The interactive effect of depressant type and dosage with frother dosage in the flotation of a PGE ore

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SYNOPSIS

The valuable components of the platinum group element (PGE) bearing ores of the Bushveld complex in South Africa constitute between 1% and as little as 0.1% of the total mass. In the processing of these ores by flotation, the naturally hydrophobic talc minerals cause overstable froths. The drainage of liquid and entrained particles is reduced thus the recovery of other gangue minerals by entrainment increases and grade decreases.

In the rougher float depressants are added to produce a manageable froth and improve the grade by reducing the overall amount of the naturally floating gangue in the concentrates. Depending on dosage, depressants may also affect the recovery of the valuable minerals in the ore positively by slime cleaning or negatively by depression. Depression of stabilising gangue minerals such as talc decreases the froth stability and may also affect the recovery of valuables.

Frothers are added to flotation systems to create stable froths. They increase the water layer around bubbles and the carrying capacity of the froth and thus recovery by entrainment. The drainage of entrained particles from the froth may be further increased by increasing the froth depth.

This study investigated the interactive effects of depressant dosage and type, frother dosage and froth depth on the recovery and grade of copper and nickel sulphides, recovery of water, floatable and entrained gangue in the flotation of a Merensky ore. Since it is known that water recovery is closely related to froth stability it was used to infer froth stability in this study. Two types of depressants carboxymethyl cellulose (CMC) and guar gums which are usually used in the flotation of PGE bearing ores were used. The frother was Dow 250.

Results showed that increasing either guar or CMC dosages from 50 to 100 g/t enhanced the recovery of copper and nickel sulphides. This was attributed to the slime cleaning action of the depressants and their stabilising effects. A further increase of dosage to 300 g/t decreased the recovery of copper and nickel indicating that depression of sulphides occurs at high depressant dosages.

Both the use of guar and CMC depressants reduced the recovery of floatable gangue with increasing dosage as expected. The guar depressant showed greater depression ability at 50 g/t dosage than the CMC depressant while the CMC was more effective at 100 and 300 g/t dosage. Reduction of water recovery by the CMC depressant was greater than that of the guar depressant indicating that the CMC depressant had greater destabilising effects on the froth. It is known that the CMC depressant has a strong negative charge while the guar depressant is only slightly charged. The guar depressant may have caused aggregation of particles which has less destabilising effects than the dispersed particles in the presence of the CMC depressant.

The froth recoveries showed that the effects of depressant and frother dosages counteract each other and that the decrease in the recovery of copper and nickel sulphides obtained at higher depressant dosages can be reversed by increasing frother dosage. However although increased frother dosage readily reverses the depressant effects, an increase of water and recovery by entrainment reduces the grade. The effect of depressant dosage increase on the water and froth stability is small in comparison to the effect of increased frother dosage. Thus for the levels tested the benefit of improved grade obtained by depressant addition would be lost.

The increase of froth depth to reduce entrainment resulted in a reduction of the recoveries of the valuable minerals but with the desired increase in grade. Smaller increments of frother dosage are required to produce effective reversal of depressant effects on the recovery of valuable minerals to achieve a good overall flotation performance.

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NOMENCLATURE

CMC	Carboxymethyl cellulose
Cu	Copper
d	Depressant dosage in grams per ton
DEP267	A Depramin type CMC reagent
DOW	Dowfroth
DS	Degree of substitution
EDTA	Ethylene diaminetetraacetic acid
e_g	The degree of entrainment of gangue
f	Frother dosage in grams per ton
FF30	A Finnfix type CMC reagent
F_M	Quantity of metal recovered by true flotation
gr	Grade of metal
h	Froth depth in centimetres
H^+	Hydrogen ion
IMP4	An Acrol type guar depressant
k_t	First order equilibrium rate constant
KU9	A guar depressant from GM associates
M	Cumulative mass percent of floatable gangue
M_{in}	Ultimate mass percent recovery of floatable gangue
Ni	Nickel
OH^-	Hydroxyl ion
PGE	Platinum group element
pH	Hydrogen ion concentration
R	Cumulative mass percent recovery
rec	Recovery
R_g	Recovery of gangue
R_{in}	Ultimate mass percent recovery
R_M	Cumulative mass recovery of a hydrophobic mineral
R_w	Cumulative mass recovery of water
SIBX	Sodium isobutyl xanthate
t	Flotation time

1 INTRODUCTION

In South Africa platinum group elements (PGE's) occur in and are recovered by flotation from a number of reefs of the Bushveld complex such as the Merensky, UG2 and Plat reefs. Ores from the Merensky reef have a typical PGE content varying from 3-11 g/t and contain approximately 1% base-metal sulphides, largely as chalcopyrite, pentlandite and pyrrhotite. The values therefore constitute a much smaller mass percent of the ore than is usual in flotation systems and most of the mass of the flotation concentrates is made up of gangue material.

Feldspar and pyroxene are the most abundant gangue in the ore at approximately 24-40% and 52-59% of the total mass. These minerals are generally hydrophilic although there is evidence that their recovery via metal ion activation may occur. The ore also contains 1-5% of talcaceous minerals which are naturally hydrophobic and highly floatable. Due to its unique structure, even though its percentage in the ore is low, talc has a disproportionate effect on the flotation in that it causes froth stabilisation which leads to increased entrainment of other gangue minerals.

The effective separation and recovery of minerals in flotation depends critically on both recoveries in the pulp phase and the stability and structure of the froth phase. Frothers are added to flotation systems to create a stable froth zone and permit effective recovery of the floating particles. Increasing froth stability increases the recovery of water and with it the recovery of particles by entrainment. In order to reduce entrainment, the water recovery can be decreased by increasing the froth depth.

Depressants are added to reduce the recovery of floatable gangue. In the flotation of Merensky ore, polysaccharide gangue depressants such as guar gum derivatives and carboxymethyl cellulose's (CMC's) are added to depress talc and produce a manageable froth. Depression of gangue, particularly in the cleaner circuits, is also necessary to increase concentrate grade and optimise cost-effective downstream processing of the concentrates.

Many studies have investigated and shown that hydrophobic particles contribute to froth stability. Prevention of froth stabilising talc reaching the froth by depression thus decreases froth stability and therefore reduces the recovery of gangue by entrainment.

Depressants may have either a positive or negative effect on the recovery of sulphide minerals. It has been shown by other researchers that depressants may improve sulphide mineral hydrophobicity by slime cleaning. Improved hydrophobicity then decreases froth stability and thus the recovery of gangue by entrainment. However depressants may decrease the hydrophobicity of sulphides by adsorbing on some active sites as on gangue. This may occur particularly with unliberated mineral particles.

This thesis investigates the interactive effects of depressant type and dosage, frother dosage and froth depth on the flotation performance of a Merensky ore and evaluates how the effects of depressant dosage on flotation performance are modified by frother dosage. Flotation performance in this project is characterised by the grade and recovery of copper and nickel sulphides and the rate of flotation of copper and nickel sulphides, water and total solids and the mass of both entrained and floatable gangue.

Batch flotation experiments were used for the investigation and these reflect rougher circuit conditions where grade considerations differ from those aimed at in the cleaner circuit. In plant practice during the flotation of PGE ores the addition of depressant in the rougher is necessary to counter an overstable and unmanageable froth by the depression of the hydrophobic talc in the ore.

Figure 1-1 illustrates the scope of this project. After the scope of the thesis is set out, Chapter 2 critically assesses the literature relevant to this work and the objectives of this investigation. The experimental work and procedures designed to investigate the effects of depressant type and dosage, frother dosage and froth depth are described in Chapter 3. Results of the flotation tests conducted are described in Chapter 4 and discussed in Chapter 5. The major conclusions from this work are then reported in Chapter 6.

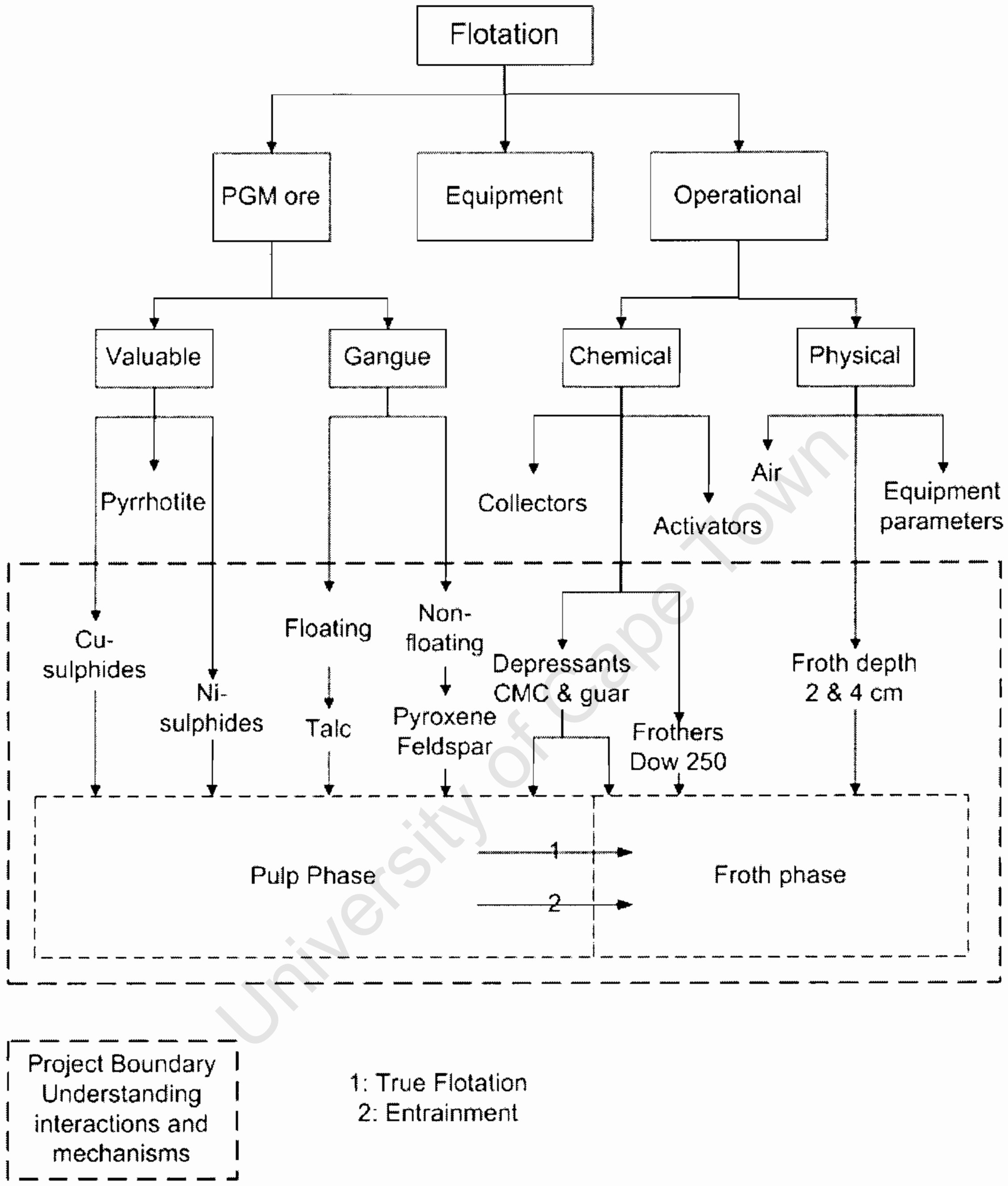

Figure 1-1: Illustration of the scope of the thesis

2 LITERATURE REVIEW

2.1 THE FLOTATION PROCESS AND WHAT INFLUENCES IT

Flotation is a process used to separate valuable minerals from the undesired gangue components of an ore by exploiting differences in their hydrophobicity. A schematic of the flotation process is illustrated in Figure 2-1. The surfaces of the valuable minerals are made hydrophobic by reagents called collectors. The hydrophobic mineral can then attach to air bubbles in an aerated and agitated pulp and the mineral-bubble aggregate rises in the pulp till it reaches the top of the froth where it is recovered to the concentrate. In addition to minerals recovered by this mechanism of true flotation, fine particles may be recovered by entrainment. Depressants are added to reduce the natural hydrophobicity of some gangue minerals. Other reagents added to facilitate the flotation process are frothers, activators and modifiers. The roles of the different reagents in the flotation process will be found in the later sections.

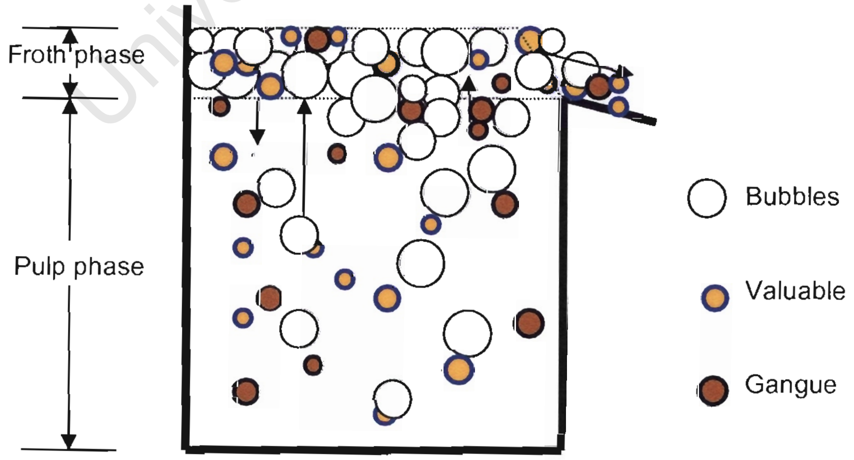

Figure 2-1: Schematic of the flotation process

The water around the bubbles in the froth carries fine entrained material which may also be recovered in the concentrate. Entrainment is a non-selective recovery mechanism and is the main cause of recovery of gangue minerals that are fully liberated and dispersed in a pulp. The froth zone allows the separation of valuable mineral from the gangue by the drainage of entrained material back to the pulp. The more stable the froth the greater the mass of water carried over. Although some inter-bubble water and some larger particles may drain back to the pulp during flotation, finer particles remain suspended in the inter-bubble water and are recovered in the concentrate.

Flotation is a complex process with many sub processes and interacting variables. The process is also subject to a wide variety of disturbances. Thus it can be considered as an interactive system of equipment components, operational components and chemical components (Klimpel, 1988) as illustrated in Figure 2-2. Collectors, activators and depressants affect the chemical environment of flotation pulp and either enhance or reduce the probability of bubble-mineral aggregates being formed (Lynch et al., 1981). Frothers are needed for the formation of stable froths and effective collection and recovery. The effects of depressants and frothers are very important to this project thus they will be discussed in the following sections.

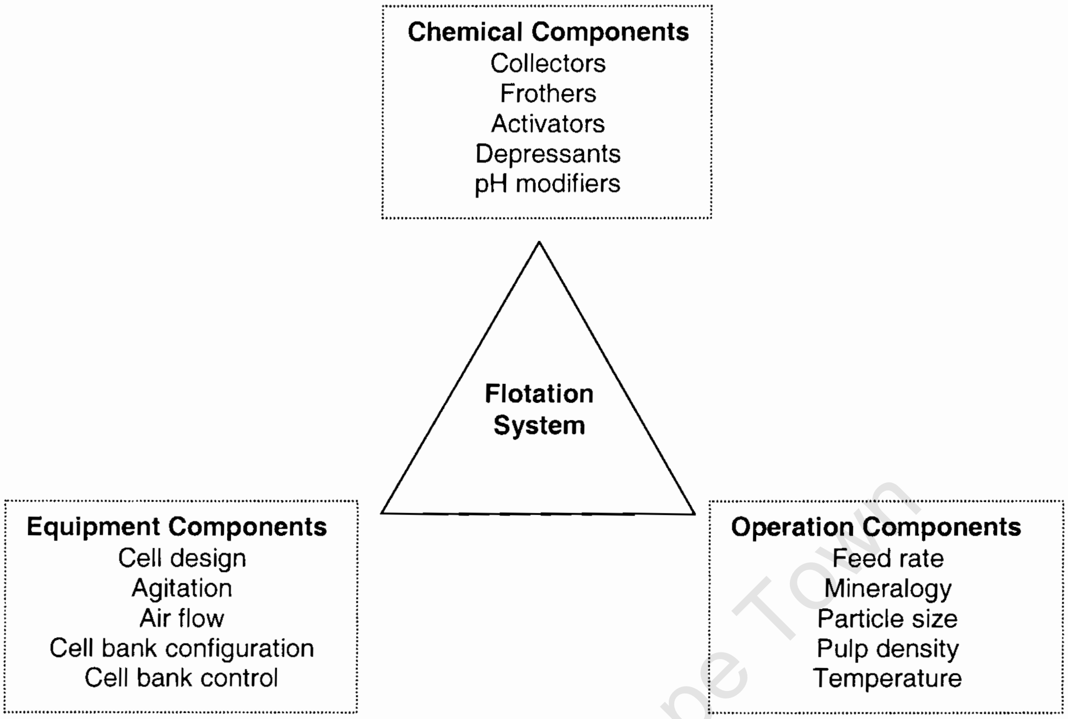

Figure 2-2: The interactive system of flotation [Source: Klimpel (1988)]

2.1.1 Frothers

Frothers are needed in flotation systems for the formation of stable froths and effective collection and recovery. The frother provides a large air-water interface for the floating mineral (Leja and He, 1984) and influences the kinetics of attachment of the particles to the bubbles (Lovell, 1982; Leja, 1982 and Subrahmanyam and Forssberg, 1988). In addition frothers assist in maintaining a stable froth which is capable of supporting the minerals carried to the surface until they can be recovered from the cell (Lynch et al., 1981; Harris, 1982; Lovell, 1982).

