pentlandite is the major Ni containing mineral in the selected Merensky ore. However at 500 g/t depressant dosages the depressant activity was enhanced, which saw the average Ni recovery dropping from a maximum of 60 % to a minimum of 45% possibly due to the depression of unliberated pentlandite in the form of pentlandite-gangue composites.

In the absence of a depressant, Cu grades were found to be between 0.8 % and 0.7 % with increasing ionic strength owing to the increase in mass pull, whereas Ni grades decreased from 1.5 % to 1.0% showing that the increase in ionic strength had a significant effect on the sulphide grades under 'depressantless' conditions. This behaviour is attributed to the enhanced frothability which led to increased solids recovery which resulted in higher amounts of gangue reporting to the concentrates and hence the decrease in the sulphides grades.

Cu recovery increased with increasing ionic strength, and decreased with increasing depressant dosage. The reduction in Cu recovery was more pronounced for CMC than guar showing a stronger depressant effect of CMC than guar in high ionic strength conditions. The recovery of Ni showed a slight decrease but yet significant at 0 g/t and 100 g/t depressant dosages for both CMC and guar, with a maximum or final Ni recovery of about 60 %, however at a higher depressant dosage of 500 g/t, and higher ionic strengths (5SPW and 10SPW), the depressing behaviour of CMC and guar were different and hence differences in the Ni recovery were more defined. These findings have shown a significant decrease in Ni recovery to a minimum of about 45 % in the presence of either depressant at 500 g/t dosage. This result showed that the increase in ionic strength enhanced the depressing ability of the polysaccharides as depressants of NFG such as talc under high ionic strength plant water. The decrease in Ni recovery under these conditions is linked to the depression of pentlandite-gangue composites or unliberated pentlandite (Becker *et al*., 2009).

The presence of a depressant led to significant increases in both Cu and Ni grades as expected. The decreasing trend with increasing ionic strength in the sulphide minerals grades was greatly evident in the presence of a depressant. Although the presence of a depressant increased the grades for all water types, the increase in Cu and Ni grades dropped significantly as the TDS and ionic strength increased, thus magnifying the impact that interaction between ions/depressant and mineral could have on a PGM flotation plant.

The results showed that CMC was more effective at increasing Cu and Ni grades at 100 g/t and 500 g/t than guar, as higher mineral grades were obtained when using CMC than with guar. This outcome can be attributed to the nature of these depressants, as guar does not have the strong negative charge density which can disperse pulps as is the nature of CMC (Wiese *et al.*, 2007). Thus the presence of ions in plant water enhanced the depressant activity of both depressants, and led to even higher enhancements in the case of the CMC depressant. The highest Cu grade achieved was roughly 3.75 %, and this was obtained at 1SPW with 500 g/t; the highest Ni grade obtained was about 6 % under the same conditions.

In summary, at a depressant dosage of 500 g/t all NFG had been rendered hydrophilic and was depressed so that floating gangue reporting to the concentrate could only do so by means of entrainment. It was observed that under low depressant dosages such as 100 g/t, CMC had a greater ability to depress NFG as shown by the solids, Cu and Ni recoveries. For all water types, CMC resulted in a significantly higher entrainment factor than guar.

9.2.5 Effect of Ionic strength on Depressant Behaviour

Depressants are paramount in the flotation of PGM bearing ores as they have a significant impact in preventing NFG from reporting to the concentrates. This action is regarded as one of critical importance because less dilution of the concentrate means lower costs on downstream processes, as less processing would be required to refine and purify the recovered valuables.

Solids and water recovery findings have shown that the presence of a depressant could combat the impact of ions on froth stability by depressing quite a significant amount of mass and water, and thus mitigate the excessively high froth and foam mobility in the flotation system. It was found that the amount of solids reporting to concentrate dropped drastically at 100 g/t and 500 g/t. It was also observed that the depressant activity of the guar depressant was significantly higher than CMC at the very low ionic strengths of the 1SPW and 3SPW types, and thus showing guar to have been a more effective depressant than the CMC under normal water qualities as also shown by Wiese (2009), but the depression of solids at 500 g/t depressant dosage was dramatically higher for CMC than in the case of the guar depressant possibly because of the differences in the properties of these two depressants. These results seem to suggest that higher CMC dosages lead to a reduction in the rate of solids and water reporting to concentrate, as froth stabilising NFG is depressed dramatically and its rate of flotation decreased as the ionic strength is increased due to CMC being a froth destabilising reagent.

The changes in Cu and Ni grades in the presence of a depressant were more pronounced compared to the changes seen in the absence of any depressant at varied ionic strengths, suggesting that an increase in ionic strength had minimal effect on the quality of the concentrates as measured by Cu and Ni grades when there was no depressant in the flotation system. It can be postulated that in the absence of any depressant, the interactions between the ions and mineral particles are not strong enough to effectively produce changes in the sulphide mineral grades.

However, when this is evaluated at holistically, a general argument can be drawn; that frothability is the major player and contributor to the flotation behaviour changes as it was observed that the increase in ionic strength resulted in increased amounts of solids reporting to the concentrates, which resulted in a decrease in Cu and Ni grades owing to the increase in gangue recovery.

The use of polysaccharides at 100 g/t and 500 g/t showed tremendous increases in Cu and Ni grades at all ionic strengths. One notable impact was that at the selected dosages the performance of both CMC and guar did not deviate much, however at higher ionic strengths such as 5SPW and 10SPW the CMC depressant showed an enhanced performance in increasing Cu and Ni grades, this phenomenon was expected as Shortridge *et al.* (1999) also found that the presence of ions such as Mg^{2+} and Ca^{2+} in the flotation system can enhance the depressant activity of the CMC polymer due to its strong negative charge density when compared to guar. These concentrate grade findings suggest that the CMC depressant resulted in a greater depression of naturally floatable gangue than the guar depressant. This can be explained by the surface properties or nature of these two polysaccharides, with CMC having a very strong negative charge leading to a greater adsorption of CMC onto gangue and hence a higher degree of coagulation would be expected. However with guar the negative charge is weaker than that of CMC, hence the increase in ionic strength in the presence of Mg^{2+}, Ca^{2+} and Na^{+} would not lead to a strong adsorption of gangue, hence a low coagulation and lesser degree of depression at high ionic strength.

The increase in ionic strength caused a significant drop in NFG flotation and entrainability which indicates that an interaction occurs between the ions and the surface of NFG such as talc. It is known that talc has a highly negative zeta potential at a pH of 9 (Morris, 1996; Steenberg, 1982), which is attributed to the water layer surrounding the planes of talc. It is possible that the ions Mg^{2+} and Ca^{2+} adsorb onto the planar surface, displacing the water shield surrounding it and thus reduce the surface hydrophobicity thereof. It would also be expected of the divalent cations Mg^{2+} and Ca^{2+} to give a greater contribution to the enhanced depression of NFG at higher ionic strength than the monovalent cation Na^{+}. Guar showed a poorer performance in decreasing gangue recovery, and its entrainment factors remained fairly constant with changes in ionic strength, and were significantly higher than when using CMC. This showed that increasing the ionic strength of plant water in the presence of guar did not result in a significant reduction in the natural floatability of gangue. It is possible that sufficient adsorption of these ions on the NFG surface was already obtained at the lower ionic strength and increasing the ions in the system would therefore not result in further adsorption.

9.3 Effect of Ionic strength on Foamability

Foam height, bubble size and bubble coalescence are considered to be key factors which determine the stability of the froth in a flotation system. Knowledge and understanding of the froth stability in flotation plants is of vital importance because achievable mineral recovery and concentrate grades depend strongly on these factors. Furthermore the rate of particle collection is a strong function of air rate and bubble diameter, both of which affect the gas hold-up. Thus, knowledge of the actual gas hold-up and bubble size in froth flotation is presently considered a key aspect in the study of new control strategies for flotation columns. The impact of increasing the ionic strength of plant water on foamability was investigated in order to verify the postulation by Corin *et al.* (2011) that an increase in froth stability in the presence of solids (i.e. 3-phase) can be directly linked to the increase in the 2-phase foamability of the frother rather than any changes in the hydrophobicity of the solids and because it has been found that some concentrators in mineral processing do not employ frother due to the high salt content in plant water from recycle water (ca. 30 000 ppm) (Quinn *et al.*, 2007). Two phase (solution-air) tests were undertaken, firstly in a laboratory batch float to quantify the effect of ionic strength on water recovery; and secondly in a laboratory froth column to quantify the effect of ionic strength on froth height and froth collapse rate; and thirdly on the UCT Bubble Size Analyser to quantify the impact of ionic strength on bubble diameter and bubble size distribution. These measurements focused on gas dispersion properties (i.e. bubble size, froth height, froth collapse rate and gas hold-up) and froth recovery.