Frothers are generally heteropolar surface-active organic reagents. Their polar group forms hydrogen bonds with water while the non-polar group interacts with air. Frothers thus induce frothing by reducing the surface tension of the solution as a result of their preferential adsorption on to the air-water surface. According to Harris (1982), the possibility of particle-bubble contact and the rate of flotation are greatly increased due to the surface activity of frothers.

Frothers also interact with collectors in the moment of particle to bubble collision facilitating the particle-bubble attachment (Leja and Schulman, 1954). The surface activity of frothers increases the dispersion of air in the flotation machine and decreases the size of air bubbles and thus increases the bubble surface area (Klassen and Mokrousov, 1963).

The coalescence of individual bubbles is reduced by the ability of the frother to increase the stability of the hydrated layer surrounding the bubbles thus preventing the bursting of this layer when the bubbles collide with other bubbles (Klassen and Mokrousov, 1963), therefore increasing the stability of the froth phase.

Frothers must be soluble in water and have negligible collecting power to be fully effective (Wills, 1992). Although weak collecting ability of frothers may be beneficial, since it can lead to an increased recovery of minerals in the concentrate, it can lead to deterioration of flotation selectivity (Klassen and Mokrousov, 1963). The most effective frothers include in their composition the groups such as hydroxyl, carboxyl, carbonyl, amino and sulpho. The alcohols (-OH) are the most widely used since they have practically no collector properties. The OH group has strong hydrophilic properties and is very weakly adsorbed on minerals. Frothers such as carboxyls are also powerful collectors thus they are used as both collectors and frothers.

The alcohol groups provide selective, often brittle froth which allows good control and materials transfer through the launders and pumps. The glycol ether group is stronger, with more persistent froths than the alcohol groups, while the polyglycols are the strongest surface active frothers utilised. Examples of these are polypropylene glycol methyl ethers, the DOWFROTH frothers which are represented by the formulae:

$$CH_3 - (O - C_2H_4)_n - OH \quad \text{and} \quad CH_3 - (O - C_3H_6)_n - OH$$

The glycol methyl ethers are low viscosity liquids which are completely or partially soluble in water. They produce fine fragile froths that are usually very selective and have no collector action (Lovell, 1982). DOWFROTH frothers are known to produce froth of high selectivity on most ores. DOWFROTH frothers are used on a wide variety of sulphide ores at pulp alkalinities ranging from pH 12.5 to pH 3.5 (DOW, 1976).

The stability of the froth and the flotation performance depends also on the type and amount of frother added. Studies on frothers and froth stability by Lynch et al. (1982) and Cooper et al. (1985) indicated that when there is little or no frother added to the pulp, the bubble distribution in the pulp will be course and higher grades are obtained as indicated by Smar et al. (1994). The bubble-particle assemblages tend to disintegrate due to bubble collapse near the pulp surface reducing the transfer rate of material from the froth to the concentrate. An increase in frother concentration generally results in the reduction of the average bubble size in the pulp and results in the formation of a more stable froth and thus higher recoveries.

2.1.2 Depressants

Naturally floatable gangue enters the concentrate by flotation. Depressants are used to increase the selectivity of flotation by adsorbing onto the surface of hydrophobic gangue particles thus rendering them hydrophilic and preventing their flotation.

There are many types of depressants, inorganic or organic. For example inorganic depressants such as alkali sulphides and alkali cyanides are used in sulphide mineral flotation (Gaudin, 1957). The major groups of organic depressants are polyglycol ethers, polysaccharides and polyphenols. The polysaccharide type depressants such as cellulose and guar are used as selective depressants for talc and siliceous materials and are the focus of this investigation.

The Carboxymethyl cellulose, (CMC) and guar gum are the two most commonly used classes of polymeric depressants in PGE flotation. These polysaccharides are long chain macromolecules which reduce the flotation of talc by adsorbing on the surface making it hydrophilic thus preventing its flotation. This way, more effective separation can be achieved thereby improving grade of the concentrate.

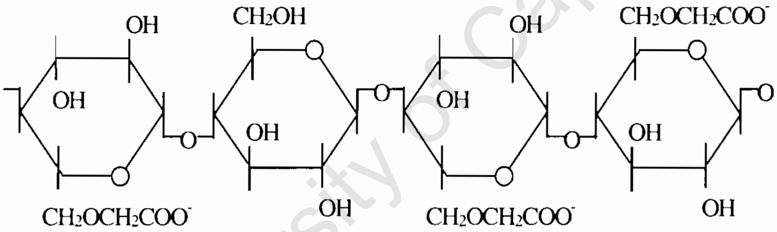

Figure 2-3: The structure of a CMC depressant

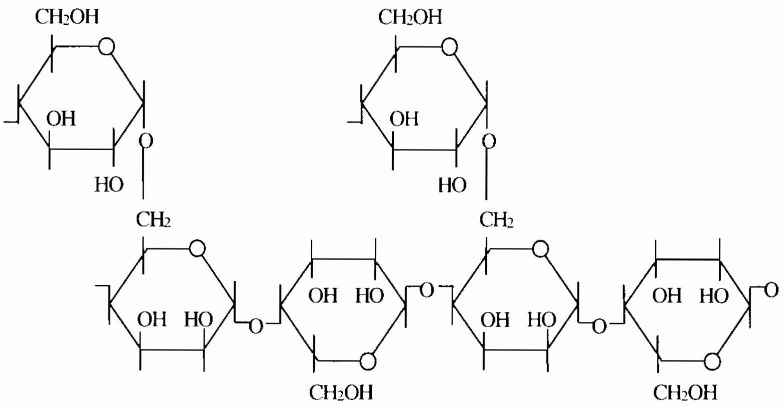

Figure 2-4: The structure of a guar depressant

The difference in structure and charge of these depressants illustrated in Figure 2-3 and 2-4 influences their adsorption onto gangue minerals and the mechanism of depression.

CMCs are anionic linear polymers prepared from cellulose that is a linear polymer of β-anhydroglocose units. The degree of substitution (DS) of the CMC molecule is defined as the number of hydroxyl groups in the anhydroglucose unit which have reacted to form derivatives (Pugh, 1989). Guar gums are considered non-ionic and give high viscosity aqueous solutions (Pugh, 1989).

2.1.2.1 Effect of depressants on talc particles

Talc is a naturally floating gangue mineral found in PGE ores. Talc is a layered magnesium silicate of composition $Mg_3(Si_4O_{10})(OH)_2$. Its layers are held together by van der Waals bonds. The ions within the layers are bound together by ionic electrostatic forces. When the talc breaks during grinding two different surfaces are formed. The basal cleavage planes are formed by the breakage of the van der Waals forces between layers and the edges are formed as a result of the rupture of ionic/covalent bonds within layers. The cleavage planes are neutral and hydrophobic while the edges have charged species and are hydrophilic.

Polymer adsorption on talc and the subsequent depression of talc is influenced by many variables. These include polymer type and concentration, molecular weight, degree of substitution, pH, ionic strength and the presence of other species in solution.

The adsorption of depressants on talc particles has been studied by many investigators. Steenberg and Harris (1984), Jenkins and Ralston (1998) and Morris et al. (2002) found that the adsorption densities of guar on talc were larger in comparison to CMC depressant and by Rath et al. (1997) larger in comparison to a dextrin depressant. It was found that the adsorption of polymers occurs on the basal plane first and then onto the edges. The areas occupied by the guar and the CMC depressants on the hydrophobic plane of talc were larger than the areas occupied on the edges (Steenberg and Harris, 1984).

Steenberg and Harris (1984) suggested that the low charge density and hydrophobic nature of the plane enables the molecules to spread out onto the uncharged surface whereas on the hydrophilic edges depressants tend to be more densely packed. Rath et al. (1997) attributed the higher adsorption densities of guar to the cis-configuration of the hydroxyl groups of guar compared to the trans-configuration of dextrin hydroxyl groups and also to the higher molecular weight of guar. The adsorption of CMC and polyacrylamides (Morris et al., 2002), is likely to occur in a flat conformation via hydrophobic interaction of the depressants and the talc surface.

The main mechanism for adsorption proposed by Steenberg and Harris (1984) was the hydrogen bonding of the depressant hydroxyl groups to the charged sites on the mineral surface. Rath et al. (1995), proposed that the adsorption of guar could occur through formation of guar gum-magnesium complexes, the interaction of guar with hydroxylated talc surface through hydrogen bonding or by chemical interaction with magnesium ions. When talc was treated with EDTA to form EDTA-magnesium complexes (Rath et al., 1997), the floatability in the presence of guar increased indicating that the magnesium ions in the talc matrix were involved in the interaction of talc with depressant.

Studies of the adsorption of guar gum on talc by Rath et al. (1995), Jenkins and Ralston (1998) and Morris et al. (2002) showed that the adsorption density of polymer on talc and the subsequent depression of talc intensified with increase in the concentration of depressant. Rath et al. (1995) suggested that some conformational rearrangement of polymer occurs with increasing guar concentration, which results in the increased extension of the looping chain thus shielding the hydrophobic plane from the interface. It has been shown that there exists a depressant concentration for maximum depression of talc after which no further depression occurs (Steenberg and Harris, 1984; Rath et al., 1995; Shortridge et al., 2000; Somasundaran et al., 2003). Shortridge et al. (2000) assumed that maximum surface area coverage of the guar was achieved at maximum depression. In contrast, Somasundaran et al. (2003) found that the adsorption of guar on talc reached saturation only at concentrations higher than 400 ppm indicating that maximum depression of guar on talc is achieved without complete coverage of talc by guar.

Shortridge et al. (2000) reported the dependence of talc floatability on depressant dosage and type. Flotation tests showed that selected modified guar gums depressed talc more in comparison to the CMC depressants under the same conditions. This is consistent with the lower adsorption densities achieved with CMC depressants. The differences in depression ability were attributed to the adsorbed molecule conformation on the surface of talc in agreement with Steenberg and Harris (1984). The guar depressant suggested an adsorption conformation with extended loops and tails which resulted in firm shielding of the talc surface from the air bubbles.

2.1.2.2 Effect of depressants on sulphides

Depressants may clean the slime particles on minerals or depress the valuable mineral. Edwards et al. (1980) found that the existence of slime coatings on pentlandite depressed its flotation. The slime coatings with positive surface charges were treated with modifiers such as CMC and dextrin to render their surface potential negative thus preventing their depression effect on pentlandite. The treatment of slimes improved with increased concentration of modifier.

Most depressants are not entirely selective. For example in the flotation of sulphide minerals (chalcopyrite and sphalerite), Lynch et al. (1981) found that sodium cyanide reduced the recovery of all sulphide minerals although reduction was greater in the case of gangue than valuable sulphides.

Rath et al. (2001) investigated the effect of guar gum adsorption of on chalcopyrite. They found that its adsorption density on chalcopyrite increased with concentration. They suggested that guar gums tend to form hydrogen bonds with hydrated minerals. The negative potentials of the surface are reduced and the mineral surface becomes hydrophilic and is depressed. Thus the flotation recovery of chalcopyrite was reduced when guar gum concentration increased.

2.2 THE FROTH PHASE IN FLOTATION

2.2.1 Importance of the froth phase in flotation and its stability

It has long been established that the behaviour of the froth phase determines the performance of a flotation system (Klassen and Mokrousov, 1963). According to Lekki and Laskowski (1975), the froth is an inseparable component of a froth flotation system. The froth phase supports valuable mineral particles from the pulp phase to the froth surface. In the froth phase, floating particles are further separated from the entrained gangue minerals as a result of the selective drainage of minerals together with excess liquid back to the pulp due to the nature of the structure of the froth phase. The structure of froths formed on the pulp surface of industrial scale cells has significant effects on both the grade and recovery of valuable minerals (Cutting et al., 1986). It is believed that a small bubbled closely knit froth is favourable for high recoveries and a loosely knit froth of large bubbles good for grades.

Froth stability has been recognised as the major parameter governing froth recovery and separation, hence the flotation performance (Klassen and Mokrousov, 1963; Livshits and Dudenkov, 1965; Dippenaar, 1982; Subrahmanyam and Forssberg, 1988). A stable froth is essential for the achievement of good grade and high recovery. The correct stability provides additional selectivity during flotation, that is, a further degree of separation of the valuable mineral from the non-floatable gangue.

Harris (1982) distinguished two types of froths, unstable or metastable. Unstable froths are known to continuously break down as liquid drains from between the bubbles. Here bubbles remain almost spherical until they touch and coalesce. In metastable froths, the drainage of the liquid from between bubbles proceeds to such an extent that the films of liquid between become almost planner lamellae of almost uniform thickness.

When froth is not sufficiently stable, the mineralized bubbles rupture before they can be scraped off over the weir of the flotation cell, and in this way, mineral particles already collected become detached and settle back into pulp. On the contrary, an excessively stable froth could entrain a large amount of gangue and a concentrate of poor grade would result. Klassen and Mokrousov (1963) stated that in most cases it is possible to obtain the correct froth quality by proper control of reagent additions. Where it is not possible it is necessary to control the froth by mechanical means.

2.2.2 Factors affecting froth stability

Two major factors affecting froth stability are the solution chemistry and the nature of the particles in the froth. Solution chemistry includes the frother dosage and type, plus the ions in solution. Particle effects that dominate are their hydrophobicity, size, shape, state of aggregation and concentration in the froth.

2.2.2.1 Solution Chemistry effects on froth characteristics

The main chemical parameters influencing flotation are reagent effects and pH as illustrated in Figure 2-2. Reagents affect flotation froth stability by altering the structure and composition of the adsorption layers on the bubble surface and the nature of the mineral coating on these surfaces.

The performance of a frother in the flotation of a mineral is of utmost importance from the view point of grades and recoveries. It is generally believed that surface-active frothers are most effective since they lower the surface tension of the solution as a result of their heteropolar molecules. The frothing of solutions is correlated with the surface activity of frothers and the surface activity of solutes is indicated by its surface tension. Solutes that lower the surface tension strongly in dilute solution produce persistent or stable froths (Harris, 1982). The frother molecules which adsorb on the liquid-air interface of the bubble prevent the bubbles from coalescing (Gaudin, 1957). Frother also reduces the rising velocity of a bubble (Fuerstenau and Wayman, 1958) therefore increasing the probability of particle-bubble contact.

Froth stability is also influenced by the size of bubbles forming the froth. The smaller the bubbles forming the froth, the greater is the stability of the froth (Harris, 1982). Increasing the frother concentration decreases the mean bubble size and a reduced bubble size results in reduced bubble rise velocity.

2.2.2.2 Particle effects on froth characteristics

The presence of solids on froth greatly alters the characteristics of the froth and its stability (Dippenaar, 1978; Leja, 1982; Johansson and Pugh, 1992). The stronger the hydrophobicity of the particles the greater is the effect on froth stability. Johansson and Pugh (1992) found that intermediate hydrophobic particles with contact angle ~ 65° enhance froth stability while more hydrophobic particles with contact angle > 90° destabilise froth but particles with a low degree of hydrophobicity (contact angle < 40°) had little effect on the froth and completely wetted particles had no effect on the stability of froths. The effects described above were more pronounced for a 26-44 μm size fraction than a course fraction of 74-106 µm. The findings above suggested that the particle effect on froth is size dependent.

Livshits and Dudenkov (1965) found that insoluble highly dispersed hydrophobic precipitates, which were products of the interaction of a collector with ions in the pulp reduced the volume and the stability of flotation froths and accelerated bubble coalescence in the pulp as well as the froth and caused the reduction of bubble dispersion. It was proposed that when two bubbles are in contact with a hydrophobic particle, the wetting perimeters move along the particle in the process of forming contact angles causing the thickness of the liquid film between the bubbles to decrease resulting in the acceleration of film rupture, thus causing coalescence of the bubbles. If the particle is more hydrophobic, the wetting perimeters formed by the bubbles are nearer to each other resulting in a thinner liquid film between them which breaks easily. Based on the proposal it was predicted that course particles serve as buffers between the two bubbles and slow down bubble coalescence with rounded particles having a greater effect on coalescence than the flat drawn out particles. The very fine particles were not expected to affect coalescence, as they must be drawn onto one of the bubbles by capillary forces of the liquid.

The ability of hydrophobic particles to stabilise froth has been shown to depend also on their size and concentration in the froth (Lovell, 1976; Dippenaar, 1982; Feng and Aldrich, 1999; Tao et al., 2000). Studies have also shown that there is an optimum size range for particles to stabilise or destabilise the froth (Subrahmanyam and Forssberg, 1988). Lovell (1976) studied the froth characteristics of a phosphate ore containing mainly apatite and calcite. He found that in the presence of tall oil fatty acid only, fine particles of both minerals at low solid concentrations destabilised froths. For higher amounts of solids, froth heights in excess of those obtained with two phase froth were obtained indicating stability at higher concentrations. When additional modifiers were used, apatite destabilised the froth regardless of its solid concentration while calcite still stabilised the froth. With the tall oil fatty acid only, it was suggested that the stability was as a result of the increase in particle size due to the coagulation of particles. In the presence of reagent mixtures it was suggested that the destabilisation was caused by the dispersion of suspensions in solution.

The study by Dippenaar (1982) on quartz and galena showed that for particles in the range 4-400 μm, the mass of particles required to obtain a set decrease in froth volume was directly related to the particle size. Quartz particles smaller than 4 μm were not effective froth breakers compared to larger particles due to extensive agglomeration of the smallest particles. The masses required for reducing the froth volume where 0.16 mg for 4-6 μm and 18.8 mg for 500-589 μm size quartz. For galena 1.7 mg of 8-10 μm and 140 mg of 90-106 μm were required to reduce the froth volume. Galena had an unexplained narrow size range that showed optimal froth breaking capacity as the addition of particles larger than 106 μm could not reduce the froth volume as required.

Feng and Aldrich (1999) investigated the dependence of the froth structure on particle size variation in batch flotation of two sulphide ores from Merensky and UG2 reefs in South Africa. Fine particles resulted in higher froth loadings and higher water recoveries, which were attributed to entrainment. The medium sized particles formed smaller and stable bubbles and had better flotation performance compared to both fine and course fractions. The flotation rate was strongly affected by the bubble size, with higher flotation rates associated with smaller bubbles and medium size particle fractions. The UG2 ore had smaller bubbles than Merensky ore and exhibited higher flotation rates. In a study by Tao et al. (2000) fine coal particles of 10 μm strongly destabilised the froth. The course particles of –100 mesh destabilised the froth at low solids concentration and stabilised froth at higher concentration.

2.2.3 Particle Entrainment

Apart from adhesion to bubbles, particles can be recovered to the concentrate by entrainment as mentioned in section 2.1. Entrainment is a function of particle properties and froth character. Entrainment is an unselective mechanism of recovery, i.e. it does not distinguish between hydrophilic and hydrophobic particles (Warren, 1985; Subrahmanyam and Forssberg, 1988; Smith and Warren, 1989; Savassi et al., 1998). The recovery of hydrophilic particles in flotation is mainly caused by entrainment. The less waste material entrained the higher the grade of the concentrate.

The particle mass, size and their shape affects entrainment of the gangue particles. The flotation efficiency is dependent on particle size and there seems to be a maximum size above which particles cannot be floated. According to Subrahmanyam and Forssberg (1988), it is known that the adhesion of particles greater than 10 µm in size occurs due to collision with air bubbles. For particles less than 10 µm, the collision efficiencies are low and the mechanism of collection takes place by entrainment. Fine particle tend to entrain and affect the flotation selectivity between hydrophilic and hydrophobic particles (Kirjavainen, 1989).

Due to decreasing size, (Kerjavainen ,1989), the mass of particles and the effect of gravity become negligible and fine particles tend to behave more and more as a part of the liquid phase entrained into the froth product along with floated water regardless of the degree of hydrophobicity of the particles. Watson and Grainger-Allen (1974) floated haematite and quartz in an equilibrium cell and found that increasing the initial amount of quartz (gangue) lead to an increase in the amount of these particles being entrained. It was also found that fine gangue particles at increased amounts in the froth films increased the stability of froth and thus the overall flotation rate. Ata et al. (2003) found that in the presence of high feed concentrations of gangue, the drainage of the entrained solids was significantly hindered resulting in more solids being carried up to the concentrate. At high feed gangue concentrations, the drainage rate constant was not affected by the depth.

2.2.3.1 Relationship between entrainment and water recovery

Many authors have recognised the close relationship between entrained particles and the recovery of water (Engelbrecht and Woodburn, 1975; Warren, 1985; Subrahmanyam and Forssberg, 1988; Kirjavainen, 1989). Generally, entrainment increases with increasing water recovery and pulp density. Many factors have been identified that affect the water recovery which include frother concentration (Subrahmanyam and Forssberg, 1988; Kirjavainen, 1992), froth depth (Engelbrecht and Woodburn, 1975), aeration rate (Subrahmanyam and Forssberg, 1988 and Kirjavainen, 1992), froth retention time (Bisshop and White, 1976) and pulp density (Bisshop and White, 1976). Engelbrecht and Woodburn, (1975) commented that at constant aeration rate and froth height, the recovery of water will depend on the stability and mobility of the froth. Bubble coalescence, although leading to instability decreases amount of entrained particles contained in the froth.

The more water in the froth, the higher the proportion of the particles recovered by entrainment rather than by true flotation and the lower the concentrate grade (Smith and Warren, 1989). A linear relationship was obtained for gangue recovery and water by Engelbrecht and Woodburn, (1975) and Lynch et al. (1981) in the flotation of silica and for ash recovery by Tao et al. (2000) during flotation of coal. The silica-water relationship was however non-linear at low water recoveries (Engelbrecht and Woodburn, 1975). Kirjavainen (1989) observed a parabolic relationship between water and quartz as well as phlogopite but in small size intervals of 1 μm a linear relation was obtained. The relationship between hydrophilic gangue and water is generally given by:

$$R_g = e_g R_w$$

R_g = recovery of fine gangue

e_g = a constant known as the degree of entrainment or the entrainment factor

The separation efficiency between the valuable mineral and fully liberated and dispersed gangue is dependent on the degree of entrainment (Savassi et al., 1998).

For the floatable pyrite, Engelbrecht and Woodburn (1975) observed two regions, one which was independent of water recovery and was dependent on the hydrophobicity of pyrite particles and one which was dependent on water and responded similarly to the gangue. Under conditions that favour entrainment, the overall recovery of hydrophobic particles comprise of an entrainment portion and a flotation portion (Smith and Warren, 1989). Warren (1985) found from batch flotation tests that the recovery of hydrophobic particles was linearly related to the weight of water recovered. The relationship was described by the equation:

$$R_M = F_M + e_M R_W$$

R_M =Recovery of hydrophobic mineral

F_M = An intercept, the quantity recovered by true

Warren (1985) also found that for water recovery greater than 500 g, low concentrate grades were obtained as a result of the dominance of the entrainment contribution.

2.2.3.2 Effect of froth depth on entrainment

It is desired that the froth zone provide additional selectivity between the valuable and entrained solids by allowing the drainage of entrained particles. Froth drainage removes particles not strongly attached to bubbles, generally gangue. However the relative velocity at which a particle falls together with the net upward velocity of the slurry determines whether a particle in the slurry liquid has a net upward or downward velocity (Moys, 1978). Increasing the froth depth decreased the drainage rate of entrained solids due to the decreased liquid content at the upper levels in the froth (Ata et al., 2003). It was concluded that the higher froth depths create a suitable environment for entrained particles to be entrapped easily between the layers of the bubbles.

2.2.3.3 Effect of froth depth on froth stability and performance

As the froth depth increases, the slurry volume fraction decreases and the bubbles crowd more closely together to form froth consisting of polyhedral bubbles separated by thin films with Plateau borders at the intersection of these films. As liquid and particles continue to drain from the films, the bubbles coalesce and the bubble surface area per froth volume decreases with depth. The properties of the froth thus change as liquid drains from it. Drainage of particles can occur due to the continuous drainage of liquid from bubbles, bubble coalescence, bubble bursting and froth overloading. Bubble coalescence can be promoted by the rupture of the interstitial bubble films by particles of a certain size, hydrophobicity and charge. Coalescence also occurs due to operating parameters such as froth depth and froth loading (Ross, 1997).

In the view that particle drainage occurs because of continuous drainage of liquid and bubble coalescence, there is a reduction of bubble surface area which increases the likelihood of hydrophobic particles to detach and drop back to the pulp. When strong attachment exists between valuable minerals and bubbles, drainage will improve the grade of the concentrate. It thus becomes important to regulate the degree of coalescence by changing reagent concentration, froth removal method or froth residence time (Moys, 1978) to control the recovery. Particles may get detached according to Ross (1990) by displacement due to other more hydrophobic particles or they can become dislodged if the bubbles are not stable enough to support them. Weakly hydrophobic particles can be washed from the bubbles as a result of the shear forces that are imposed on them by the contact and friction between the bubbles, especially near the pulp-froth interface.

In the study of the effect of froth depth on the flotation of pyrite Engelbrecht and Woodburn (1975), found two different responses of pyrite recovery as the depth increased. A drainage region was observed where very little loss in pyrite occurred with depth even though there was a significant reduction in the water recovery. An overloading region was also observed where bubbles were overloaded with particles as a result of coalescence causing the froth to shed valuable minerals. This resulted from a deep froth causing high drainage of water to pulp (Lynch et al., 1981). Overloading of bubbles causes inhibition of flotation as reported by Engelbrecht and Woodburn (1975) and preferential shedding occurs as a result of overloading.

Moys (1978) investigated the effect of froth behaviour by studying flotation in a cell that allowed the development of deep froths. The grades of the copper, zinc and iron sulphides and percent solids in the froth increased with depth while the grade of the gangue in the entrained slurry decreased. When froth was removed from the top of the froth, the grade of gangue at the froth surface increased suggesting a detachment of valuable minerals from the froth.

Ross (1990) removed froth samples from different heights of a column cell in order to determine the extent of detachment of material from the froth. It was shown that the concentration of the floating particles (pyrite) in all size fractions at the pulp-froth interface was much higher than the total concentration of the species at the surface of the froth indicating that floating particles detached from the bubbles in the body of the froth. The grade profiles showed clearly that there was detachment of the coarse fraction but this effect was not clear for the finer fractions as detachment could have been obscured by the coarse fractions. The sulphur grade profiles showed a steady increase in grade with height for all size ranges implying that there was no detachment of the sulphide particles from the froth. It was suggested that the rate at which sulphide particles detached from the bubbles was slower than that at which the gangue drained from the froth.

2.3 FLOTATION OF PGE BEARING ORES IN SOUTH AFRICA

In South Africa, platinum group elements, (PGE), are concentrated from the Merensky reef and other reefs from the Bushveld complex. The Merensky ore studied in this project has a PGE content varying from 3-11 g/t (Liddell et al., 1986). The typical mineralogy of a Merensky ore is given in Table 2-1. The ore consists of approximately 1% sulphide minerals mainly pyrrhotite, pentlandite, chalcopyrite and pyrite. The PGE minerals are mostly associated with base-metal sulphides, the majority being associated with pentlandite. Minor amounts of PGEs are in the form of alloys and platinum group minerals. Thus the flotation of Merensky ore is a bulk sulphide float that recovers the base-metal sulphides containing the platinum minerals and only liberated PGM sulphide minerals (Liddell et al., 1986).

Table 2-1: Mineralogy of a Merensky ore

Mineral	Abundance
Sulphides	0.9-1.1
Feldspar	24-40
Pyroxene	52-59
Talc	0.5-5.5
Chromite	3-4.5
Others	3-4.5

The gangue minerals in the ore are mainly feldspar at 24-40% and pyroxene at 52-59%. These minerals are naturally hydrophilic thus they are likely to be recovered in the concentrate by entrainment. The ore also contains between 1-5% of talcaceous minerals, known as talc, which are naturally floatable.

It is known that the froth character is influenced by the nature of the solids present in the froth. In the absence of depressants, due to its natural floatability, talc enters the froth zone by true flotation causing a problem of considerable significance due to its stabilising characteristics even though its percentage in the ore is small. This results in the increased recovery of other gangue minerals by entrainment. In addition, excessive magnesium content in the concentrate causes inefficient smelter operation. The hydrophobic nature and the shape of talc both promote a stable froth.

In the flotation of Merensky ore, depressants are added to reduce the flotation of talc and hence improve the grade of the concentrate. However the use of depressants affects froth stability and thus flotation performance by the reduction of the amount of froth stabilising solids.

2.3.1 Effect of depressants on the flotation of Merensky ores

Dalvie (2001) investigated the effects of a guar depressant (IMP4) and a CMC depressant (FF30) on Merensky ore flotation. The guar depressant showed little effect on the grade of copper and nickel sulphides at 40 g/t compared to flotation tests without depressant. A significant improvement in grade was obtained at 100 g/t of depressant. This indicated that the guar depressant was ineffective at 40 g/t dosage probably due to the coagulation effects observed in the settling tests at the same dosage. The CMC depressant did not show significant improvement in grade even at 100 g/t. However the CMC showed an improvement of recovery of both copper and nickel sulphides. This was attributed to the dispersing effect of the depressant as well as the possible cleaning action which allowed sulphides to float better.

Depressant type and concentration in the flotation cell affects froth characteristics and flotation performance. It has been shown that higher depressant dosages lead to lower solid-water ratio and reduced overall water and solid recoveries. Higher dosages also lead to increased copper recoveries and increased nickel grades (Shortridge, 2002). Shortridge (2002) did not find significant differences in flotation performance due to different types depressants (gaur: IMP4 and CMC: FF reagents). Robertson (2003) showed that an increase in depression leads to increased grade attributing it to the recovery of less floatable gangue material and on the less entrained material due to a decrease in froth stability.

2.4 SUMMARY

The presence of talc particles in a Merensky ore causes an overstable and unmanageable froth due to its hydrophobicity and layered structure. It is known that moderately hydrophobic particles stabilise the froth while strongly hydrophobic particles destabilise the froth (Johansson and Pugh, 1992). The overstabilisation of froth retards the drainage of liquid and gangue particles from the froth and thus reduces the grade of the concentrate.

Froth stabilisation by hydrophobic particles has been described by various researchers. It was found by Lovell (1976), Dippenaar (1982) and Tao et al. (2000) that at high solids concentrations, hydrophobic particles stabilised froth and that destabilisation occurred at low solids concentrations.

The role of depressants in flotation of platinum ores is to reduce the flotation of talc and to increase the grade of the concentrate. However, the reduction of the amount of these stabilising solids in the froth causes froth destabilisation. Depressants have been found to be non-selective thus the depression of the valuable mineral in the ore may occur. Although Lynch et al. (1981) and Rath et al. (2001) showed that depressants reduced the recovery of valuable sulphide minerals, but the possible reduction of significant losses of valuable minerals was not investigated.

The literature has shown that the success of the flotation process depends on many variables including reagents addition and froth depth. These variables influence the recovery in the pulp phase as well as the froth phase. Material is recovered into the froth by two mechanisms, true flotation and entrainment. True flotation depends on the surface hydrophobicity of particles while entrainment is a function of froth stability and structure which are affected by the solution phase as well as the solid phase.

The role of frothers in flotation is well known. Frothers are added to form stable froths and to enhance the carrying capacity of the froth. It may thus be possible to reverse the effects of depressant on froth stability by increasing the frother dosage. In view of this, it would be useful to study the effects of depressant dosage and frother dosage simultaneously on the froth and recovery of valuable minerals. The objectives of this study follow in the section below.

2.5 RESEARCH OBJECTIVES AND KEY QUESTIONS

The objective of this research was to investigate the interactive and counteractive effects of two classes of reagents, depressants and frothers on the recovery, grade and rates of copper and nickel sulphides, recovery of floatable gangue, entrained gangue, solids mass and water mass in the flotation of a Merensky ore.

The following are the key questions addressed:

1. What is the effect of increased depressant dosage on the recovery, grade and rate of flotation of copper and nickel sulphides, recovery of floatable gangue, entrained gangue, solids mass and water mass?

2. How does depressant type (CMC and guar) change the effect of dosage?

3. What is the effect of increased frother dosage on the recovery, grade and rate of flotation of copper and nickel sulphides, recovery of floatable gangue, entrained gangue, solids mass and water mass?

4. How is the recovery of copper and nickel sulphides, floatable gangue, entrained gangue, solids mass and water mass affected by froth depth?

5. Is the flotation behaviour of copper sulphides affected differently from that of nickel sulphides?

6. Are the effects of increased depressant dosage influenced by changes in frother dosage? In other words are there interactive effects between depressant and frother dosages on the flotation performance?

7. How are changes in recovery of copper and nickel sulphides brought about by depressant dosage and type counteracted by frother dosage?

3 EXPERIMENTAL DETAILS

Flotation tests were conducted using standard laboratory bench scale tests to investigate the interactive effects of depressant dosage and frother dosage on the recovery of the valuable and gangue minerals in the flotation of a Merensky ore. Although this thesis is about a PGE bearing ore, PGE recoveries were not directly determined. Previous investigations have shown that copper and nickel recoveries are an effective indicator of PGE recovery. Metallurgical performance was evaluated from the grades and recoveries of copper and nickel sulphides total mass of solids recovered, water recovery and the recovery of entrained and floatable gangue. Approximately 30% of the nickel in the ore does not occur as sulphide and is not recovered by flotation.

3.1 EQUIPMENT

An Eriez laboratory stainless steel rod mill with a diameter of 200 mm was used. The mill was charged with 20 stainless steel rods with quantities and diameters as follows: 6 rods at 25 mm; 8 rods at 20 mm; 6 rods at 16 mm.

Flotation was carried out in a 3 litre modified Leeds laboratory batch flotation cell illustrated in Figure 3-1. The movable lip on the cell enabled varying the froth depths while maintaining a constant pulp level. The set impeller speed and air flowrate were carefully monitored during flotation.

3.2 THE ORE

A Merensky ore was used for the investigations. 1 kg samples of the ore were ground in a rod mill with synthetic plant water. A milling curve was established in order to determine the milling time required to obtain a flotation feed particle distribution of 60% passing 75 μm. The average grades of copper, nickel and sulphur in the flotation feed were 0.07%; 0.22%; 0.31% respectively.