The presence of ions as electrolytes in aqueous solution is known to reduce bubble coalescence (Marruci and Nicodemo, 1967). The effect of ions on bubble size and froth height has been investigated (Kurniawan *et al.*, 2011; Peng and Seaman, 2011; Finch *et al.*, 2008). These investigations suggest that some salts such as Na_2SO_4 and NaCl possess some form of frothing behaviour due to the bubble size reduction ability which was comparable to frothers such as methyl isobutyl carbinol (MIBC) and polyglycol frothers.

The effect of ionic strength on water recovery was investigated by testing four water types of varying ionic strengths in the presence of DOW 200 at 40 g/t. These 2-phase batch flotation results have shown that the increase in ionic strength led to high amounts of water being recovered to the concentrates, because the presence of the ions created more mobile foams. Thus an increase in ionic strength of plant water resulted in an increase in foamability as was also shown recently by Corin *et al.* (2011). It is possible that the presence of the ions in water at high concentration or ionic strength reduced the bubble size in the pulp phase of the batch float, and by so doing reduced bubble coalescence. Bubbles rising up from the pulp phase to the froth phase did so at an improved bubble rise velocity, hence resulting in a more mobile foam and thus increased water recovery. This result is in agreement with the findings of Laskowski *et al.* (2003) that flotation in hypersaline water (1 M NaCl) ensured total inhibition of bubble coalescence, resulting in a similar bubble size distribution to that of 10 ppm MIBC.

The four synthetic plant water types were again tested in the presence of a low dosage of DOW 200 in order to evaluate the effect of ionic strength on foam height, foam collapse time and bubble size. A 5 g/t DOW 200 dosage was selected because it was necessary to ensure that the frother dosage should be below its critical coalescence concentration (CCC) to allow non-inhibition and evidence of the effect of ions foamability as measured by foam height and bubble size.

An increase in the ionic strength increased the foam height dramatically, which also caused a significant increase in the foam collapse time. Both these findings indicate that the ions played a major role in enhancing the foamability of the system; it is suspected that the increase in foamability is due to the decrease in bubble size as already shown in Figure 9.6 and the reduction of bubble coalescence. The presence of the ions improved foamability independently of the frother as the frother which was used is a polyglycol ether, DOW 200, a non-ionic frother, so the ions could not have improved its performance but rather the ions enhanced foamability concurrently with DOW 200. Thus it can be postulated that increasing the ionic strength of plant water simply played a similar role to that of a frother which is to reduce the surface tension and thus prevent bubble coalescence from occurring and hence the increase in foam height with increasing ionic strength (Craig *et al*., 1993).

It is important to note that the foam collapse rate which is a function of the collapse time is a critical parameter in froth flotation as unstable froths tend to have very high collapse rates which might affect the flotation performance negatively due to negative impacts on the bubble-particle attachment and the sub-processes of transport of bubble-particle aggregates within froth flotation (Sweet, 1999).

The pulp-foam interface remained constant in spite of any changes in the ionic strength of plant water because the air rate was kept constant throughout the experiments, showing that the reduction in bubble size had no effect on the pulp-foam interface.

The results revealed significant impacts of ionic strength on gas dispersion properties. This was shown by the significant reduction in the bubble size, and the increase in foam height, foam collapse time, and foam recovery with increasing ionic strength. These findings could help explain why the 3-phase tests resulted in increased solids and water recovery with increasing ionic strength. This result agrees with previous findings (Corin *et al*., 2011; Quinn *et al*., 2007), and could explain why some flotation plants could operate without applying a frother to the system as the presence of ions at high ionic strength in the flotation system eliminates the need for a frother or surfactant as these ions tend to sufficiently produce bubble coalescence inhibition independently of a frother (Craig, 2004).

Since the role of a frother is to decrease bubble size and increase froth stability so as to aid bubble-particle attachment which is a sub-process in froth flotation. The findings in this study have revealed that an increase in the ionic strength of plant water must have some similar capability as a frother seeing that ionic strength impacted the frothability of the flotation system. It is known that the action of a frother results from retarding or inhibiting coalescence (Harris, 1982). The increase in ionic strength must have had some form of coalescence inhibition as it is well documented in literature that many salts inhibit bubble coalescence (Craig, 2004; Laskowski *et al.*, 2003; Hofmeier *et al.*, 1997; Craig *et al.*, 1993; Lessard and Zieminski, 1971; Marrucci and Nicodemo, 1967 (Goodall, 1992). The impact of ionic strength could be attributed to the fact that inorganic ions in water seem to slow the inter-bubble drainage, when these inorganic ions are present at high ionic strength they tend to inhibit bubble coalescence quite effectively as also postulated by Craig *et al.* (1993) and Goodall (1992). These authors attempted to determine a transition concentration or ionic strength at which salts inhibit bubble coalescence, and found that salts such as NaCl were able to inhibit bubble coalescence at a concentration of 4 M. Zieminski and Whittemore (1971) showed that increasing the ionic strength of inorganic salts in solution had a greater effect in hindering bubble coalescence and promoted frothability as was the case in the key findings of this study.

It was postulated that a critical ionic strength condition is that ionic strength beyond which no further impact would be observed on the gas dispersion properties as bubble coalescence would have been completely inhibited. The key findings of this study suggested that the ionic strength conditions chosen were within non-critical ionic strength range, because from 1SPW, 3SPW, 5SPW to 10SPW, there remained a trend of a decrease in bubble size, and trends of an increase in froth height, froth collapse rate, and froth recovery.

From the results of the study it can be seen that the solution-air interface remained constant with increasing ionic strength as the air rate was kept constant at 2 L/min as shown in Figure 6.2. The bubble size distribution measured and shown in Figure 6.9 to Figure 6.12 for 1SPW, 3SPW, 5SPW and 10SPW respectively, showed some considerable differences as the ionic strength increased in that the bubbles were mostly distributed in the finer or smaller size fractions as the ionic strength increased. A very significant effect is notable at 10SPW when the initially dominant mode in water alone at ca. 2.75 mm shifts to ca. 0.75 mm (Figure 6.7 and Figure 6.12) leading to a mean bubble diameter of 1.8 mm for frotherless distilled water and 0.98 mm for 10SPW as shown in Figure 6.6. This observation correlates with the increase in froth height and froth collapse time when increasing the ionic strength to 10SPW as reported in Figure 6.4 and Figure 6.5.

9.4 Effect of Ion type on Floatability

An investigation into the effect of ion type on the floatability of a Merensky ore was commissioned in order to determine the controlling ions in synthetic plant water, thus the ions selected are those that are present in synthetic plant water. It was deemed sufficient to test these ions at the ionic strength of 1SPW. In this discussion the results of this investigation are critically assessed and compared to that of 1SPW type.

9.4.1 Effect of Ion type on Solids and Water Recovery

The results have shown that higher amounts of solids report to the concentrate in the presence of Na salts, these recoveries exceeded those obtained with Ca and Mg salts. It was demonstrated that Mg and Ca salts led to similar solids recoveries, and that all single salts showed similar water recoveries. It was shown that the change in the anion type had no effect on solids and water recoveries, but it needs to be stated that the NO_3^- resulted in slightly lower solids recovery in each cation type. However a cation effect was observed as Na^+ being a monovalent cation led to increased solids recovery compared to the divalent Ca^{2+} and Mg^{2+} ions. The constant water recovery obtained throughout all tested salts is perhaps an indication that there was no ion type effect on the froth stability, and that in the results obtained with synthetic plant water this could imply that each of the ions present in the water system had equal influence or drive on the frothability. However this phenomenon is more difficult to explain since it is well documented in literature that divalent cations such as Ca^{2+} and Mg^{2+} result in improved frothability than the monovalent Na^+ cations (Kurniawan *et al.*, 2011; Ozdemir *et al.*, 2009; Quinn *et al.*, 2007; Craig, 2004; Craig *et al.*, 1993). The increased solids recovery in the presence of the monovalent cation, Na+, than in the case of the divalent cations is counter intuitive as the expectation was that monovalent cations would result in lower solids recovery as it was proposed that floatability is improved with higher valency of the electrolytes, this result could be atrributed to an ore type (Craig *et al.*, 1993).

The results have evidently shown an anion effect on the solids recovery in that Cl^- and SO_4^{2-} gave higher solids recovery, these anions in particular have been shown to inihit bubble coalescence and thus increase froth stability equally compared to a pure frother such as MIBC, and this phenomenon has also been linked to activation due to galvanic interactions that occur after grinding in a steel mill (Quinn *et al.*, 2007; Kirjavainen *et al.*, 2002). These results agree with literature findings that flotation under hypersaline water conditions yields ultra stable froths and improved mineral recoveries in Cu-Ni containing ores. The slightly lower solids recovery with NO_3^- than with Cl^- and SO_4^{2-} was expected, as it has been shown previously that nitrates tend to retard froth stability in froth flotation . This phenomenon could best explain why nitrates are being considered as gangue or talc depressants in the flotation of Merensky ores.