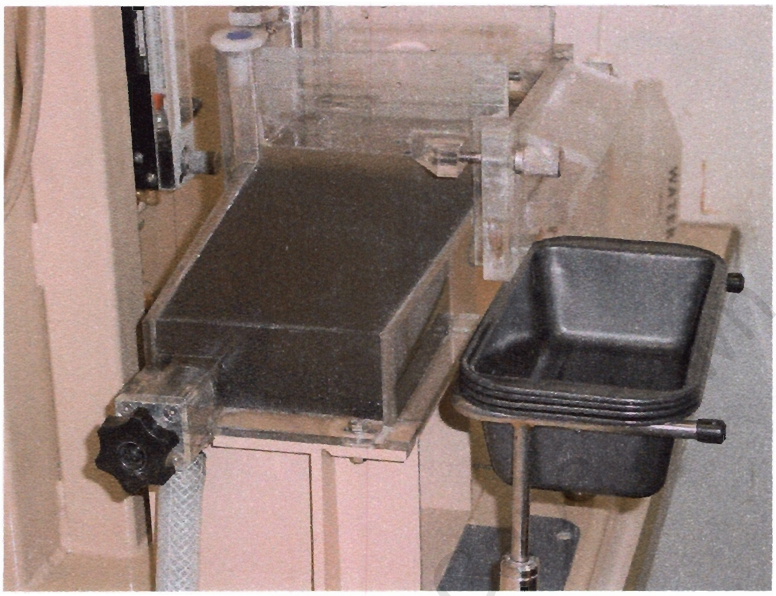

Figure 3-1: A photograph of the modified Leeds flotation cell

3.3 SYNTHETIC PLANT WATER COMPOSITION

Synthetic plant water containing similar amounts of ions typically found in the PGE flotation plants was used.

Table 3-1: Composition of synthetic plant water

Chemical salt	Formula	Mass in 1 litre, g
Magnesium sulphate	$MgSO_4.7H_2O$	0.615
Magnesium nitrate	$Mg(NO_3)_2.6H_2O$	0.107
Calcium nitrate	$Ca(NO_3)_2.4H_2O$	0.236
Calcium chloride	$CaCl_2$	0.111
Sodium chloride	$NaCl$	0.356
Sodium carbonate	Na_2CO_3	0.030

The synthetic plant water was produced by adding various chemical salts to distilled water. The salts and the amounts that were added are shown in Table 3-1.

3.4 FLOTATION REAGENTS

3.4.1 Collector

Sodium isobutyl xanthate (SIBX) supplied by SENMIN was used as a collector at a constant dosage of 80 g/t.

3.4.2 Frother

In this study DOWFROTH 250 (Dow 250) a polyglycol ether frother was used at three dosage levels of 30, 40 and 80 g/t.

3.4.3 Depressants

A carboxymethyl cellulose (CMC), and a guar depressant were used in the study. The CMC depressant DEP267 is a Depramin product prepared and supplied by Akzo Nobel. The degree of substitution (DS) of 0.67 in Table 3-2 indicates that the molecule is highly charged. The guar depressant, KU9 was supplied by GM associates. Both depressants were varied at three levels of 50, 100 and 300 g/t.

Table 3-2: Viscosity, degree of substitution and purity characteristics of the CMC (DEP267) and guar (KU9) depressants

Name	Viscosity of a 1.5% Solution cp	DS	Purity % Depressant
DEP267 1999051102	14.9	0.67	74.3
KU9 2001071209	18.8	N/A	91.4

The viscosities of solutions of the two depressants were measured at concentrations of 1.5%, 1% and 0.5% by mass. A Brookfield digital DV-I+ viscometer was used for the measurements. In Table 3-2 only the viscosities of the 1.5% solutions are given.

The viscosities indicate that the guar depressant is a larger molecule than the CMC depressant. All quantities of the CMC depressant used in this study were calculated on the basis of the active content.

3.5 FLOTATION CELL CONDITIONS

The standard flotation conditions and variables are given in Table 3-3. Only the depressant dosage, frother dosage and froth depth were varied.

Table 3-3: Standard and variable flotation cell conditions

Standard cell conditions	Variables
Aeration rate: 7 l/min	Depressant (Guar, CMC)
Impeller speed: 1200 rpm	dosage (50, 100, 300 g/t)
Frother type: DOWFROTH 250	Frother dosage (30, 40, 80 g/t)
Collector: SIBX at 80 g/t	Froth height (2 and 4 cm)

3.6 EXPERIMENTS CONDUCTED

The different experimental conditions tested are shown in Table 3-4. All experiments were done in duplicate to establish the reliability of the tests. The flotation procedure is found in Appendix 1.

Table 3-4: Experiment design showing conditions of depressant type and dosage and frother dosage and froth depth which were tested

Frother Dosage, g	Depressant Dosage, g	Guar: KU9		CMC: DEP267	
		2 cm	4 cm	2 cm	4 cm
30	50	•		•	
30	100	•		•	
30	300	•		•	
40	50	•	•	•	
40	100	•	•	•	
40	300	•	•	•	
80	50	•	•		•
80	100	•	•		•
80	300	•	•		•

It was observed that at a froth depth of 4 cm, a frother dosage of 30 g/t did not produce a froth that was stable enough for meaningful results to be obtained. At high froth depth, a frother dosage of 40 g/t was insufficient to generate enough froth volume for high CMC depressant dosages.

3.7 ANALYTICAL TECHNIQUES

3.7.1 Copper and nickel assays

Feed, concentrate and tailing samples were acid digested and then analysed for copper and nickel using a Varian SpectrAA atomic absorption spectrometer.

3.7.2 Sulphur assays

All feed, concentrate and tailing samples were assayed for total sulphur using a LECO SC-432DR sulphur analyser. The sulphur assays were used to determine the floatable total sulphide mass of minerals in the ore.

3.8 EVALUATION TECHNIQUES

3.8.1 Copper and nickel sulphides

The grade-recovery relationship of copper and nickel indicate the selectivity and efficiency of the flotation process towards the valuable PGEs.

3.8.2 Concentrate mass and water mass

The mass-water relationship determines the froth phase characteristics and the extent of gangue flotation. At constant froth depth, water recovery was used as an indicator of froth stability. It is known that the mass of water recovered is not a complete indication of froth stability but that it is strongly related to it.

3.8.3 Entrained and floatable gangue mass

The recovery of entrained gangue is directly related to the water recovery. This was calculated from an entrainment factor that was determined by Robertson

(2003) for a Merensky ore at a froth depth of 2 cm. The floatable gangue was calculated from the total mass recovered minus the total mass of sulphide mineral and entrained mass.

As described in section 2, the recovery of entrained gangue is related to water recovery and was calculated from an entrainment factor determined by Robertson (2003) as follows:

$$\text{Entrained gangue} \Rightarrow \text{Water recovery x entrainment factor}$$

This entrainment factor was formulated based on the assumption that it depends on the nature of particles and the amount of water recovered in the froth.

The amount of floatable gangue was given by the following expression:

$$\text{Floatable gangue} \Rightarrow \text{Total mass} - \text{total sulphides mass - entrained gangue}$$

3.8.4 Kinetic model

In addition to the metallurgical characteristics, the ultimate recovery and flotation rate were also used for evaluation of the flotation process. A first order kinetic model based on the cumulative fractional recoveries was used to calculate the ultimate recovery and the flotation rate.

4 RESULTS

This chapter describes the results of batch flotation tests conducted to investigate the effect of varying depressant dosage and type as well as frother dosage on the froth and recovery of both valuable and gangue components of a Merensky ore. PGE recoveries were not determined directly but previous investigations have shown that copper and nickel calculated values are an effective indicator of their recovery. Metallurgical performance was evaluated from the copper and nickel recovery and grade, total solid mass and mass of water recovered, the entrained and floatable gangue recovered. It is worth noting that approximately 30% of the nickel in Merensky ore does not occur as sulphide and is not recovered by flotation. As this figure is imprecisely known the results given here are calculated for total nickel in the concentrate sample.

4.1 REPRODUCIBILITY OF FLOTATION TESTS

The results presented in this chapter are the average values of tests done in duplicate in order to estimate the repeatability or precision of the experiments. Standard errors and 95% confidence errors were calculated for all the tests to assess the variation between the duplicate experiments. An example is given here and tabulated in Table 4-1 for the tests at 100 g/t guar depressant, 40 g/t frother dosage and 2 cm froth depth. The standard error is calculated from the sample standard deviation between the duplicate tests divided by the square root of the sample size, i.e. the number of tests. The standard error is multiplied by 1.96, the coordinate corresponding to 95% confidence limit, to determine the 95% confidence error. This error gives the range of variation of the values at 95% confidence level.

Table 4-1: Illustration of standard error calculations for solids mass copper and nickel recoveries

	Total solids, g 1	Total solids, g 2	Average solids g	Standard deviation	Standard error	Relative std.error %	95% Confidence error	Fractional error %
C1	26.42	25.95	26.19	0.33	0.23	0.90	0.46	1.76
C2	39.54	38.94	39.24	0.42	0.30	0.76	0.59	1.50
C3	44.42	45.75	45.09	0.94	0.67	1.47	1.30	2.89
C4	47.63	49.10	48.37	1.04	0.74	1.52	1.44	2.98
						1.16		**2.28**

	Copper rec, % 1	Copper rec, % 2	Av. Copper recovery %	Standard deviation	Standard error	Relative std.error %	95% Confidence error	Fractional error %
C1	73.57	73.33	73.45	0.17	0.12	0.17	0.24	0.33
C2	80.53	79.83	80.18	0.50	0.35	0.44	0.69	0.86
C3	82.18	81.87	82.02	0.22	0.15	0.19	0.30	0.37
C4	83.09	82.70	82.90	0.28	0.20	0.24	0.38	0.46
						0.26		**0.50**

	Nickel rec, % 1	Nickel rec, % 2	Av. Nickel recovery %	Standard deviation	Standard error	Relative std.error %	95% Confidence error	Fractional error %
C1	36.54	35.12	35.83	1.00	0.71	1.98	1.39	3.88
C2	45.25	43.27	44.26	1.40	0.99	2.24	1.94	4.38
C3	46.96	45.54	46.25	1.00	0.71	1.53	1.39	3.00
C4	47.88	46.41	47.15	1.03	0.73	1.55	1.43	3.04
						1.83		**3.58**

The copper recoveries are the most precise values as shown in Table 4-1. Figure 4-1 illustrates the duplicate test results for solids mass, copper and nickel recoveries.

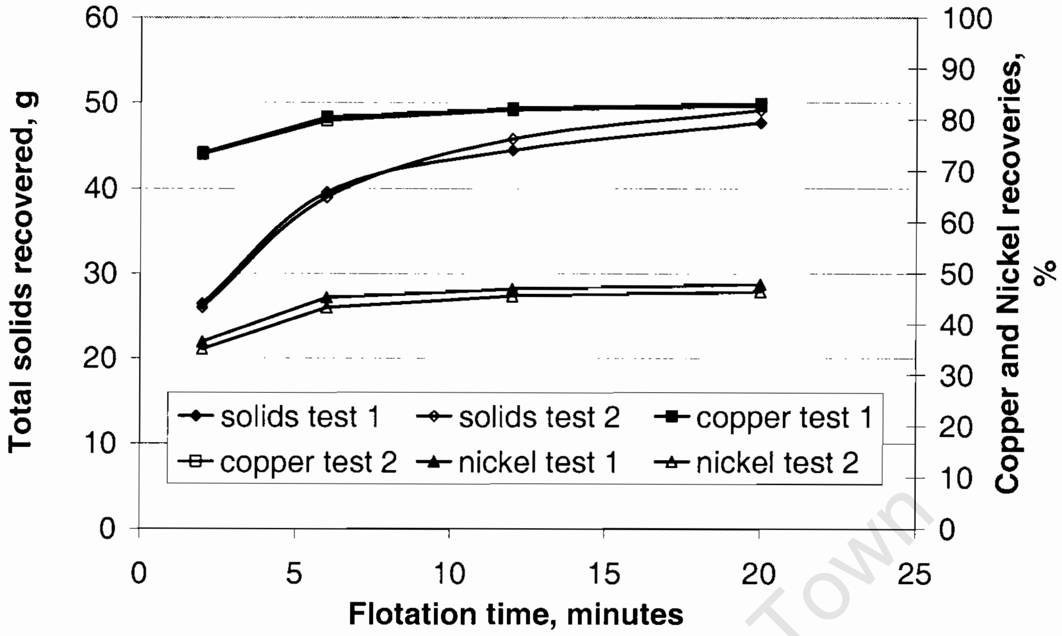

Figure 4-1: Total solids mass and copper and nickel recoveries of duplicate tests showing the reproducibility of flotation experiments

The curves in Figure 4-1 together with the values in Table 4-1 show that the reproducibility of the results justifies comparison of tests at different conditions.

4.2 SUMMARY OF FLOTATION RESULTS

The cumulative final copper and nickel recoveries and grades, solids mass, water, entrained and floating gangue at 20 minutes of flotation are summarised in Table 4-2. Note that the values presented are the average values of tests done in duplicate for each set of conditions. Also note that in the figures that follow, depressant dosage, frother dosage and froth depth will be represented by the letters, d, f and h respectively. The number next to the letter is the dosage or level used for example; d100-f40-h4 indicates a depressant dosage of 100 g/t, frother dosage of 40 g/t and froth depth of 4 cm.

Table 4-2: Summary of Flotation results showing the final total solids mass, final grade and recovery of copper and nickel sulphides as well as final masses of entrained (Ent Gang) and floatable (Flt Gang) gangue at different conditions

Guar

Frother Dosage g/t	Dep Dosage g/t	Froth Depth Cm	Final Mass g	Final Water g	Final Cu Grade %	Final Cu Rec %	Final Ni Grade %	Final Ni Rec %	Final Ent Gang g	Final Flt Gang g
30	50	2	35.8	264.0	1.3	78.4	2.2	37.1	7.4	23.4
30	100	2	29.9	275.2	1.5	80.3	2.7	38.4	7.7	17.0
30	300	2	12.4	140.8	3.6	74.1	6.1	36.0	4.0	3.4
40	50	2	56.6	552.1	1.0	82.7	1.7	46.0	15.5	34.2
40	100	2	48.4	527.4	1.2	82.9	2.0	47.1	14.8	26.6
40	300	2	30.3	459.0	1.8	77.7	3.1	48.4	12.9	11.1
80	50	2	120.6	1466.8	0.5	85.2	1.0	56.5	41.2	73.2
80	100	2	116.6	1557.0	0.5	87.9	1.1	56.3	43.8	64.4
80	300	2	88.6	1376.0	0.7	86.7	1.4	54.8	38.7	42.1
40	50	4	22.1	63.4	2.2	72.8	3.0	35.1	1.8	16.2
40	100	4	13.0	25.6	2.9	61.0	4.4	29.8	0.7	8.4
80	50	4	43.2	219.2	1.3	83.3	2.2	44.5	6.2	30.4
80	100	4	36.3	198.0	1.5	81.9	2.6	40.6	5.6	23.8
80	300	4	21.5	169.6	2.4	76.9	3.9	39.8	4.8	10.1

CMC

Frother Dosage g/t	Dep Dosage g/t	Froth Depth Cm	Final Mass g	Final Water g	Final Cu Grade %	Final Cu Rec %	Final Ni Grade %	Final Ni Rec %	Final Ent Gang g	Final Flt Gang g
30	50	2	39.8	318.7	1.3	82.9	2.0	38.2	9.0	25.7
30	100	2	28.8	207.7	1.6	79.0	2.7	36.1	5.8	17.7
30	300	2	7.7	75.1	5.4	68.0	8.3	29.7	2.1	1.4
40	50	2	58.8	586.3	1.1	80.6	1.7	47.6	16.5	35.7
40	100	2	42.3	420.0	1.4	83.8	2.2	52.2	11.8	24.3
40	300	2	14.7	210.8	3.4	73.3	6.2	43.2	5.9	2.7
80	50	4	46.1	285.9	1.3	80.1	2.1	45.9	8.0	31.4
80	100	4	33.8	146.4	1.7	79.9	2.8	45.5	4.1	23.2
80	300	4	9.5	61.3	4.0	64.6	8.5	39.4	1.7	2.4

4.3 COPPER AND NICKEL GRADES AND RECOVERIES

Grade-recovery curves for copper and nickel are shown in Figures 4-2 to 4-9 to represent grade and recovery of chalcopyrite and pentlandite respectively. The recovery of nickel is lower than that of copper while nickel grade is higher at similar conditions.

At constant frother dosage, an increase in depressant dosage shows an increase in the grades of copper and nickel as a consequence of floatable gangue reduction. Figures 4-2, 4-4, 4-6 and 4-8 show that the grade of copper and nickel at 300 g/t dosage of depressant and 30 g/t frother dosage was very high but there was a very large drop in recovery. Depressant dosage has a much bigger effect on the grade of nickel than of copper. The decrease in recovery with depressant dosage was very significant at 300 g/t for both copper and nickel.

At the same frother dosage and depressant dosage the CMC depressant (Figures 4-6 to 4-9) obtains higher grades than guar (Figures 4-2 to 4-5) and has a larger effect on the reduction of copper and nickel recoveries at 300 g/t dosage. The difference in grade between frother dosages was smaller with the CMC depressant than guar especially at 300 g/t depressant dosage as shown in Figures 4-4 and 4-8.

At constant depressant dosage an increase in frother dosage increases the recoveries of copper and nickel and decreases the grades significantly as a result of the increase in stability and recovery by entrainment. Large changes in the grade and recovery are obtained with the highest depressant dosage and lowest frother dosage as illustrated in Figures 4-2, 4-4 and 4-6, 4-8. Frother dosage has a greater effect on nickel recovery than copper.

At a higher froth depth, better grades are obtained except recoveries are lower. The recovery of copper and nickel sulphides increased from 50 to 100 g/t depressant dosage at 2 cm froth depth but at 4 cm recovery decreased at these depressant conditions.

The change in grades and recoveries of copper and nickel with increasing depressant dosage increases with a decrease in frother dosage and nickel shows larger changes.