9.4.2 Effect of Ion type on Cu and Ni Recovery and Grade

The change in ion type had no effect on Cu and Ni recoveries. The final Cu recovery achieved was about 90 %, whilst that of Ni reached a maximum of about 60 %. These findings were similar to those obtained when 1SPW was tested at 0 g/t depressant dosage, and again showing no controlling ion whatsoever when floating in the presence of synthetic plant water. If the solids recovery findings in Figure 7.1 are compared to Cu and Ni recoveries in Figure 7.18, it can be postulated that higher solids recovery with Na^+ ions was due to gangue activation, Figure 7.9 and the slightly lower solids recovery with NO_3^- was due to gangue deactivation or prevention from reporting into the concentrates seeing that Cu-Ni recoveries remained unchanged even though the solids recoveries were increased.

A cation effect was observed on the copper and nickel grades in that Na^+ gave significantly lower Cu and Ni grades as shown in Figure 7.9 and Figure 7.18 respectively, this finding is in agreement with the speculation that the presence of Na^+ gave a slight activation to gangue, hence the dilution of the concentrates. Also if Figure 7.13 and Figure 7.22 are considered in detail significant differences in the grades when using SO_4^{2-} and Cl^- are noted, however an anion effect became evident as the NO_3^- resulted in significantly higher Cu and Ni grades of 0.65 % and 1.3 % respectively owing to the decrease reported in solids recovery which is speculated to be an inactivation or retarding of gangue particles. Whereas the rest of the anions gave similar copper and nickel grades of about 0.58 % and 1.1 % respectively, and these findings were very similar to those obtained when using 1SPW.

The activation of gangue minerals as influenced by ion type is not a completely new phenomenon, Mailula, (2004) showed that activation is enhanced in the presence of KNO_3, and the presence of $Ca(NO_3)_2$ showed a decrease on the activation of pyroxene, this work showed exactly the same phenomenon in that gangue activation became more prevalent in the presence of the monovalent Na^+ than in Ca^{2+} and Mg^{2+} solutions. The mechanism involved is not clear but there is evidence that Ca^{2+} ions interfere with the adsorption of a polysaccharide depressant species onto the mineral and hence less xanthate is adsorbed and this will reduce the recovery of gangue minerals such as talc. The difference in metal ions used (i.e. Na^+ and Ca^{2+}) has shown that monovalent and divalent metal ions have different properties and these alter the flotation behaviour. Shortridge (2002) also showed that the presence of Ca^{2+} and Mg^{2+} ions in solution reduced the natural flotation of talc. It is thus suggested that the presence of divalent ions have a greater degree of adsorption onto the mineral surface and hence lower recoveries of gangue particles.

An investigation of speciation of $Ca(NO_3)_2$, $CaCl_2$, and $CaSO_4$ indicated that at pH 9, the predominant form of the calcium ions in solution was Ca^{2+} with less than 1 % of these species being in the form of $CaOH^+$ (King, 1982). It leads to the conclusion that it was unlikely that these hydrated monovalent ions played any significant role in adsorption at the talc surface at the pH values used. Two possible mechanisms are that calcium species present at this pH adsorb onto the mineral surface and hence reduce the degree of adsorption or there may be a reaction in solution. No reaction between xanthate and the calcium species is expected thus there would be no expectation of increased hydrophobicity of the mineral surface.

9.5 Effect of Ion type on Foamability

2–Phase laboratory batch floats were performed in order to quantify the influence of ion type on the water recovery. The results of this investigation are shown in Figure 8.4 where the single ion results are compared to those of 1SPW water. The results did not show any cation effect or anion effect. According to these findings the ions showed similar findings or an equal influence on the foamability. It is more difficult to explain these results because it was expected that the water recovery would be higher in the presence of Ca^{2+} and Mg^{2+} than in the presence of Na^{+}, and if this phenomenon had occurred it would be said that it is illustrating the valence effect, because previous studies have shown that in salt solutions the water recovery increased with increasing valence, that is, divalent cations resulted in increased water recoveries than monovalent cations owing to the ability of divalent cations to inhibit bubble coalescence and thus create a more stable foam (Quinn *et al.*, 2007). Thus it can be postulated that there is a direct link between 2-phase and the 3-phase foamability and frothability phenomena since the 3-phase tests also did not show any influence on water recovery by ion type.

The gas dispersion properties, viz., bubble size and froth height investigated in this study did not show any influence with respect to ion type, but what became evident is that all ions reduced the bubble size equally, and gave similar results to 1SPW, and this suggests that the salt ions tested in this study had equal influence in retarding bubble coalescence as increasing the valence number also did not show dominance in reducing bubble size. These results did not provide evidence to the influence of valence number on surface tension and bubble coalescence reduction and therefore could not agree with published findings on this same subject (Quinn et al., 2007) where Ca^{2+} solutions significantly reduced the bubble size. It is possible that the salt solutions ionic strength of 0.0213 M was too weak to enable specific ion effect on bubble coalescence, and that could probably provide a reason to the differences between these findings and literature findings in which the salt solutions were tested at higher ionic strengths ranging between 0.1 to 1 M (Quinn et al., 2007; Craig, 2004),

Although this study has not shown any influence on foamability by ion type, it has shown that salt ions have an influence on foamability as shown by the tremendous increase in water recovery with increasing salt solution ionic strength as shown in Figure 8.1, and the significant decrease in bubble size with increasing salt content in water compared to that of a frotherless distilled water as illustrated in Figure 6.6 and Figure 8.5. The effect of salt ions on the foamability are attributed to their ability to decrease bubble coalescence at higher salt concentrations, and therefore produce stable froths with similar characteristics as those when a frother is applied in the flotation of Cu-Ni ores. This behaviour is said to be advantageous in mineral processing plants as it reduces the need to add surface-active reagents such as a frother; this also has a positive impact in reagent cost savings.

10. CONCLUSIONS

The objective of this study was to investigate the influence of ion type and ionic strength on the flotation behaviour of a platinum bearing ore from the Merensky reef and to determine whether water recycling, which gives rise to increased ionic strength, has any detrimental effects on the flotation performance of PGMs containing ore. At the commencement of this investigation the main objective or aim of this study, on the basis of published findings on similar but different systems, was divided into three major Key Questions. The following conclusions are presented as answers to the key questions, and are based on the experimental tests and key findings of this investigation.

How does the increase in ionic strength of plant water affect the flotation behaviour of a selected Merensky ore? The key deliverables from the experimental tests which were set out to answer to this key question were the solids and water recovery, entrainment, Cu-Ni recovery, and concentrate grade.

The findings of this study have clearly shown that the increase in the ionic strength of synthetic plant water has led to a tremendous increase in the solids and water recovery to the concentrate at all depressant dosages, and this phenomenon is attributed to frothability enhancement due to the froth stability of the system being improved with increasing ionic strength of plant water without changing the hydrophobicity of the mineral particles. Therefore the study has shown that the presence of ions at high ionic strength in the flotation system tend to induce the surface activity, in a similar manner as when a frother dosage is increased, to improve froth mobility/stability and thereby enhance the process of bubble-particle attachment and hence the increase in solids and water recovery.

The increase in ionic strength increased the BMS recovery as measured by Cu and Ni recoveries; however the concentrate grades dropped significantly at higher ionic strengths of plant water owing to the higher solids and water recovery at higher ionic strengths which introduced more NFG to the final concentrate as the increase in the ionic strength resulted in an increase in the total gangue entrainment and therefore presented more concentrate diluting NFG. Thus this study has clearly shown that the presence of ions in water have a strong influence on the NFG recovery and therefore concentrate grades.

Batch flotation results showed that the presence of a depressant (CMC or guar) at high dosages of 500 g/t caused a decrease on the final Cu recovery. The reduction on the final Ni recovery is attributed to depression of pentlandite-gangue composite particles or unliberated pentlandite/Ni. The reduction in Ni recovery was greater in the presence of CMC than guar owing to the depressant effectiveness improvement at high ionic strength, and the negative charge density of CMC. The concentrate grades increased with increasing depressant dosage, with CMC giving the most improvement at 500 g/t than guar. It is known that guar adsorbs on mineral surfaces via hydrogen bonding whereas CMC adsorption occurs via an acid/base interaction (Wiese, 2009;

Parolis et al., 2008; Khraisheh et al., 2005). Hence, the depressant type effect is attributed to the different adsorption mechanisms between CMC and guar, with CMC inducing the dispersion of particles at higher dosages resulting in froth destabilization as a result of its charge nature and improvement in the presence of divalent cations.

At all depressant dosages the increase in the ionic strength caused an increase in the entrainment of NFG hence the decrease in concentrate grades. However there was a decrease in the amount of NFG reporting to the concentrate per unit water, that is, the entrainment factor decreased with increasing ionic strength, and this was more evident in the presence of CMC than guar, and again illustrating the fact that the ionic conditions had no apparent effect on the effectiveness of guar as a depressant. This showed that increasing both the depressant dosage and ionic strength further increased the coagulation on guar and caused more dispersion on CMC.

The recovery of water and entrained gangue decreased with increasing depressant dosage contributing to increased concentrate grade. This is due to the decrease in froth stability which could be attributed to the removal of hydrophobic gangue or the increase in the hydrophilicity of sulphides. The increase in the amount of NFG recovered from the increase in ionic strength was significantly counteracted by the addition of a depressant.

How does foamability change with increasing ionic strength? This key question would be answered by investigation the water recovery, bubble size, and foam height.

In agreement with the 3-phase batch test findings, the water recovery increased with increasing ionic strength showing that the 3-phase frothability enhancement is linked to the enhanced 2-phase foamability, and that the presence of the synthetic plant water ion combination at high ionic strength played a significant role in enhancing the foam mobility possibly by reducing bubble coalescence.

The increase in ionic strength caused a reduction in the bubble size as was measure by the UCT Bubble Size Analyser. These findings further confirmed that the increase in ionic strength had a significant influence in inhibiting bubble coalescence and this could suggest that the presence of ions reduced the surface tension, and hence allowed the necessary bubble size development.

The foam height together with the foam collapse time increased with increasing ionic strength; it is clear that the presence of ions created a more stable foam due to bubble coalescence being retarded in the foam column system. The 2-phase results have shown that the 3-phase froth stability improvement is directly linked to the 2-phase foamability, and that the presence of ions in synthetic plant water may be enough to create a stable froth without the addition of a frother in order to aid froth stability in a flotation process.

How does the flotation behaviour of selected ions compare with that of 1SPW on a Merensky ore? This key question was answered on the basis of the findings on solids and water recovery, Cu-Ni recovery, and concentrate grade.

The solids and water recovery by ion type did not show tremendous deviations from those obtained using 1SPW water. However Na^+ gave slightly higher solids recoveries than the divalent cations, and thus showing that a cation effect existed in the system. This behaviour was counterintuitive because based on literature findings (Kurniawan et al., 2011; Quinn et al., 2007; Craig, 2004) monovalent cation solutions tend to yield lower solids recoveries than divalent cation solutions. These findings showed that the presence of Na^+ led to gangue activation. The solids and water recoveries obtained for Ca^{2+} and Mg^{2+} did not show any significant differences, and this could be attributed to the fact that these two divalent cations should exhibit equal influence on froth stability, as they have the same valence number. It was also found that NO_3^- ions resulted in slightly lower solids recovery than Cl^- and SO_4^{2-}, this showing an anion effect which was attributed to either the depressing ability of nitrates or to gangue deactivation when using NO_3^-.

Ion type did not show any apparent influence on Cu and Ni recoveries as they remained fairly constant throughout all tested single salt solutions. It can therefore be concluded that at the selected ionic strength the single salts had equal or similar influence on BMS recoveries and thus showed no cation and or anion effect on these recoveries. It is worthwhile mentioning that Cu-Ni recoveries obtained with all single salt solutions did not differ from that which was achieved when using 1Plant water, and this perhaps suggests that there was no controlling ion in the process of sulphide particle-bubble attachment and transport through to the froth phase.

The concentrate grades were slightly lower for Na^+ than Ca^{2+} and Mg^{2+} owing to the enhanced gangue activation in the presence of Na^+ ions in solution. However there was a more notable increase on the concentrate grades in the presence of NO_3^- ions than the Cl^- and SO_4^{2-} ions due to the deactivation of gangue in NO_3^- solutions. Thus the concentrates grades depended on whether the ion type enhances or retards gangue activation.

How does foamability change with different ions? The key aspects in answering this question are the water recovery and bubble size.

The water recovery remained unchanged at all single salt solutions, and the achievable water recovery did not deviate from the 1SPW response, thus showing no indication of an ion type effect on water recovery at the selected ionic strength. The change in the ion type did not show any apparent influence on the bubble size, all single salts showed equal influence on the bubble size at the ionic strength of 1SPW. The bubble size measurement did not deviate from that of 1SPW. These results showed no clear valence effect (i.e. monovalent or divalent) on the water recovery and the bubble size at the selected ionic strength, and this suggests that the ions had equal impact on bubble coalescence. Therefore it can be concluded that at the 1SPW ionic strength the foamability of the system remained unchanged with different ions in solution, hence the 3-phase constant water recovery with various ions, suggesting constant frothability, can be linked to the 2-phase foamability results.

In summary the two major objectives of water recycling in the mineral processing industry are; firstly to reduce the demand of fresh water because the production and transportation of fresh water is usually expensive and can to a certain extent affect the operating costs of mineral processing plants; and secondly to reduce the volume of effluent because the effluents from the process operations are potentially detrimental to the environment as they can contain both suspended solids as well as many toxic chemicals in solution. Therefore such considerations, which are both environmental and economic, clearly point to the necessity of water treatment/recycling, reduction and reuse in the mineral processing industry, hence the importance of strategic management of water in metallurgical circuits. As part of water management in mineral processing, this study investigated the use of recycle water in flotation with the focus on increased inorganic compounds, viz., ions and their ionic strength. This study has shown that the increase in the ionic strength led to an increase in Cu-Ni recovery; however the concentrate grades were adversely affected, asserting that the increase in ionic strength of plant water and thus water recycling altered the chemistry of the system. The major influence to these findings was the enhancement in frothability and any excessive froth mobility levels that led to an increase in gangue activation and recovery, but it has also been shown that this major drive or influence can be mitigated by adding a suitable polysaccharide depressant into the flotation system.

In a previous study by Slatter et al. (2009), it was found that platinum flotation followed the same trend with nickel, copper, palladium and sulphur flotation for a Merensky ore. Therefore although this study has not considered the PGMs recoveries and grades, if the flotation performance measured by BMS flotation be a good proxy for PGMs flotation behaviour, then water recycling should not present any negative effects on the flotation of a Merensky ore.

11. RECOMMENDATIONS

On the basis of the results and the conclusions of this study, the following recommendations have been put forward:

- ✓ Perform PGMs assays on the concentrates and tails samples so as to get a better insight of the PGMs flotation trends with increasing ionic strength.
- ✓ Conduct flotation tests at higher pH values for the four ionic strength conditions to determine whether the presence of hydroxyl species such as $Mg(OH)_2$ and $Ca(OH)_2$ in solution have any influence on the froth stability and gangue recovery.
- ✓ Conduct surface tension measurements for all synthetic plant water types and ion types to ascertain the influence of ionic strength on frothability.
- ✓ Perform further tests on the salts of K^+ and Al^{3+} to gain a better understanding of the effect of cation type, valence number in particular and compare the results with those obtained with Na^+, Ca^{2+} and Mg^{2+} so as to establish whether bubble coalescence increases with an increasing valence number.
- ✓ Investigate the effect of ion type on floatability using guar and CMC at dosages of 100 g/t and 500 g/t for an even better understanding of the interactions between ions/depressant/minerals as this could affect the behaviour of polysaccharides in the flotation of PGMs containing ores and may impact the flotation performance.

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13. APPENDICES

13.1 Appendix A – Batch Flotation Data for Synthetic Plant Water types

Run no.	Reagents	Sample	Time, min	Mass Pull, g	Cum Mass Pull, g	Cum Water Rec, g	Cum Cu Grade, %	Cum Cu Rec, %	Cum Ni Grade, %	Cum Ni Rec, %	Entrained gangue, g	Floating gangue, g
Test 2 A	1SPW	C1	3	14.42	14.42	65.44	2.94	66.88	3.78	34.26	3.46	7.75
		C2	7	17.27	31.69	196.14	1.55	77.52	2.67	53.22	10.38	16.04
	40 g/t D200	C3	13	18.85	50.54	371.44	1.04	83.23	1.83	57.97	19.65	24.91
		C4	21	19.75	70.29	606.90	0.79	87.72	1.37	60.65	32.11	31.73
	150 g/t SIBX	F		994.89								
		Tails		924.60								
Test 2 B		C1	3	16.39	16.39	84.61	2.85	70.55	3.88	38.66	4.48	8.36
	1SPW	C2	7	15.52	31.91	184.60	1.63	78.51	2.76	53.59	9.77	17.42
		C3	13	19.10	51.01	358.51	1.09	83.86	1.87	57.88	18.97	26.52
	40 g/t D200	C4	21	21.13	72.14	631.66	0.81	88.35	1.38	60.39	33.41	30.70
		F		1010.19								
	150 g/t SIBX	Tails		921.81								
Test 2 A	3SPW	C1	3	16.35	16.35	86.71	2.86	68.49	3.74	36.28	4.53	8.12
		C2	7	15.01	31.36	212.70	1.68	77.25	2.78	51.69	11.12	17.09
	40 g/t D200	C3	13	20.23	51.59	431.52	1.10	82.98	1.85	56.66	22.57	25.49
		C4	21	22.88	74.47	760.98	0.81	87.88	1.35	59.64	39.80	29.89
	150 g/t SIBX	F		1021.16								
		Tails		946.69								
Test 2 B		C1	3	15.76	15.76	88.66	2.85	69.23	3.98	38.89	4.53	7.92
	3SPW	C2	7	14.71	30.47	217.61	1.64	77.14	2.86	54.11	11.12	17.90
		C3	13	26.10	56.57	425.72	0.96	83.94	1.70	59.72	22.57	25.02
		C4	21	21.10	77.67	754.32	0.74	88.18	1.29	62.33	39.80	29.13
	40 g/t D200	F		1006.57								
	150 g/t SIBX	Tails		897.83								