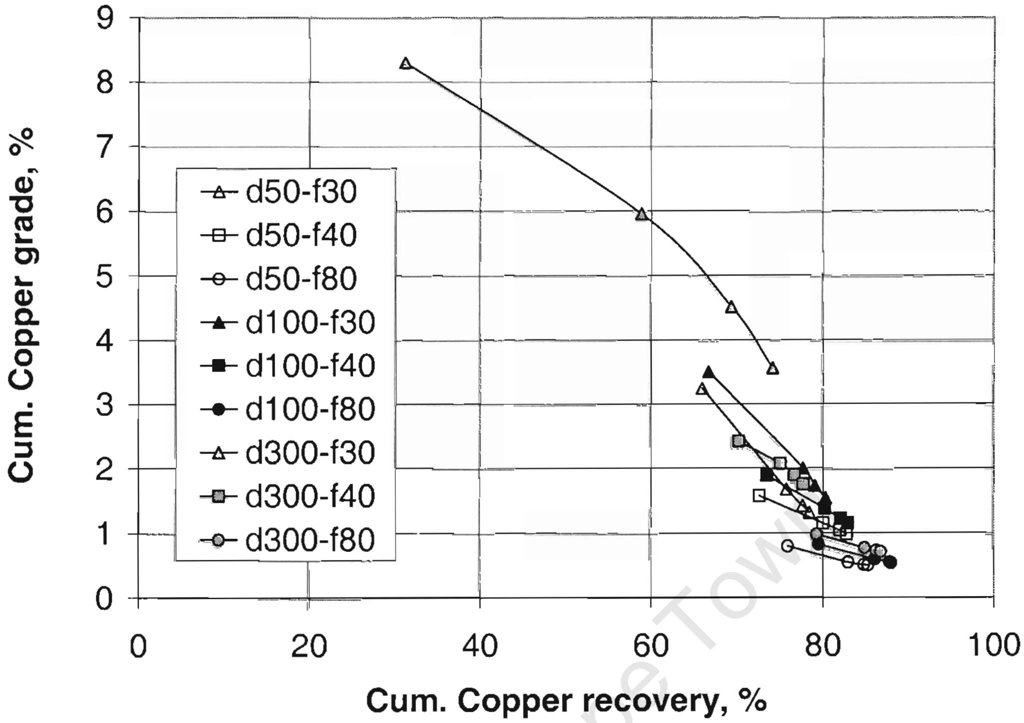

Figure 4-2: Effect of guar depressant addition with various frother dosages on the grade-recovery relationship of copper sulphides at 2 cm froth depth

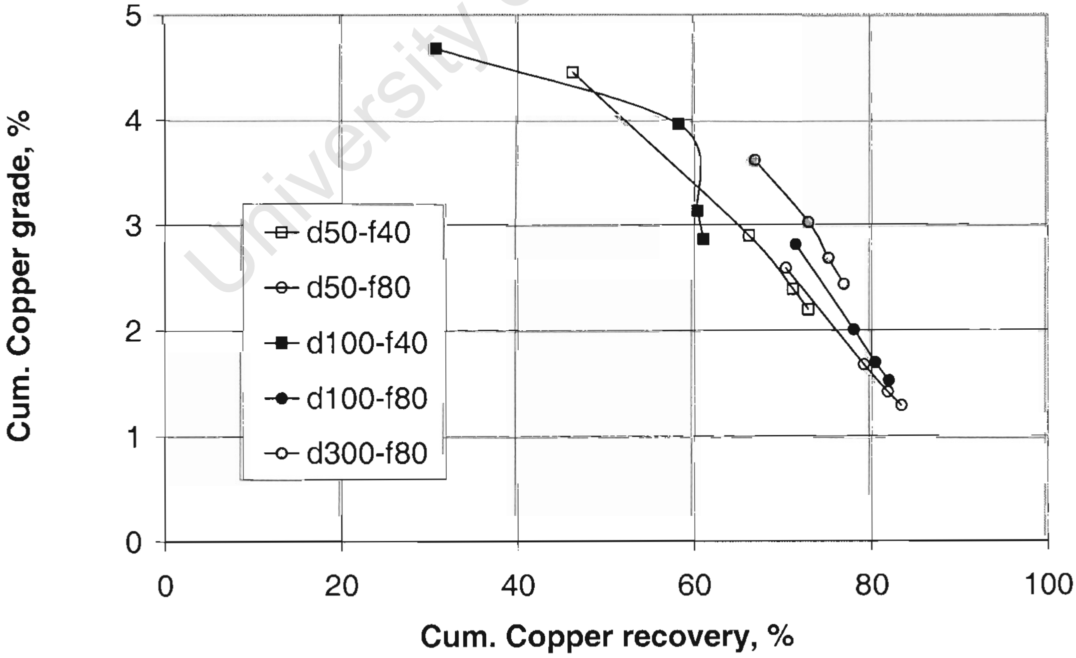

Figure 4-3: Effect of guar depressant addition with various frother dosages on the grade-recovery relationship of copper sulphides at 4 cm froth depth

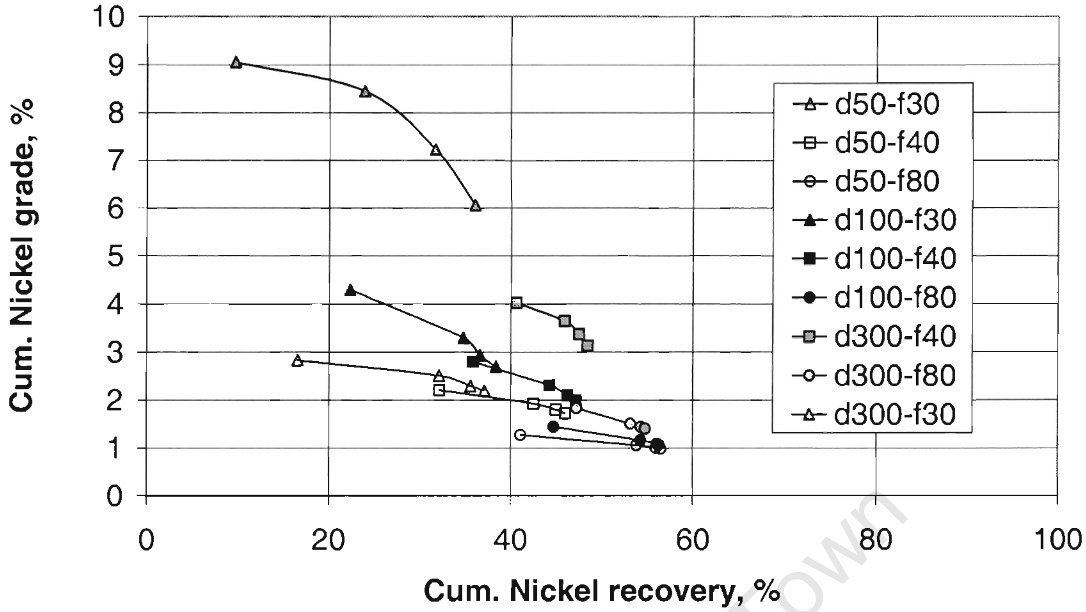

Figure 4-4: Effect of guar depressant addition with various frother dosages on the grade-recovery relationship of nickel sulphides at 2 cm froth depth

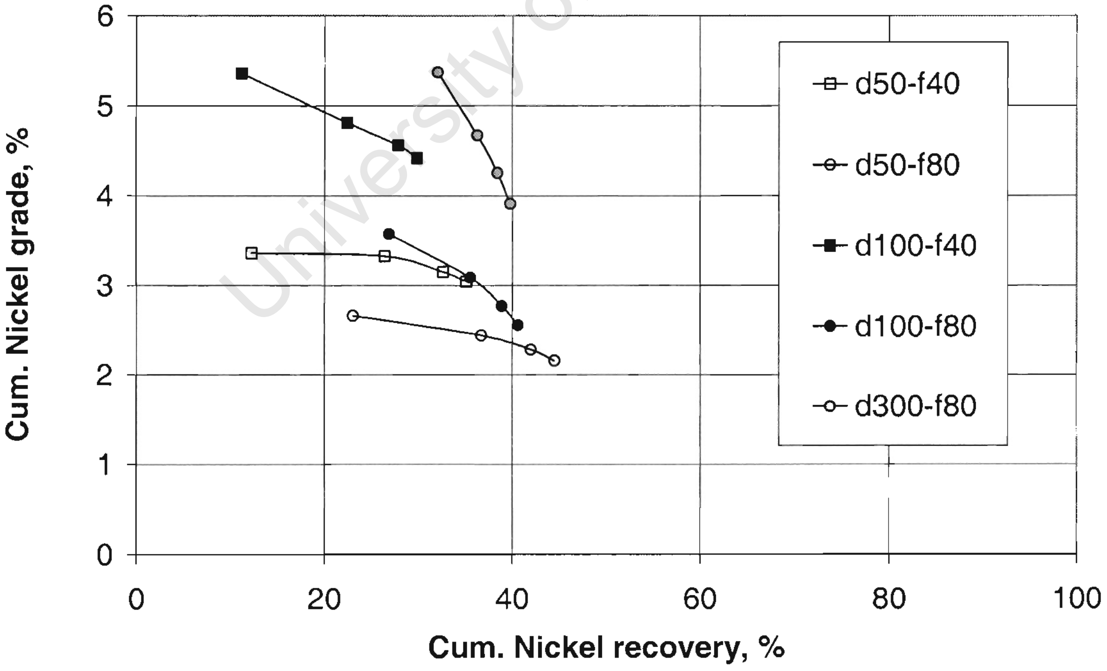

Figure 4-5: Effect of guar depressant addition with various frother dosages on the grade-recovery relationship of nickel sulphides at 4 cm froth depth

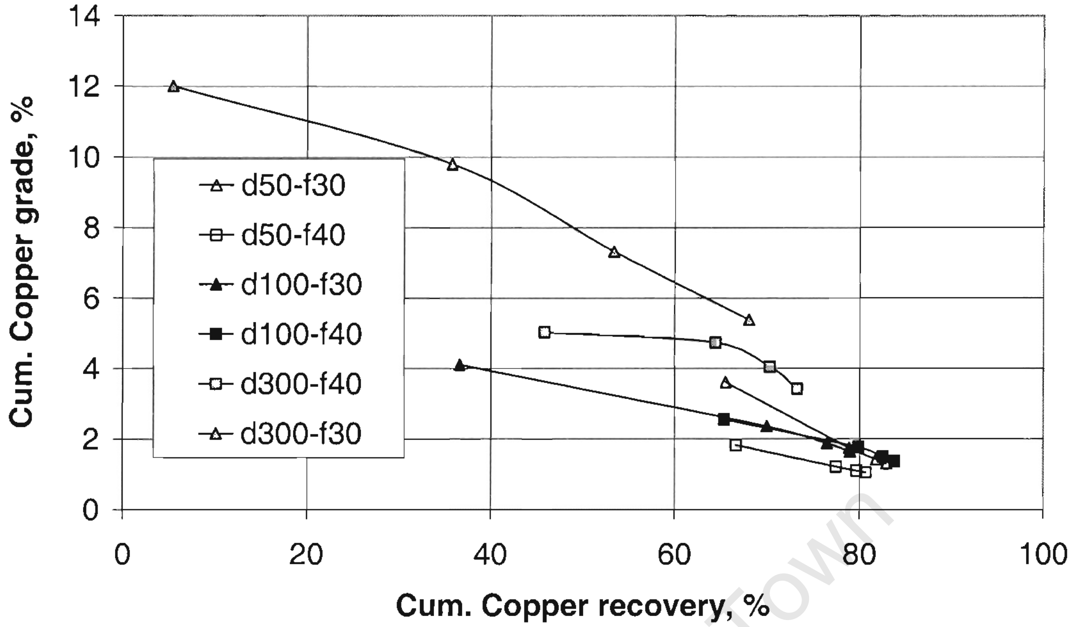

Figure 4-6: Effect of CMC depressant addition with various frother dosages on the grade-recovery relationship of copper sulphides at 2 cm froth depth

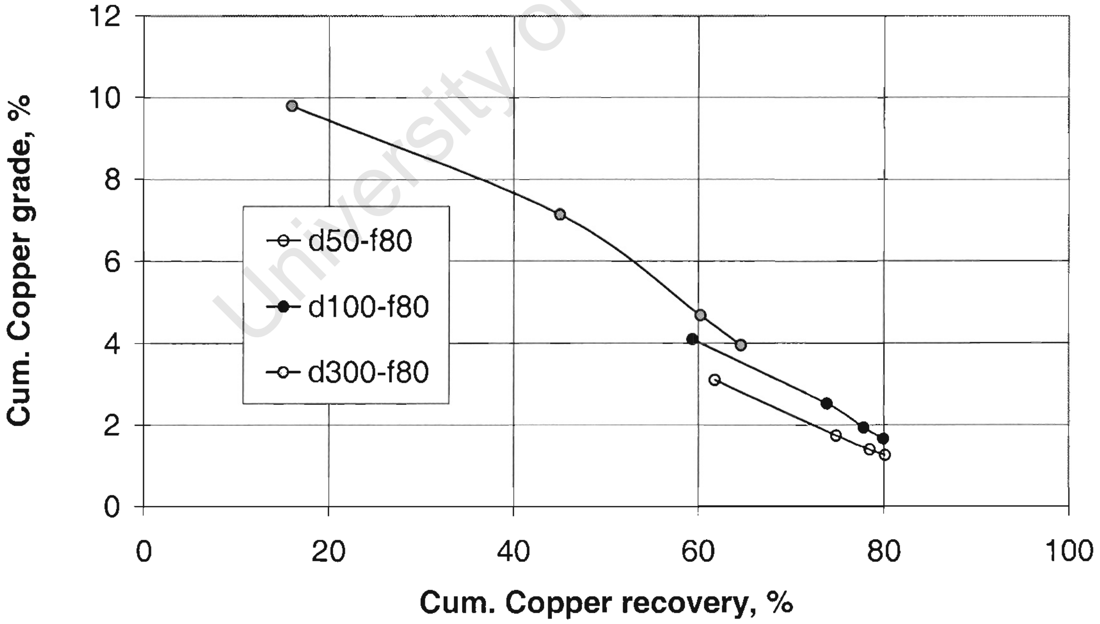

Figure 4-7: Effect of CMC depressant addition with various frother dosages on the grade-recovery relationship of copper sulphides at 4 cm froth depth

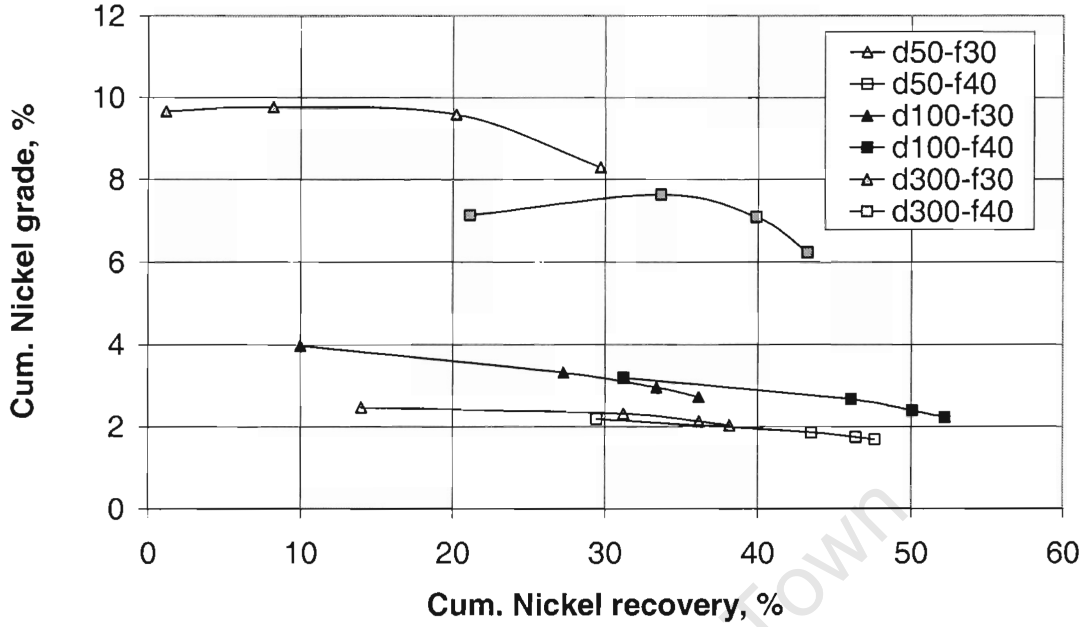

Figure 4-8: Effect of CMC depressant addition with various frother dosages on the grade-recovery relationship of nickel sulphides at 2 cm froth depth

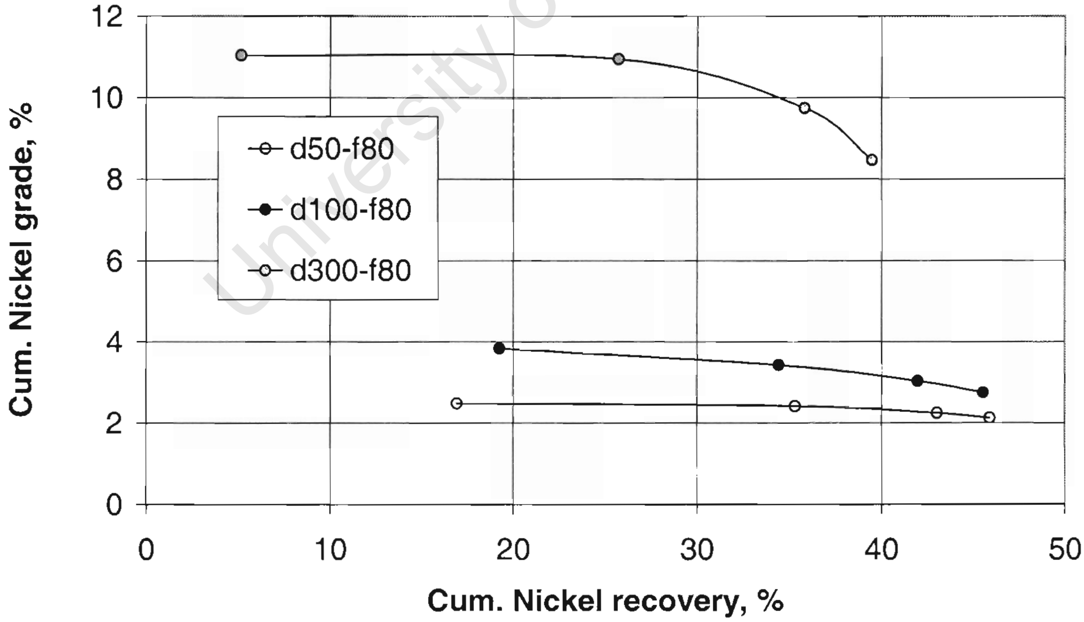

Figure 4-9: Effect of CMC depressant addition with various frother dosages on the grade-recovery relationship of nickel sulphides at 4 cm froth depth

The final grades and recoveries of copper and nickel at different depressant and frother dosages at 20 minutes of flotation are shown in Figures 4-10, 4-11 and 4-12. The figures show clearly that the final grades of nickel achieved at a particular depressant dosage are higher than the grades of copper. The CMC depressant obtains higher grades than the guar as illustrated in Figure 4-11 and 4-12.