Run no.	Reagents	Sample	Time, min	Mass Pull, g	Cum Mass Pull, g	Cum Water Rec, g	Cum Cu Grade, %	Cum Cu Rec, %	Cum Ni Grade, %	Cum Ni Rec, %	Entrained gangue, g	Floating gangue, g
Test 2 A	5SPW	C1	3	21.83	21.83	134.45	2.13	70.22	3.22	42.68	6.01	11.75
		C2	7	14.83	36.66	274.30	1.40	77.43	2.49	55.35	12.26	19.42
	40 g/t D200	C3	13	26.31	62.97	614.62	0.88	83.92	1.58	60.28	27.47	29.70
		C4	21	24.66	87.63	1068.45	0.67	88.61	1.19	63.17	47.76	33.70
	150 g/t SIBX	F		987.53								
		Tails		899.90								
Test 2 B		C1	3	23.29	23.29	132.13	2.10	73.57	3.14	44.95	5.91	13.49
	5SPW	C2	7	14.93	38.22	274.50	1.38	79.63	2.41	56.52	12.27	21.37
		C3	13	21.25	59.47	617.27	0.95	84.61	1.65	60.46	27.59	26.59
	40 g/t D200	C4	21	22.15	81.62	1072.24	0.72	88.72	1.26	63.10	47.93	28.02
		F		977.77								
	150 g/t SIBX	Tails		883.51								
Test 2 A	10SPW	C1	3	22.96	22.96	155.45	2.09	69.66	3.28	44.36	6.93	11.63
		C2	7	22.65	45.61	382.61	1.18	77.89	2.24	60.17	17.06	23.21
	40 g/t D200	C3	13	33.53	79.14	899.68	0.74	84.73	1.39	64.81	40.13	32.94
		C4	21	30.62	109.76	1570.61	0.56	89.85	1.05	67.78	70.05	33.31
	150 g/t SIBX	F		939.73								
		Tails		829.97								
Test 2 B		C1	3	27.46	27.46	158.76	1.81	71.21	2.76	45.52	7.08	13.31
	10SPW	C2	7	18.47	45.93	382.79	1.18	78.03	2.11	58.14	17.07	20.92
		C3	13	33.90	79.83	908.01	0.74	84.76	1.31	62.78	40.50	30.66
	40 g/t D200	C4	21	27.31	107.14	1571.16	0.58	89.43	1.02	65.41	70.07	28.10
		F		1005.99								
	150 g/t SIBX	Tails		882.59								

Run no.	Reagents	Sample	Time, min	Mass Pull, g	Cum Mass Pull, g	Cum Water Rec, g	Cum Cu Grade, %	Cum Cu Rec, %	Cum Ni Grade, %	Cum Ni Rec, %	Entrained gangue, g	Floating gangue, g
Test 2 A	1SPW 40 g/t D200 100 g/t CMC 150 g/t SIBX	C1	3	5.06	5.06	20.27	5.02	45.89	6.35	20.95	1.50	0.82
		C2	7	12.76	17.82	144.03	2.36	75.93	4.03	46.89	10.67	3.53
		C3	13	9.80	27.62	248.63	1.63	81.35	3.03	54.58	18.42	4.04
		C4	21	13.92	41.54	419.68	1.14	85.77	2.12	57.49	31.10	5.23
		F		1001.00								
		Tails		959.46								
Test 2 B	1SPW 40 g/t D200 100 g/t CMC 150 g/t SIBX	C1	3	5.17	5.17	22.62	3.74	46.61	5.95	22.81	1.68	1.21
		C2	7	10.53	15.70	148.04	1.84	69.57	3.59	41.83	10.97	3.49
		C3	13	9.73	25.43	251.99	1.24	75.75	2.44	45.99	18.67	4.69
		C4	21	12.82	38.25	424.27	0.88	80.98	1.73	49.05	31.44	5.10
		F		1007.49								
		Tails		954.36								
Test 2 A	3SPW 40 g/t D200 100 g/t CMC 150 g/t SIBX	C1	3	5.92	5.92	27.11	5.73	58.60	8.26	29.97	1.81	1.05
		C2	7	10.33	16.25	149.92	2.74	76.88	4.87	48.50	10.00	3.28
		C3	13	11.81	28.06	320.47	1.70	82.37	3.29	56.63	21.38	4.08
		C4	21	14.58	42.64	566.15	1.18	86.64	2.27	59.30	37.76	5.21
		F		977.27								
		Tails		934.63								
Test 2 B	3SPW 40 g/t D200 100 g/t CMC 150 g/t SIBX	C1	3	5.89	5.89	29.32	4.58	50.57	6.50	24.04	1.96	1.06
		C2	7	10.64	16.53	146.01	2.38	73.83	4.34	45.04	9.74	3.10
		C3	13	11.58	28.11	310.70	1.53	80.33	3.05	53.89	20.72	4.69
		C4	21	15.31	43.42	560.38	1.05	85.30	2.09	56.96	37.38	5.25
		F		1013.82								
		Tails		953.69								

Run no.	Reagents	Sample	Time, min	Mass Pull, g	Cum Mass Pull, g	Cum Water Rec, g	Cum Cu Grade, %	Cum Cu Rec, %	Cum Ni Grade, %	Cum Ni Rec, %	Entrained gangue, g	Floating gangue, g
Test 2 A	5SPW 40 g/t D200 100 g/t CMC 150 g/t SIBX	C1	3	9.42	9.42	74.59	3.80	61.47	7.02	33.19	3.79	1.39
		C2	7	10.14	19.56	211.00	2.14	71.69	4.51	44.21	10.72	3.13
		C3	13	12.97	32.53	395.65	1.38	77.14	3.13	51.04	20.10	4.13
		C4	21	15.87	48.40	683.46	0.98	81.37	2.19	53.28	34.72	5.51
		F		1352.36								
		Tails		1303.96								
Test 2 B	5SPW 40 g/t D200 100 g/t CMC 150 g/t SIBX	C1	3	9.57	9.57	63.28	5.00	64.50	8.26	37.52	3.21	1.92
		C2	7	10.36	19.93	197.89	2.96	79.33	5.49	51.90	10.05	3.57
		C3	13	12.86	32.79	390.26	1.90	83.75	3.78	58.75	19.83	4.89
		C4	21	16.12	48.91	680.88	1.32	87.18	2.63	61.04	34.59	5.10
		F		1218.26								
		Tails		1153.11								
Test 2 A	10SPW 40 g/t D200 100 g/t CMC 150 g/t SIBX	C1	3	10.60	10.60	81.35	3.74	65.10	6.50	34.31	3.60	1.82
		C2	7	10.85	21.45	227.99	2.14	75.30	4.80	51.28	10.10	3.71
		C3	13	15.74	37.19	458.31	1.33	81.23	3.29	60.83	20.30	4.78
		C4	21	21.39	58.58	932.43	0.90	86.41	2.20	64.23	41.31	5.59
		F		1058.60								
		Tails		1000.02								
Test 2 B	10SPW 40 g/t D200 100 g/t CMC 150 g/t SIBX	C1	3	10.09	10.09	80.99	3.67	66.75	7.02	39.32	3.59	1.96
		C2	7	10.25	20.34	225.96	2.06	75.47	4.58	51.64	10.01	3.01
		C3	13	14.14	34.48	452.34	1.30	80.78	3.13	59.87	20.04	4.62
		C4	21	20.55	55.03	921.79	0.87	86.17	2.07	63.08	40.84	5.06
		F		1002.49								
		Tails		931.71								

Run no.	Reagents	Sample	Time, min	Mass Pull, g	Cum Mass Pull, g	Cum Water Rec, g	Cum Cu Grade, %	Cum Cu Rec, %	Cum Ni Grade, %	Cum Ni Rec, %	Entrained gangue, g	Floating gangue, g
Test 2 A	1SPW	C1	3	1.71	1.71	19.03	13.56	47.10	6.62	8.39	1.41	0.00
		C2	7	2.90	4.61	41.88	7.49	70.08	7.66	26.17	3.10	0.00
	40 g/t D200	C3	13	2.88	7.49	64.59	5.17	78.61	7.33	40.68	4.79	0.00
	500 g/t CMC	C4	21	2.29	9.78	88.69	4.11	81.62	6.50	47.15	6.57	0.00
	150 g/t SIBX	F		982.43								
		Tails		972.65								
Test 2 B		C1	3	1.67	1.67	20.94	12.65	51.09	6.69	9.61	1.55	0.00
	1SPW	C2	7	2.69	4.36	43.74	6.76	71.32	7.41	27.82	3.24	0.00
		C3	13	2.89	7.25	66.69	4.39	76.95	6.32	39.44	4.94	0.00
	40 g/t D200	C4	21	2.24	9.49	90.26	3.46	79.51	5.42	44.32	6.69	0.00
	500 g/t CMC	F		1010.89								
	150 g/t SIBX	Tails		974.27								
Test 2 A	3SPW	C1	3	2.71	2.71	22.84	11.07	53.28	6.95	12.13	1.52	0.00
		C2	7	4.62	7.33	47.64	5.79	75.35	6.75	31.86	3.18	0.16
	40 g/t D200	C3	13	2.89	10.22	75.23	4.49	81.58	6.36	41.85	5.02	0.23
	500 g/t CMC	C4	21	2.85	13.07	109.56	3.64	84.55	5.63	47.44	7.31	0.26
	150 g/t SIBX	F		1023.73								
		Tails		1010.66								
Test 2 B		C1	3	2.67	2.67	22.91	11.39	56.33	8.60	16.13	1.53	0.00
	3SPW	C2	7	4.60	7.27	48.64	5.79	78.01	6.39	32.64	3.24	0.00
		C3	13	2.85	10.12	77.43	4.34	81.43	5.39	38.33	5.16	0.00
	40 g/t D200	C4	21	2.77	12.89	113.60	3.52	84.12	4.72	42.75	7.58	0.00
	500 g/t CMC	F		1058.51								
	150 g/t SIBX	Tails		1020.75								

Run no.	Reagents	Sample	Time, min	Mass Pull, g	Cum Mass Pull, g	Cum Water Rec, g	Cum Cu Grade, %	Cum Cu Rec, %	Cum Ni Grade, %	Cum Ni Rec, %	Entrained gangue, g	Floating gangue, g
Test 2 A	5SPW	C1	3	5.75	5.75	43.29	7.55	71.57	7.49	27.42	2.20	0.18
		C2	7	2.18	7.93	89.51	6.07	79.26	7.27	36.71	4.55	0.00
	40 g/t D200	C3	13	3.14	11.07	127.68	4.56	83.24	6.20	43.67	6.49	0.00
	500 g/t CMC	C4	21	2.80	13.87	165.01	3.74	85.48	5.43	47.95	8.38	0.51
	150 g/t SIBX	F		1033.20								
		Tails		1019.33								
Test 2 B		C1	3	5.67	5.67	45.19	6.13	70.16	8.76	31.79	2.30	0.00
	5SPW	C2	7	2.23	7.90	96.33	4.78	76.16	7.63	38.59	4.89	0.00
		C3	13	3.39	11.29	128.87	3.51	80.12	6.13	44.32	6.55	0.15
	40 g/t D200	C4	21	2.43	13.72	167.68	2.97	82.32	5.42	47.61	8.52	0.29
	500 g/t CMC	F		1062.23								
	150 g/t SIBX	Tails		1018.25								
Test 2 A	10SPW	C1	3	8.27	8.27	110.53	4.41	70.14	6.58	34.44	4.90	0.00
		C2	7	3.41	11.68	177.40	3.52	79.10	5.79	42.79	7.86	0.00
	40 g/t D200	C3	13	2.40	14.08	217.62	3.04	82.15	5.29	47.15	9.64	0.00
	500 g/t CMC	C4	21	3.51	17.59	275.63	2.51	84.77	4.49	50.05	12.21	0.00
	150 g/t SIBX	F		978.13								
		Tails		960.54								
Test 2 B		C1	3	8.29	8.29	110.20	4.24	70.47	5.95	32.99	4.88	0.00
	10SPW	C2	7	3.53	11.82	180.32	3.31	78.47	5.16	40.83	7.99	0.00
		C3	13	2.65	14.47	219.18	2.82	81.65	4.67	45.20	9.71	0.18
	40 g/t D200	C4	21	3.49	17.96	277.75	2.34	84.12	4.00	48.04	12.30	0.72
	500 g/t CMC	F		1020.99								
	150 g/t SIBX	Tails		972.89								

Run no.	Reagents	Sample	Time, min	Mass Pull, g	Cum Mass Pull, g	Cum Water Rec, g	Cum Cu Grade, %	Cum Cu Rec, %	Cum Ni Grade, %	Cum Ni Rec, %	Entrained gangue, g	Floating gangue, g
Test 2 A	1SPW	C1	3	7.33	7.33	56.93	7.62	66.64	7.59	29.55	3.01	2.31
		C2	7	7.74	15.07	141.52	4.78	85.91	6.69	53.54	7.49	4.31
	40 g/t D200	C3	13	7.40	22.47	271.39	3.36	89.96	5.11	60.96	14.36	6.12
	100 g/t guar	C4	21	10.80	33.27	411.78	2.34	92.99	3.61	63.76	21.78	6.95
	150 g/t SIBX	F		1030.96								
		Tails		997.69								
Test 2 B		C1	3	7.42	7.42	60.73	5.33	66.08	7.29	33.17	3.21	2.69
	1SPW	C2	7	7.70	15.12	145.07	3.27	82.65	5.43	50.35	7.67	4.99
		C3	13	7.54	22.66	274.63	2.29	86.87	4.09	56.85	14.53	6.19
	40 g/t D200	C4	21	10.71	33.37	420.92	1.62	90.46	2.90	59.38	22.27	7.12
	100 g/t guar	F		1028.53								
	150 g/t SIBX	Tails		963.95								
Test 2 A	3SPW	C1	3	10.01	10.01	88.63	3.82	67.27	6.36	37.97	4.64	2.68
		C2	7	8.22	18.23	205.22	2.49	79.79	4.61	50.12	10.73	4.51
	40 g/t D200	C3	13	9.87	28.10	340.26	1.72	84.90	3.43	57.50	17.80	6.13
	100 g/t guar	C4	21	14.30	42.40	586.37	1.20	89.39	2.39	60.44	30.67	7.06
	150 g/t SIBX	F		1045.99								
		Tails		1003.59								
Test 2 B		C1	3	9.84	9.84	93.84	4.49	69.02	6.71	36.35	4.91	3.30
	3SPW	C2	7	8.54	18.38	201.43	2.85	81.87	5.06	51.19	10.53	5.11
		C3	13	10.37	28.75	340.50	1.93	86.74	3.70	58.56	17.81	6.28
	40 g/t D200	C4	21	14.35	43.10	578.21	1.35	90.84	2.58	61.24	30.24	7.16
	100 g/t guar	F		1062.76								
	150 g/t SIBX	Tails		998.29								

Run no.	Reagents	Sample	Time, min	Mass Pull, g	Cum Mass Pull, g	Cum Water Rec, g	Cum Cu Grade, %	Cum Cu Rec, %	Cum Ni Grade, %	Cum Ni Rec, %	Entrained gangue, g	Floating gangue, g
Test 2 A	5SPW	C1	3	10.66	10.66	100.91	3.63	68.71	6.09	37.57	4.51	2.67
		C2	7	9.60	20.26	219.58	2.19	78.66	4.31	50.49	9.82	4.72
	40 g/t D200	C3	13	14.21	34.47	455.05	1.39	84.93	2.98	59.41	20.34	6.16
	100 g/t guar	C4	21	16.02	50.49	802.05	1.00	89.59	2.13	62.09	35.85	7.19
	150 g/t SIBX	F		1020.30								
		Tails		969.81								
Test 2 B		C1	3	10.85	10.85	102.11	4.28	69.15	6.60	37.95	4.56	3.18
	5SPW	C2	7	9.61	20.46	227.77	2.67	81.33	4.86	52.73	10.18	4.63
		C3	13	14.10	34.56	458.57	1.69	86.73	3.35	61.27	20.50	6.24
	40 g/t D200	C4	21	16.39	50.95	813.40	1.20	90.73	2.36	63.69	36.36	7.41
	100 g/t guar	F		1083.20								
	150 g/t SIBX	Tails		1014.46								
Test 2 A	10SPW	C1	3	13.41	13.41	148.76	3.31	72.42	5.92	43.61	6.63	3.02
		C2	7	8.19	21.60	272.05	2.25	79.29	4.38	52.04	12.13	4.82
	40 g/t D200	C3	13	17.82	39.42	627.28	1.33	85.42	2.84	61.53	27.98	5.66
	100 g/t guar	C4	21	21.53	60.95	1120.66	0.91	90.45	1.92	64.42	49.98	7.83
	150 g/t SIBX	F		1047.22								
		Tails		986.27								
Test 2 B		C1	3	13.26	13.26	163.32	3.21	72.11	5.40	41.14	7.28	2.99
	10SPW	C2	7	7.94	21.20	282.53	2.19	78.73	4.06	49.40	12.60	4.95
		C3	13	17.21	38.41	646.28	1.30	84.80	2.67	58.89	28.82	6.33
	40 g/t D200	C4	21	20.78	59.19	1131.52	0.90	89.91	1.82	61.85	50.47	7.96
	100 g/t guar	F		1029.26								
	150 g/t SIBX	Tails		952.19								