In Figure 4-10, it can be seen that an increase in the dosage of the guar depressant from 50 to 100 g/t increases the copper recovery at all frother dosages. Nickel recovery increases only at 30 and 40 g/t frother. Increased CMC dosage to 100 g/t as shown in Figure 4-12 decreased copper and nickel recoveries at 30 g/t frother and increased their recoveries at 40 g/t frother. However a further increase of either CMC or guar to 300 g/t decreases the recoveries of copper and nickel.

Increased frother dosage increased the recovery of copper and nickel sulphides at all depressant dosages even at 300 g/t where there is a decrease in recovery, as shown in Figures 4-10 to 4-12 but the grades decreased.

In Figure 4-11, it is shown that the grades of the sulphides were higher with the deeper froth depth than the lower depth as shown in Figure 4-10. The recoveries of copper and nickel sulphides were lower at the high froth depth regardless of frother dosage.

The decrease in recovery of copper and nickel sulphides with depressant is more pronounced at the lower frother dosage of 30 g/t. In a situation where the froth was more stable, that is at high frother dosage (80 g/t) depressant increase to 300 g/t had a little effect on recovery compared to the lower frother dosages.

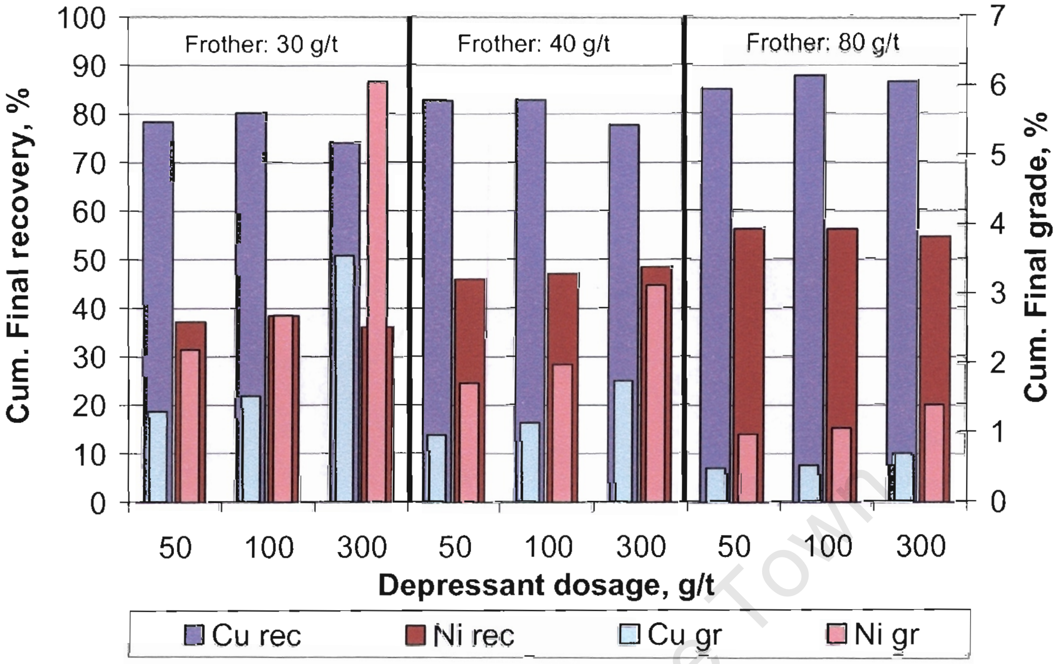

Figure 4-10: Effect of guar depressant dosage and frother dosage on the final grade and recovery of copper and nickel sulphides 2 cm froth depth

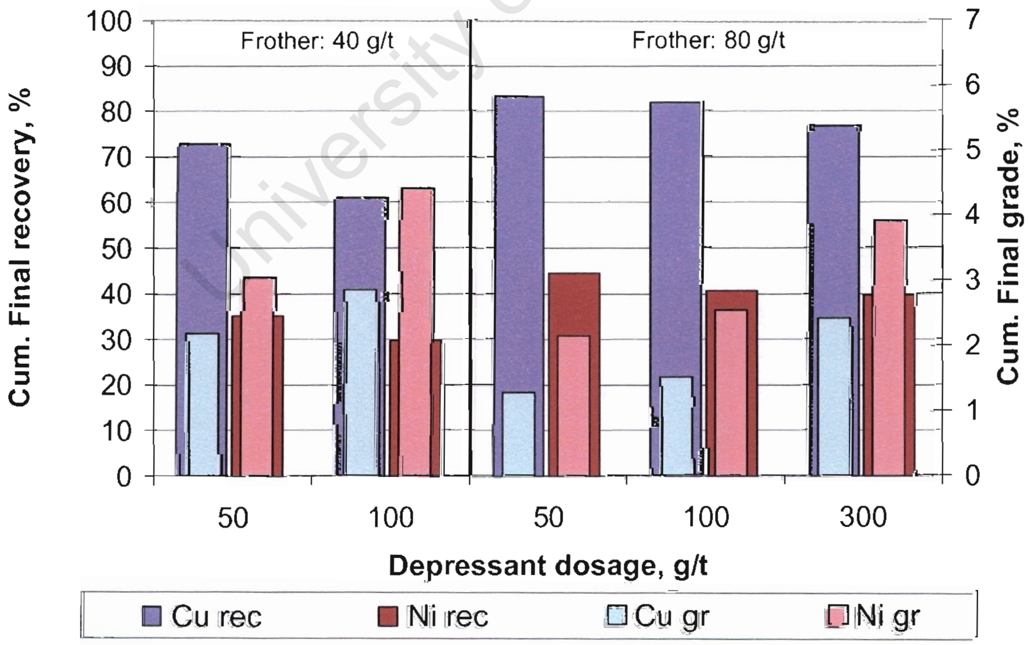

Figure 4-11: Effect of guar depressant dosage and frother dosage on the final grade and recovery of copper and nickel sulphides at 4 cm froth depth

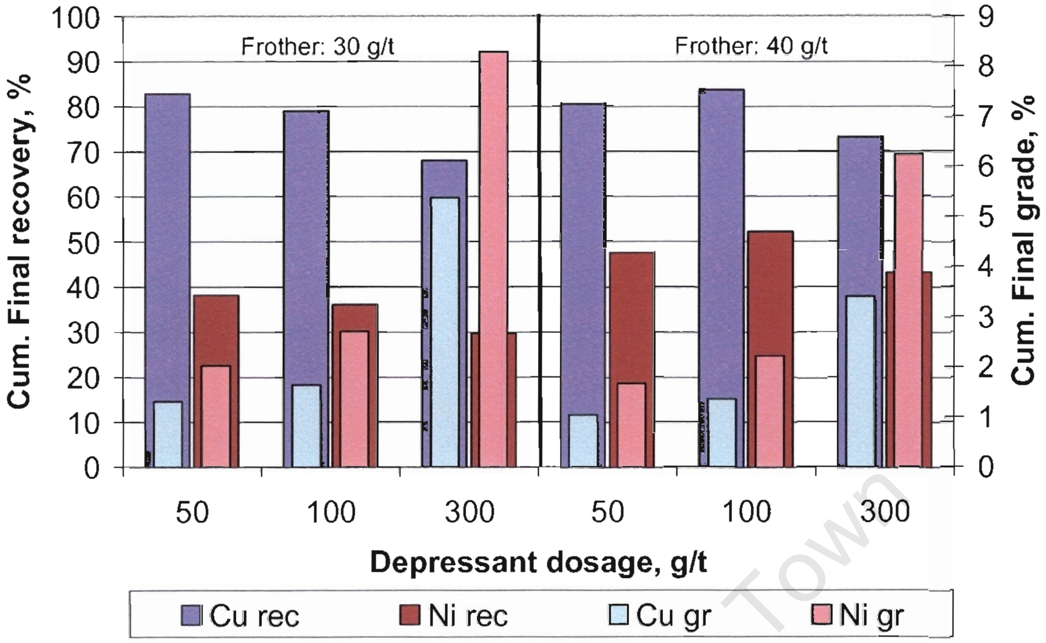

Figure 4-12: Effect of CMC depressant dosage and frother dosage on the final grade and recovery of copper and nickel sulphides at 2 cm froth depth

The graphs show that high grades are readily achieved by a combination of high depressant dosage and low frother dosage however this is at a cost in recovery.

If the frother dosage is increased in order to maximise recovery even at the highest depressant dosage, the benefit of increasing depressant addition is reduced such that depressant increase has little effect on grade which remains low.

The results shown here indicate that the effect of depressant on the recovery of copper and nickel valuables is influenced by the level of depressant dosage as well as the frother dosage used.

4.4 EFFECT OF DEPRESSANT AND FROTHER ON THE RATES OF RECOVERY OF TOTAL SOLIDS AND SULPHIDES

The rates of recovery of total solids and percentage copper and nickel at a froth depth of 2 cm are illustrated in Figures 4-13 to 4-18 for both guar and CMC depressants. At a particular frother dosage, high depressant additions reduce the rate of recovery of total solids as in Figure 4-13. The rate of recovery of copper and nickel sulphides decreases slightly with increase in depressant dosage. The increase in total solids, copper and nickel recovered in a given time with increase in frother dosage may be attributed to increased froth stability and thus the increase of gangue recovery by entrainment.

As seen in Figure 4-14 and 4-17, the more hydrophobic copper sulphide is only minimally affected by either frother or depressant dosage except at the lowest frother dosage and highest depressant addition. The relatively high hydrophobicity and floatability of the chalcopyrite makes it less affected by changes in froth stability. The slower floating pentlandite shown in Figure 4-15 and 4-18 is more strongly affected but final recoveries are again much more dependent on frother dosage than depressant dosage. It is apparent however that at the 20 minutes of flotation measured, the flotation was not complete and that final recoveries at longer flotation times will be similar.

Clearly changes in frother dosage and the resultant change in froth stability bring about the greatest effect on final recovery compared to changes in depressant dosage.

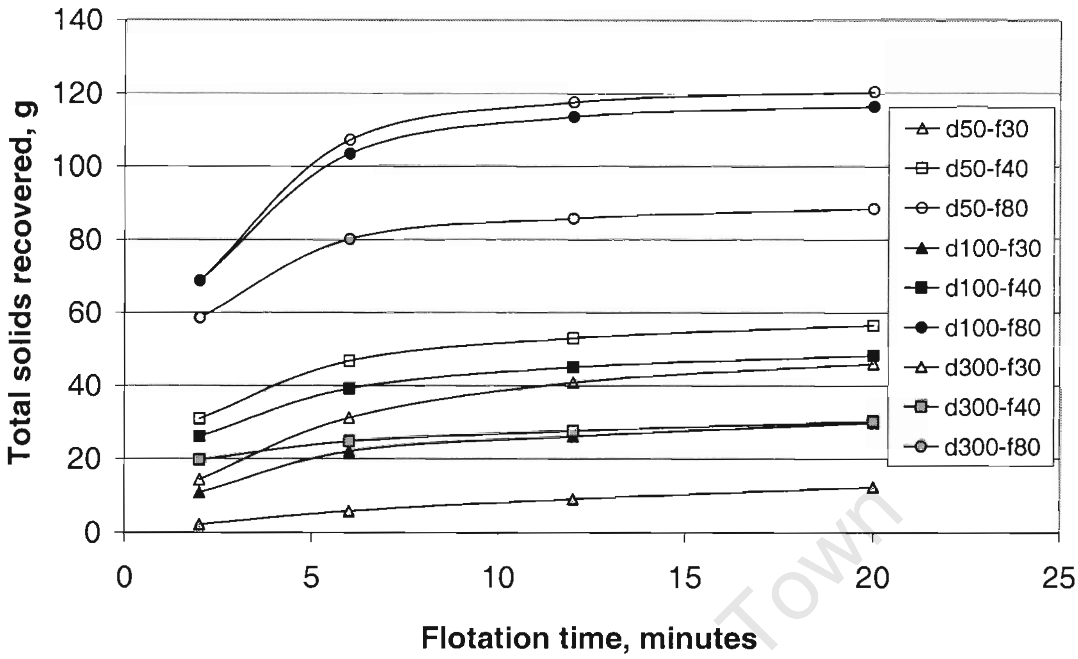

Figure 4-13: Recovery rate of total solids as a function of guar depressant dosage and frother dosage at 2 cm froth depth

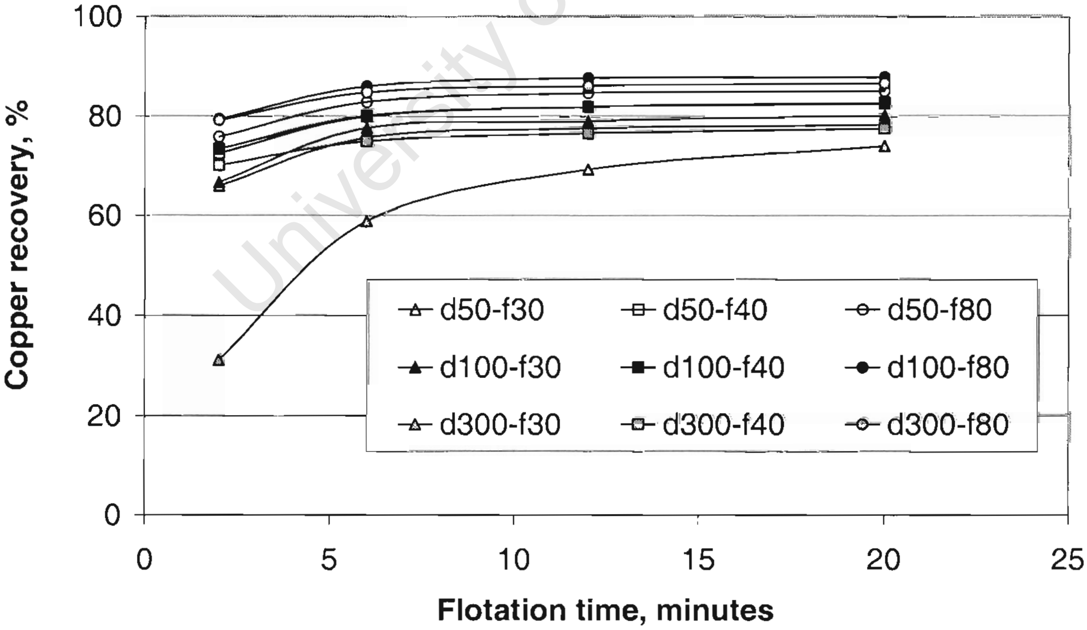

Figure 4-14: Recovery rate of copper as a function of guar depressant dosage and frother dosage at 2 cm froth depth

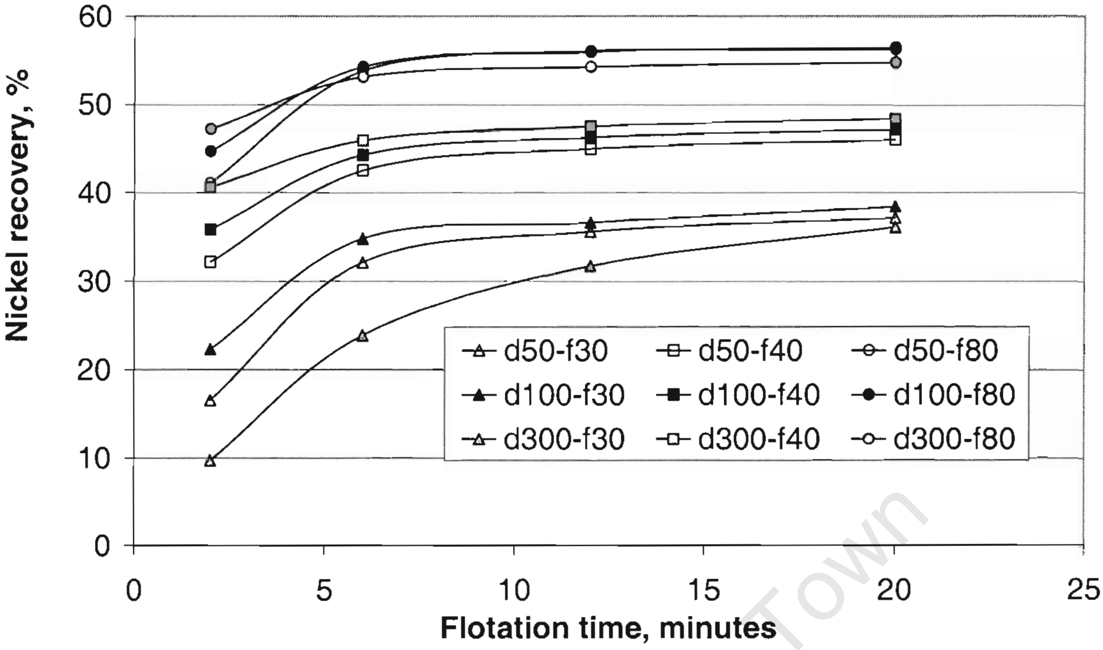

Figure 4-15: Recovery rate of nickel as a function of guar depressant dosage and frother dosage at 2 cm froth depth

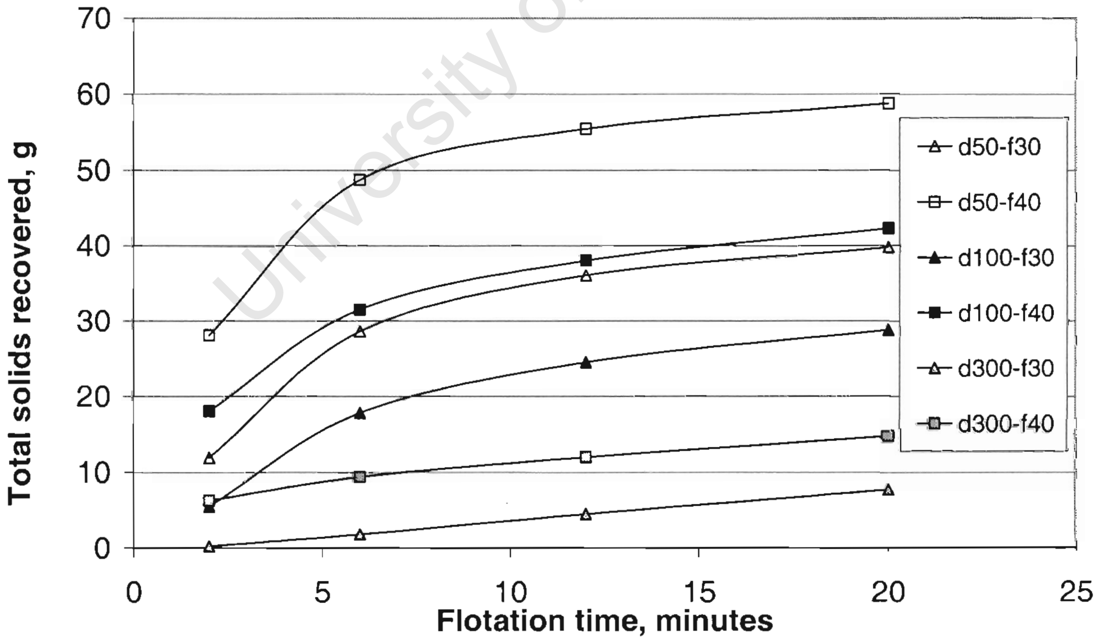

Figure 4-16: Recovery rate of total solids as a function of CMC depressant dosage and frother dosage at 2 cm froth depth

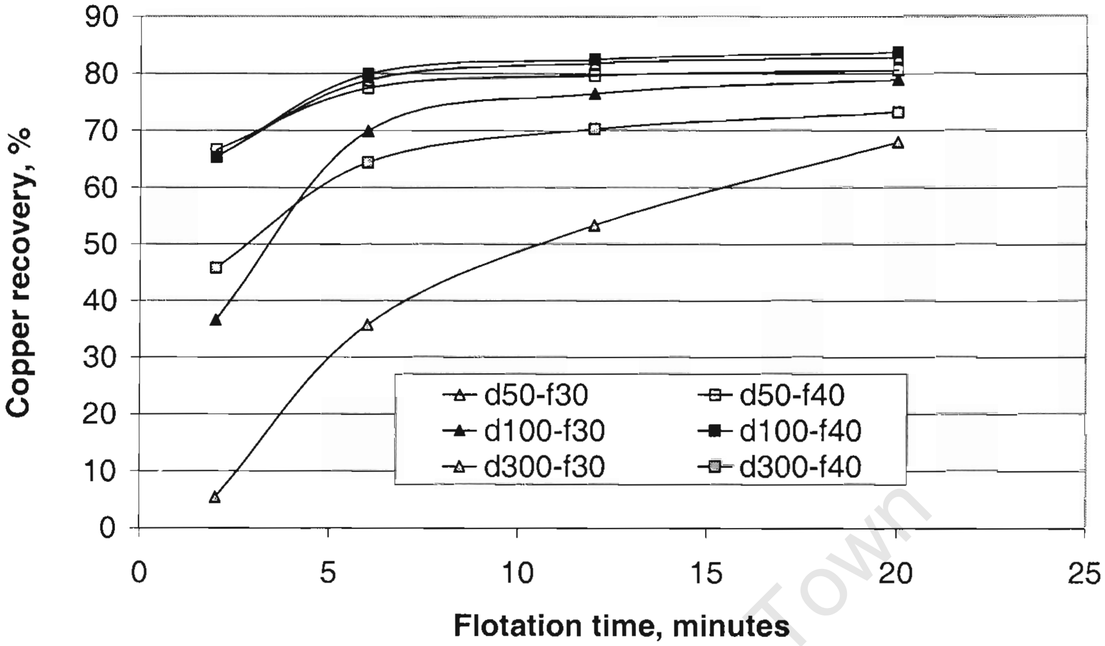

Figure 4-17: Recovery rate of copper as a function of CMC depressant dosage and frother dosage at 2 cm froth depth

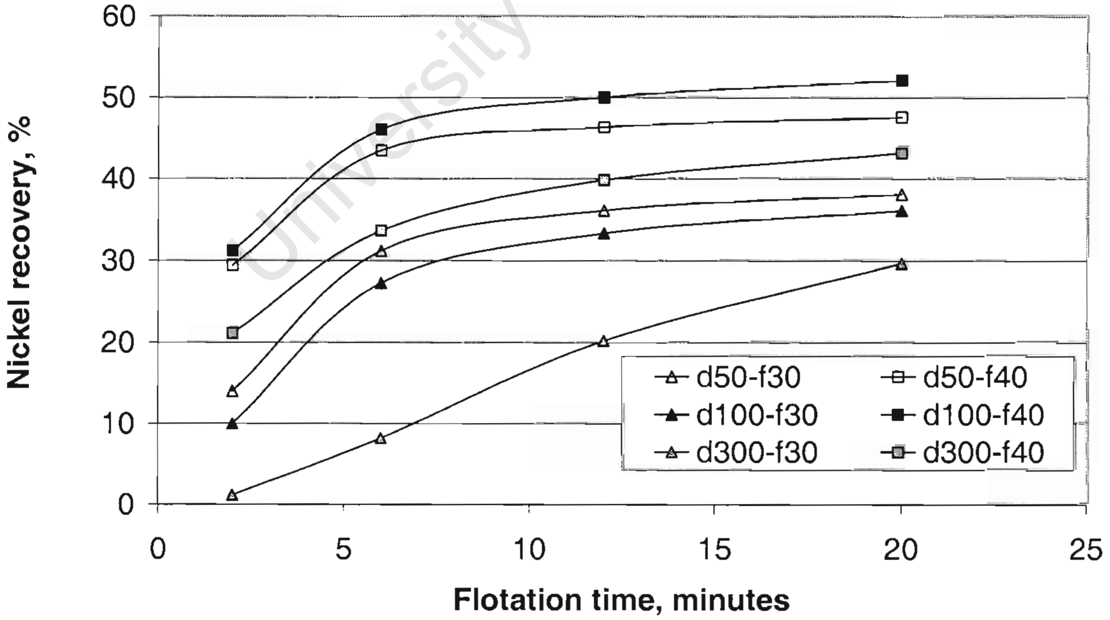

Figure 4-18: Recovery rate of nickel as a function of CMC depressant dosage and frother dosage at 2 cm froth depth

4.4.1 Fitting rate data to the Klimpel equation

To analyse the data further and get an understanding of the effects arising from the change in the variables, the time-recovery profiles were fitted to the Klimpel rate equation below:

$$R = R_{in}\left\{1-\left[\left(\frac{1}{k_t t}\right)(1-\exp(-k_t t))\right]\right\}$$

R: the cumulative recovery at time t, (%)
R_{in}: infinite time recovery, (%)
k: the first order rate constant (min^{-1})

For sulphides, the model was applied to the recovery calculations. For the floatable gangue however, since its initial content in the feed is unknown and thus making it impossible to calculate its recovery, the masses recovered were used in the equation which becomes:

$$M = M_{in}\left\{1-\left[\left(\frac{1}{k_t t}\right)(1-\exp(-k_t t))\right]\right\}$$

M: the cumulative mass of gangue recovered at time t, (g)
M_{in}: the mass of gangue recovered at infinite time, (g)
k: the first order rate constant (min^{-1})

The parameters of the Klimpel equation were calculated for each and every test for the valuables and the gangue. The average values of these parameters are illustrated in Table 4-3 and 4-4.

Table 4-3: Average Klimpel parameters, ultimate recovery (Rinf) and rate constant (k), for chalcopyrite (Cu), pentlandite (Ni) and floatable gangue (Flt G) with changes in guar depressant (KU9) dosage at different frother dosages and froth depths

Frother dosage g/t	Dep. dosage g/t	Froth depth cm	Average Cu Rinf %	Average Cu k 1/min	Average Ni Rinf %	Average Ni k 1/min	Average Flt G Rinf %	Average Flt G k 1/min
30	50	2	80.06	2.87	41.19	0.64	26.93	0.41
30	100	2	82.01	2.71	40.64	0.98	19.22	0.39
30	300	2	82.06	0.54	43.70	0.29	33.60	0.01
40	50	2	83.83	3.72	47.74	1.46	36.19	0.85
40	100	2	83.78	4.03	48.45	1.88	27.87	0.77
40	300	2	78.08	4.87	49.00	3.34	43.15	2.25
80	50	2	86.14	4.54	58.57	1.83	78.29	1.40
80	100	2	89.16	4.64	58.15	2.17	67.71	1.31
80	300	2	87.60	5.24	49.00	2.89	10.80	1.41
40	50	4	76.78	1.18	40.39	0.43	19.47	0.31
40	100	4	67.84	0.78	33.89	0.45	10.36	0.29
80	50	4	84.30	3.04	47.40	0.75	33.47	0.48
80	100	4	82.37	3.70	41.71	1.27	25.69	0.49
80	300	4	77.13	3.96	39.86	2.47	10.65	0.52

Table 4-4: Average Klimpel parameters, ultimate recovery (Rinf) and rate constant (k), for chalcopyrite (Cu), pentlandite (Ni) and floatable gangue (Flt G) with changes in CMC depressant (DEP267) dosage at different frother dosages and froth depths

Frother dosage g/t	Dep. dosage g/t	Froth depth cm	Average Cu Rinf %	Average Cu k 1/min	Average Ni Rinf %	Average Ni k 1/min	Average Flt G Rinf %	Average Flt G k 1/min
30	50	2	85.11	2.16	43.71	0.50	30.50	0.35
30	100	2	87.55	0.67	43.01	0.36	23.92	0.20
30	300	2	-	0.16	-	0.04	36.73	-
40	50	2	82.38	2.62	50.42	1.10	38.61	0.68
40	100	2	86.25	2.31	54.97	1.06	27.00	0.46
40	300	2	76.25	1.12	46.01	0.66	26.54	0.01
80	50	4	81.93	1.99	52.29	0.46	37.23	0.33
80	100	4	81.90	1.80	50.23	0.53	29.29	0.24
80	300	4	76.10	0.43	52.87	0.22	37.01	0.01

The results in Table 4-3 show that the rates of copper and nickel sulphides increased with the addition of guar depressant at 40 and 80 g/t frother and that the rates were decreased at the lowest frother dosage. The CMC depressant reduced the rates of recovery of the copper and nickel regardless of frother.

In Table 4-3 it is also seen that the ultimate recovery of copper and nickel sulphide generally decreased with increased guar dosage.

At 2 cm froth depth, the ultimate recovery of copper increases with depressant dosage at 30 g/t frother and decreases at 40 g/t and 80 g/t frother and at 4 cm depth with both guar and CMC depressants. The ultimate recovery of nickel increases at 30 and 40 g/t frother with a low froth depth but decreases at 80 g/t frother and the high froth depth.

The rate constant for copper with the guar depressant decreases at 30 g/t frother at the lower froth depth and at 40 g/t frother with a depth of 4 cm. At 40 and 80 g/t frother and low froth depth and at 80 g/t frother dosage and high froth depth the rate constant increases with depressant. The rate constant of nickel increases at all frother dosage levels except at 30 g/t frother. With the CMC depressant the rate constant for copper and nickel decreases with increasing depressant dosage for all frother dosages tested.

The rate of recovery of floatable gangue was reduced by increasing both guar and CMC depressant dosages as shown in Tables 4-3 and 4-4. Increase of both CMC and guar depressant reduced the ultimate recovery of the floatable gangue.

Statistical significance testing was carried out on the parameters to investigate the significance of the effect of variable changes carried out. A two-way ANOVA was conducted at 95% confidence level to evaluate the differences in the ultimate recovery and the first order rate constant at the different conditions.

Results of the ANOVA shown in the Appendices can be summarised as follows:
The ultimate recovery of copper sulphides was decreased by increasing guar depressant dosage regardless of froth depth at 40 and 80 g/t frother, the decrease was more significant at 4 cm depth than at 2 cm. At low frother dosage of 30 g/t, no effect of increased depressant dosage on the ultimate recovery was

indicated. This is in contrast with Figures 4-14 and 4-17 which showed a significant decrease in the recovery of copper with increasing depressant at 30 g/t frother. However the graphs do indicate that the recovery at infinite time at 300 g/t may be approaching a value similar to that with 50 and 100 g/t dosage.

The ultimate recovery of nickel was improved by increasing guar depressant dosage at 2 cm froth depth while no effect was observed at 4 cm froth depth. The ultimate recovery was seen to decrease with increased CMC dosage.

The first order rate constant of copper was decreased by increasing guar dosage at low frother dosages and froth depth and at lower frother dosages at high froth depth but increased at the higher frother dosages. With increasing dosage of CMC the rate constant of copper decreased at all conditions tested.
The rate constant for nickel increased with guar at all frother dosages except at 30 g/t dosage but decreased with CMC.

Increasing the guar or CMC dosage resulted in a significant decrease in the ultimate recovery of floatable gangue.

Frother dosage generally increased the ultimate recovery of copper, nickel and floatable gangue with the effect being greater at the lower froth depth. The effect of frother is to generally increase the rate constant. The effect is however influenced by the depressant dosage especially at 2 cm froth depth, where the interactive effects of depressant and frother are high. Increases in depressant and frother dosage have a generally counteracting effect on flotation performance.

4.5 TOTAL SOLIDS-WATER RECOVERY RELATIONSHIP

The relationships between the total solids recovered and water recoveries are shown in Figures 4-19 to 4-22. An increase in the dosage of either CMC or guar depressant at constant frother dosage reduced as expected the total solids recovered in the concentrate indicating the reduced recovery of hydrophobic as well as entrained gangue.

As can be seen in Figures 4-19 to 4-22, there is a decrease in water recovered with depressant increase. This is indicative of a reduction in the stability of the froth resulting from the reduction in the hydrophobicity of the floating gangue particles. As mentioned earlier water recovery is closely related to and an indicator of froth stability.

The ratio of solids to water recovered was decreased with an increase in depressant dosage indicating a decrease in froth stability. This is seen clearly with the reduction in the slope of the curves especially at 300 g/t depressant dosage.

The decrease of both solids and water recovery was more significant with changes in CMC dosage than with guar dosage.