Run no.	Reagents	Sample	Time, min	Mass Pull, g	Cum Mass Pull, g	Cum Water Rec, g	Cum Cu Grade, %	Cum Cu Rec, %	Cum Ni Grade, %	Cum Ni Rec, %	Entrained gangue, g	Floating gangue, g
Test 2 A	1SPW	C1	3	8.37	8.37	102.17	4.33	69.02	7.23	36.92	5.40	0.00
		C2	7	3.43	11.80	135.16	3.56	79.96	6.48	46.64	7.15	0.00
	40 g/t D200	C3	13	2.37	14.17	162.31	3.11	83.88	5.89	50.93	8.59	0.24
	500 g/t guar	C4	21	2.14	16.31	191.67	2.78	86.51	5.43	54.01	10.14	0.46
	150 g/t SIBX	F		1063.11								
		Tails		1046.80								
Test 2 B		C1	3	7.96	7.96	92.87	4.59	67.97	7.53	36.25	4.91	0.00
	1SPW	C2	7	3.54	11.50	127.56	3.70	79.19	6.64	46.21	6.75	0.00
		C3	13	2.43	13.93	158.24	3.25	84.11	5.97	50.33	8.37	0.19
	40 g/t D200	C4	21	2.28	16.21	190.90	2.87	86.51	5.43	53.27	10.10	0.41
	500 g/t guar	F		1069.18								
	150 g/t SIBX	Tails		1032.55								
Test 2 A	3SPW	C1	3	11.30	11.30	128.84	3.38	68.80	5.40	39.12	6.74	0.81
		C2	7	2.84	14.14	172.75	3.04	77.59	5.09	46.15	9.03	0.69
	40 g/t D200	C3	13	3.28	17.42	209.68	2.68	84.25	4.63	51.76	10.97	1.44
	500 g/t guar	C4	21	3.30	20.72	305.07	2.34	87.20	4.17	55.36	15.96	0.00
	150 g/t SIBX	F		1007.77								
		Tails		987.05								
Test 2 B		C1	3	10.94	10.94	125.06	3.96	74.42	6.60	42.75	6.54	0.00
	3SPW	C2	7	2.95	13.89	170.38	3.47	82.80	6.11	50.25	8.91	0.00
		C3	13	3.38	17.27	204.01	2.92	86.64	5.36	54.79	10.67	0.65
	40 g/t D200	C4	21	3.30	20.57	295.96	2.51	88.74	4.73	57.55	15.48	0.00
	500 g/t guar	F		1001.99								
	150 g/t SIBX	Tails		965.25								

Run no.	Reagents	Sample	Time, min	Mass Pull, g	Cum Mass Pull, g	Cum Water Rec, g	Cum Cu Grade, %	Cum Cu Rec, %	Cum Ni Grade, %	Cum Ni Rec, %	Entrained gangue, g	Floating gangue, g
Test 2 A	5SPW	C1	3	12.88	12.88	196.72	3.08	71.39	4.99	38.07	8.79	0.00
		C2	7	3.08	15.96	237.09	2.75	79.15	4.62	43.67	10.60	0.26
	40 g/t D200	C3	13	3.36	19.32	298.05	2.39	83.04	4.17	47.66	13.32	0.42
	500 g/t guar	C4	21	4.72	24.04	422.33	2.00	86.40	3.63	51.60	18.88	0.00
	150 g/t SIBX	F		1027.02								
		Tails		1002.98								
Test 2 B		C1	3	12.09	12.09	174.65	3.25	71.51	5.28	39.10	7.81	0.10
	5SPW	C2	7	3.43	15.52	223.31	2.83	79.99	4.84	46.03	9.98	0.64
		C3	13	3.51	19.03	289.08	2.43	83.96	4.32	50.37	12.92	0.73
	40 g/t D200	C4	21	4.77	23.80	414.95	2.01	87.18	3.73	54.33	18.55	0.00
	500 g/t guar	F		1060.27								
	150 g/t SIBX	Tails		1003.56								
Test 2 A	10SPW	C1	3	14.96	14.96	215.83	2.99	72.60	4.88	42.96	9.63	0.78
		C2	7	4.18	19.14	272.32	2.61	81.21	4.41	49.62	12.15	1.66
	40 g/t D200	C3	13	5.10	24.24	386.41	2.16	85.28	3.81	54.34	17.23	1.19
	500 g/t guar	C4	21	5.93	30.17	573.91	1.80	88.29	3.29	58.34	25.60	0.00
	150 g/t SIBX	F		1031.27								
		Tails		1001.10								
Test 2 B		C1	3	14.80	14.80	220.18	2.71	69.70	3.94	36.73	9.82	0.68
	10SPW	C2	7	4.02	18.82	283.98	2.41	78.74	3.68	43.73	12.67	1.08
		C3	13	4.84	23.66	390.76	2.03	83.18	3.27	48.78	17.43	0.66
	40 g/t D200	C4	21	5.94	29.60	562.21	1.69	86.56	2.85	53.23	25.07	0.00
	500 g/t guar	F		1086.81								
	150 g/t SIBX	Tails		1037.24								

13.2 Appendix B – Batch Flotation Data for Single Salts

Reagents	Run no.	Sample	Time, min	Mass Pull g	Cum Mass g	Cum Water g	Copper Grade %	Copper Rec %	Nickel Grade %	Nickel Rec %
NaCl Dow 200 SIBX	1	C1	3	9.44	9.44	12.68	4.12	67.86	4.18	23.87
		C2	7	26.91	36.35	158.88	1.26	80.03	2.36	51.85
		C3	13	31.07	67.42	454.14	0.72	84.71	1.39	56.85
		C4	21	23.27	90.69	717.59	0.55	87.18	1.08	59.45
		F		966.07						
		T		840.16						
		T2		16.54						
		T3		18.68						
	2	C1	3	10.01	10.01	13.38	3.92	69.08	4.13	23.98
		C2	7	26.73	36.74	163.07	1.26	81.80	2.42	51.72
		C3	13	33.05	69.79	473.18	0.71	87.04	1.41	57.22
		C4	21	23.28	93.07	738.16	0.55	89.42	1.11	59.95
		F		989.85						
		T		862.89						
		T2		16.83						
		T3		17.06						
Na_2SO_4 Dow 200 SIBX	1	C1	3	10.32	10.32	11.26	3.68	66.44	3.88	23.36
		C2	7	24.68	35.00	127.50	1.29	79.01	2.46	50.20
		C3	13	28.02	63.02	357.74	0.76	83.57	1.50	55.04
		C4	21	24.50	87.52	598.76	0.56	86.26	1.13	57.71
		F		970.55						
		T		850.71						
		T2		16.35						
		T3		15.97						
	2	C1	3	12.34	12.34	12.84	3.32	71.74	3.96	29.45
		C2	7	22.46	34.80	129.51	1.33	81.29	2.41	50.59
		C3	13	33.80	68.60	364.79	0.72	86.09	1.36	56.11
		C4	21	25.60	94.20	612.52	0.54	88.58	1.04	58.97
		F		962.80						
		T		834.89						
		T2		17.18						
		T3		16.53						

Reagents	Run no.	Sample	Time, min	Mass Pull g	Cum Mass g	Cum Water g	Copper Grade %	Copper Rec %	Nickel Grade %	Nickel Rec %
NaNO$_3$ Dow 200 SIBX	1	C1	3	13.22	13.22	20.18	3.48	72.20	4.31	33.72
		C2	7	26.80	40.02	194.45	1.30	81.76	2.12	50.23
		C3	13	31.37	71.39	509.74	0.77	86.56	1.34	56.36
		C4	21	22.10	93.49	766.06	0.61	88.91	1.07	59.40
		F		1004.44						
		T		870.01						
		T2		20.57						
		T3		20.37						
	2	C1	3	13.59	13.59	19.02	3.48	72.54	4.54	34.85
		C2	7	26.71	40.30	176.31	1.32	81.88	2.25	51.29
		C3	13	33.20	73.50	493.51	0.77	87.11	1.39	57.50
		C4	21	23.13	96.63	749.82	0.60	89.51	1.11	60.46
		F		996.36						
		T		862.51						
		T2		18.56						
		T3		18.66						
MgCl2 Dow 200 SIBX	1	C1	3	11.45	11.45	29.44	3.72	71.62	4.34	28.40
		C2	7	28.47	39.92	250.90	1.22	81.94	2.33	53.32
		C3	13	28.16	68.08	573.38	0.75	86.27	1.49	58.11
		C4	21	19.20	87.28	831.09	0.60	88.37	1.21	60.30
		F		967.86						
		T		845.17						
		T2		17.96						
		T3		17.45						
	2	C1	3	11.85	11.85	30.28	3.58	71.56	4.06	27.52
		C2	7	27.64	39.49	236.73	1.23	81.98	2.29	51.74
		C3	13	28.98	68.47	563.22	0.75	86.42	1.45	56.70
		C4	21	20.11	88.58	824.96	0.59	88.55	1.17	59.08
		F		987.86						
		T		864.24						
		T2		17.04						
		T3		18.00						

Reagents	Run no.	Sample	Time, min	Mass Pull g	Cum Mass g	Cum Water g	Copper Grade %	Copper Rec %	Nickel Grade %	Nickel Rec %
$MgSO_4$ Dow 200 SIBX	1	C1	3	14.03	14.03	23.22	3.29	73.55	3.95	32.09
		C2	7	32.49	46.52	334.95	1.13	83.56	2.05	55.21
		C3	13	25.28	71.80	655.10	0.76	87.03	1.43	59.34
		C4	21	17.68	89.48	882.39	0.62	88.89	1.18	61.33
		F		990.24						
		T		866.56						
		T2		16.39						
		T3		17.81						
	2	C1	3	12.58	12.58	21.51	3.34	71.57	4.07	30.53
		C2	7	31.01	43.59	329.77	1.10	81.78	2.05	53.30
		C3	13	29.79	73.38	663.43	0.69	86.45	1.32	57.91
		C4	21	18.34	91.72	886.21	0.57	88.47	1.10	59.96
		F		970.60						
		T		845.53						
		T2		16.55						
		T3		16.80						
$Mg(NO_3)_2$ Dow 200 SIBX	1	C1	3	12.57	12.57	22.73	3.38	70.83	3.92	28.39
		C2	7	28.43	41.00	244.79	1.19	81.27	2.19	51.91
		C3	13	27.63	68.63	554.46	0.75	85.49	1.43	56.69
		C4	21	19.27	87.90	793.72	0.60	87.59	1.16	59.03
		F		973.46						
		T		849.23						
		T2		18.74						
		T3		17.59						
	2	C1	3	12.30	12.30	22.80	3.60	67.81	4.11	26.47
		C2	7	28.90	41.20	245.35	1.28	80.69	2.49	53.72
		C3	13	28.09	69.29	557.19	0.81	85.64	1.63	59.09
		C4	21	18.89	88.18	795.06	0.65	87.73	1.33	61.32
		F		993.68						
		T		865.13						
		T2		19.04						
		T3		21.33						

Reagents	Run no.	Sample	Time min	Mass Pull g	Cum Mass g	Cum Water g	Copper Grade %	Copper Rec %	Nickel Grade %	Nickel Rec %
CaCl2 Dow 200 SIBX	1	C1	3	11.88	11.88	39.31	3.32	73.14	3.95	29.25
		C2	7	25.26	37.14	264.23	1.20	82.71	2.30	53.25
		C3	13	25.76	62.90	574.57	0.74	86.85	1.47	57.75
		C4	21	18.31	81.21	821.55	0.59	88.98	1.18	59.87
		F		974.34						
		T		857.91						
		T2		18.20						
		T3		17.02						
	2	C1	3	11.53	11.53	32.67	3.38	72.95	4.30	31.20
		C2	7	22.40	33.93	259.63	1.28	81.31	2.40	51.32
		C3	13	28.36	62.29	571.79	0.74	85.91	1.43	56.12
		C4	21	21.18	83.47	840.49	0.57	88.48	1.12	58.65
		F		976.26						
		T		859.17						
		T2		15.99						
		T3		17.63						
CaSO4 Dow 200 SIBX	1									
		C1	3	12.67	12.67	27.23	3.29	71.53	4.14	32.14
		C2	7	29.86	42.53	287.24	1.12	81.56	1.86	48.54
		C3	13	27.76	70.29	619.37	0.71	85.57	1.24	53.60
		C4	21	19.36	89.65	858.86	0.57	87.56	1.02	56.09
		F		979.67						
		T		854.76						
		T2		18.09						
		T3		17.17						
	2	C1	3	11.95	11.95	29.45	3.37	70.90	3.98	30.62
		C2	7	28.43	40.38	281.34	1.14	81.20	1.83	47.63
		C3	13	26.95	67.33	609.00	0.72	85.69	1.22	52.79
		C4	21	19.74	87.07	845.06	0.57	87.64	0.99	55.38
		F		985.64						
		T		861.06						
		T2		18.61						
		T3		18.90						

Reagents	Run no.	Sample	Time, min	Mass Pull g	Cum Mass g	Cum Water g	Copper Grade %	Copper Rec %	Nickel Grade %	Nickel Rec %
Ca(NO3)2 Dow 200 SIBX	1	C1	3	8.34	8.34	7.61	4.52	65.04	4.48	22.38
		C2	7	22.54	30.88	184.80	1.48	78.96	2.74	50.67
		C3	13	26.92	57.80	498.33	0.85	84.31	1.64	56.76
		C4	21	19.36	77.16	756.67	0.65	86.57	1.28	59.20
		F		992.85						
		T		875.94						
		T2		19.85						
		T3		19.90						
	2	C1	3	7.03	7.03	6.53	5.04	63.14	4.28	18.11
		C2	7	24.98	32.01	194.33	1.39	79.22	2.65	51.03
		C3	13	28.60	60.61	519.48	0.78	84.46	1.58	57.57
		C4	21	19.87	80.48	781.18	0.61	87.28	1.24	60.24
		F		972.17						
		T		853.62						
		T2		18.65						
		T3		19.42						
1Plant Dow 200 SIBX	1	C1	3	11.59	11.59	16.63	3.93	73.81	4.00	29.02
		C2	7	27.28	38.87	209.91	1.32	83.30	2.02	49.29
		C3	13	27.68	66.55	504.03	0.81	87.22	1.31	54.69
		C4	21	20.40	86.95	759.21	0.63	89.28	1.05	57.46
		F		957.48						
		T		834.05						
		T2		17.36						
		T3		19.12						
	2	C1	3	9.31	9.31	14.91	4.09	66.94	4.18	25.48
		C2	7	25.11	34.42	203.07	1.30	78.95	2.02	45.58
		C3	13	29.72	64.14	507.47	0.74	83.64	1.24	51.91
		C4	21	19.89	84.03	760.33	0.58	85.91	1.00	54.79
		F		959.90						
		T		838.80						
		T2		18.16						
		T3		18.91						

13.3 Appendix C – Bubble Size Analyser Experimental Procedure

Figure 13.1: UCT Bubble Size Analyser Setup

13.3.1 Equipment settings

1) Set the peristaltic pump at 50rpm
2) Fill the FLUSH water reservoir

13.3.2 Procedure for each Run

3) Put solution in a column
4) Toggle the UCT bubble size analyser to ON mode
5) Press Red START button, light should be on READY
6) Toggle the bubble pump to ON
7) Ensure that the capillary is below the water surface and inside the stream of bubbles
8) Turn open the knob at the bottom of column to allow air into the column, generating bubbles. Open knob fully
9) Turn computer on
10) Start BUBCAP software on computer
    a) Enter file name to distinguish tests
    b) Click OK
    c) Click on START, the prompt should read “waiting for data”

11) Fill burette with water by
    a) Invert burette
    b) Put drain pipe into drain container
    c) Switch the pump to FLUSH
    d) START the peristaltic pump
    e) Ensure burette is full and there are no bubbles leading up to the burette
    f) Simultaneously STOP pump and switch it to SAMPLE
    g) Put burette straight up
    h) Put drain pipe back into column (recycle)
12) To run a test, simultaneously,
    a) Start stop watch
    b) Push STOP/GO switch down to GO
    c) Turn peristaltic pump to START
13) To end a test, simultaneously
    a) Press Red STOP button, “Transmit data” light should be on
    b) Push START/GO switch up
    c) Stop peristaltic pump
    d) Stop stopwatch
    e) Mark volume of gas collected in burette
    f) Check that software has captured all 3 data blocks and input volume when required by software
14) Press Red START button, light should be on “Ready”
15) The software will be ready for a new data set, return to (10)
16) When all data sets have been collected, click EXIT

Start BUBBLEPRO for data analysis