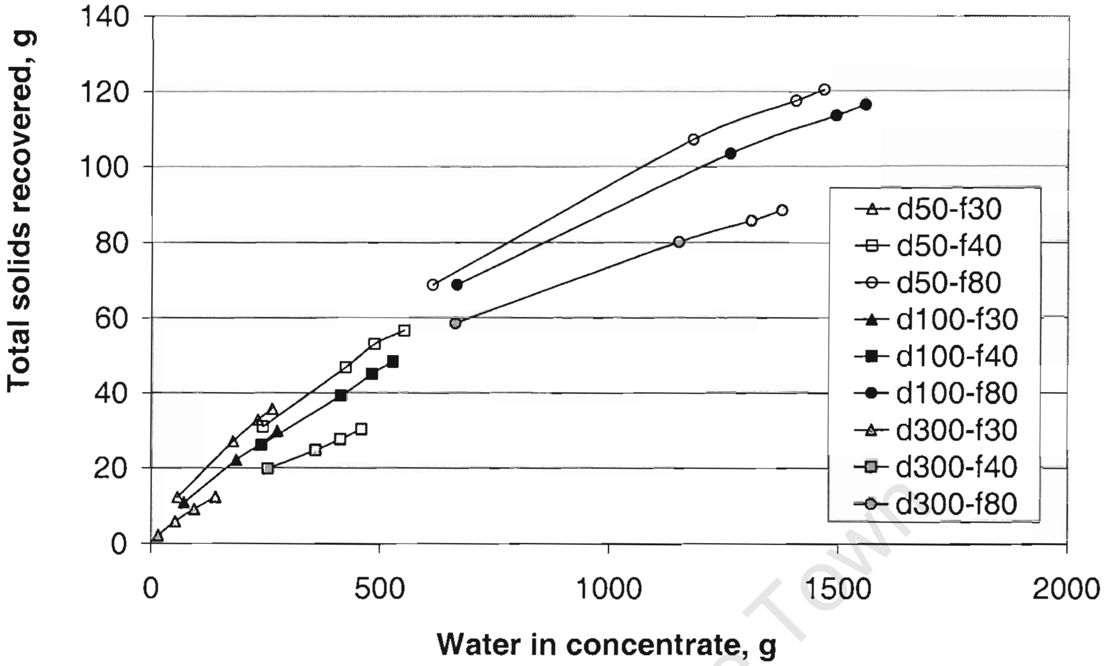

Figure 4-19: Solid- water relationship: Effect of varying guar dosage and frother dosage at 2 cm froth depth

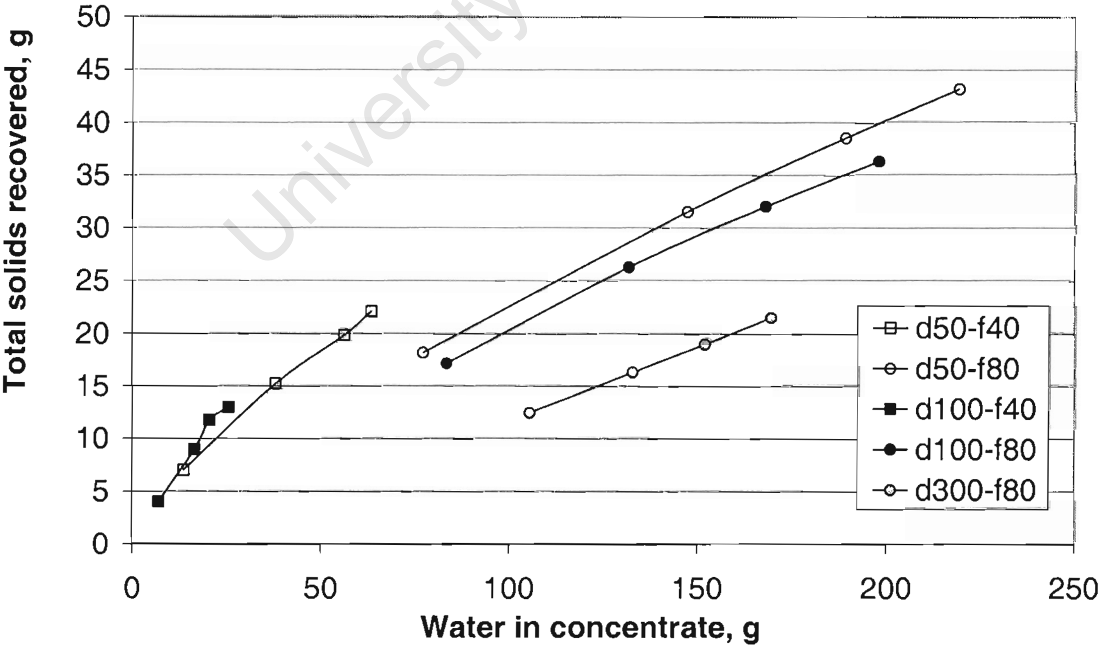

Figure 4-20: Solid- water relationship: Effect of varying guar dosage and frother dosage at 4 cm froth depth

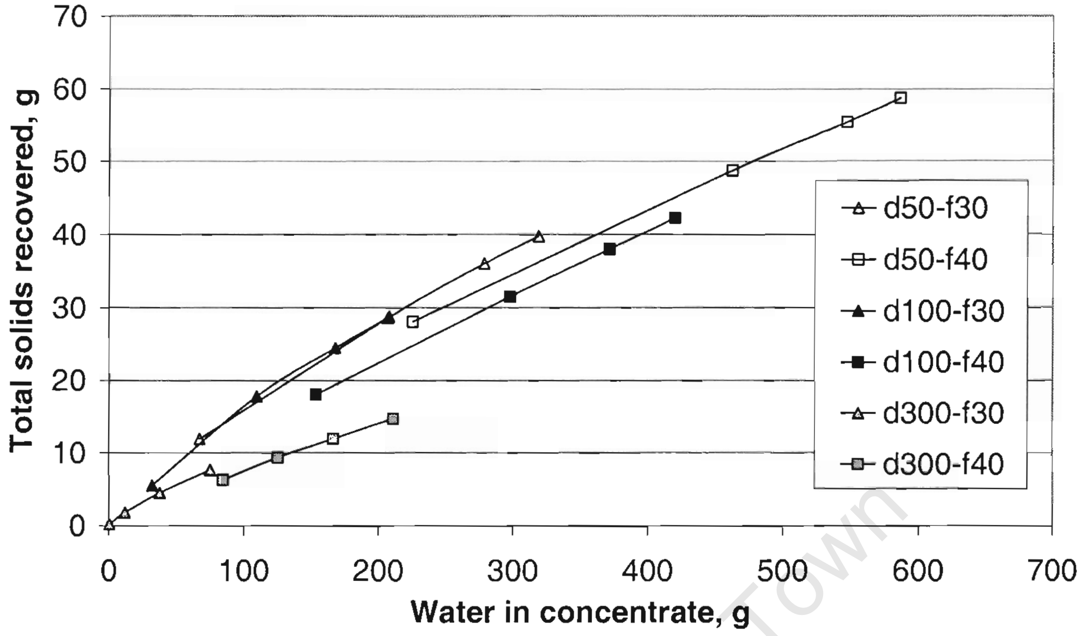

Figure 4-21: Solid- water relationship: Effect of varying CMC dosage and frother dosage at 2 cm froth depth

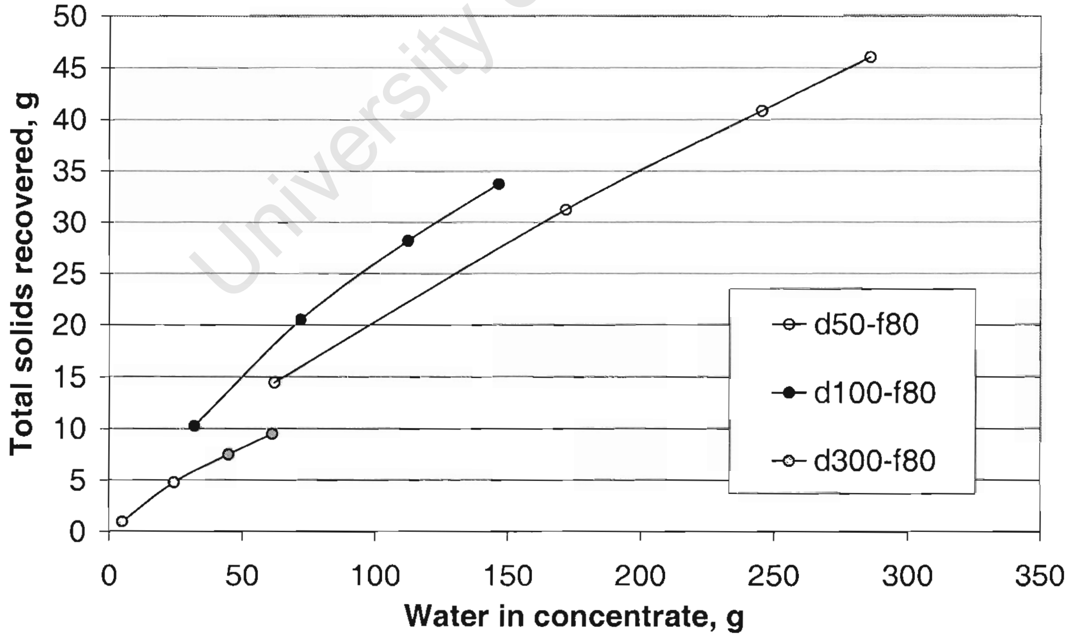

Figure 4-22: Solid- water relationship: Effect of varying CMC dosage and frother dosage at 4 cm froth depth

The amount of water recovered with the two types of depressants at 2 cm froth depth is compared in Figure 4-23.

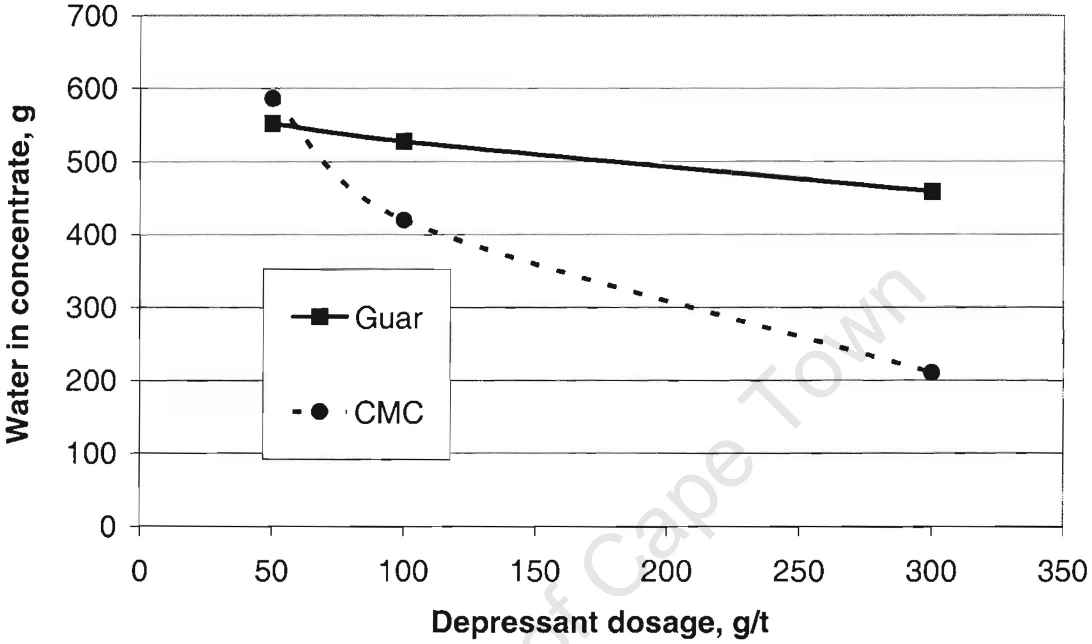

Figure 4-23: Comparing the effects of guar and CMC dosages on water recovery at 40 g/t frother

Increasing guar addition produced only a relatively small reduction in water recovered in the 20 minutes of flotation compared to the CMC depressant indicating that the CMC depressant had a greater effect on the stability of the froth than guar.

At constant depressant dosage, an increase in frother dosage increased both solids and water reflecting an increase in froth stability.

The solid and water masses recovered at 4 cm froth depth were much less than those at the 2 cm depth as shown in Figure 4-19 and 4-20 and Figures 4-21 and

4-22. Increasing the froth depth greatly reduces water recovery which is not fully restored even at high frother dosages as shown in Figure 4-24. Note that at high froth depth the froth was visibly less stable and brittle.

Increasing frother dosage produced larger changes in water recovery than changes in depressant dosage even when the latter was increased to 300 g/t. Although the reduction of water recovery achieved by increasing either depressant type was small in comparison with the effect of a change in frother dosage as shown in Figure 4-24, it does indicate that strong depression of hydrophobic particles leads to some reduction in froth stability.

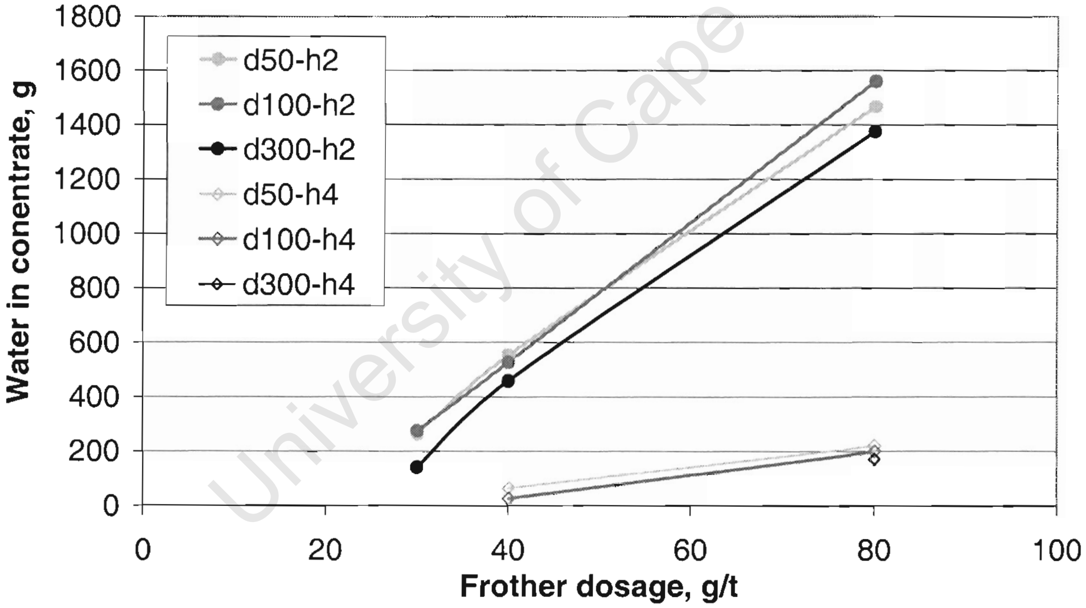

Figure 4-24: Effect of frother dosage on water recovery at various depressant dosages and froth depths

Therefore frother dosage compared to depressant dosage was seen as the most significant determinant of solids and water recovery. Froth depth had a greater effect on recovery than depressant dosage.

4.6 EFFECT OF DEPRESSANT AND FROTHER DOSAGE ON GANGUE RECOVERY

The recoveries of water and calculated values for entrained and floating gangue obtained by the method described in section 3.8.3 at different depressant and frother dosages are summarised in Figures 4-25 and 4-26. This relationship may not hold for all conditions, for example at 300 g/t of depressant dosage it is expected that all or most of the floatable gangue be removed, but Figure 4-25 shows a high recovery of the floatable gangue at 300 g/t dosage.

As noted above, at constant frother dosage a large change in depressant dosage has only a small effect on water recovery. However there is a very large increase in water recovery with increase in frother dosage. The results show that frother dosage has a larger effect on the stability of the froth than the removal of hydrophobic gangue by depressant.

At a constant frother dosage there is, as expected, a significant decrease in the mass of floating gangue recovered with increase in depressant dosage reflecting the reduction in the hydrophobicity of floatable gangue. As shown in the Figures 4-25 and 4-26, the contribution to total mass of the floating gangue is reduced significantly with increasing depressant dosage.

The CMC and guar depressant addition had similar effects on the floatable gangue at the lowest frother dosage. Guar reduced the floatable gangue recovered more than the CMC depressant at 50 g/t dosage with a frother dosage of 40 g/t.

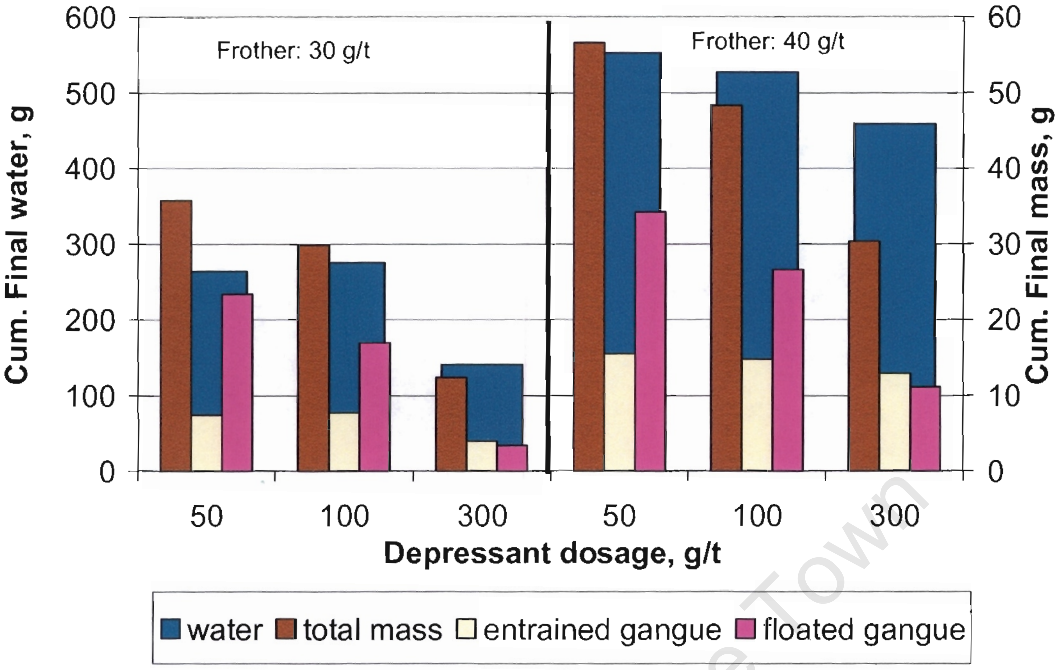

Figure 4-25: Effect of guar depressant and frother dosages on the final values of water recovery, entrained gangue and floated gangue recovery at 2 cm froth depth

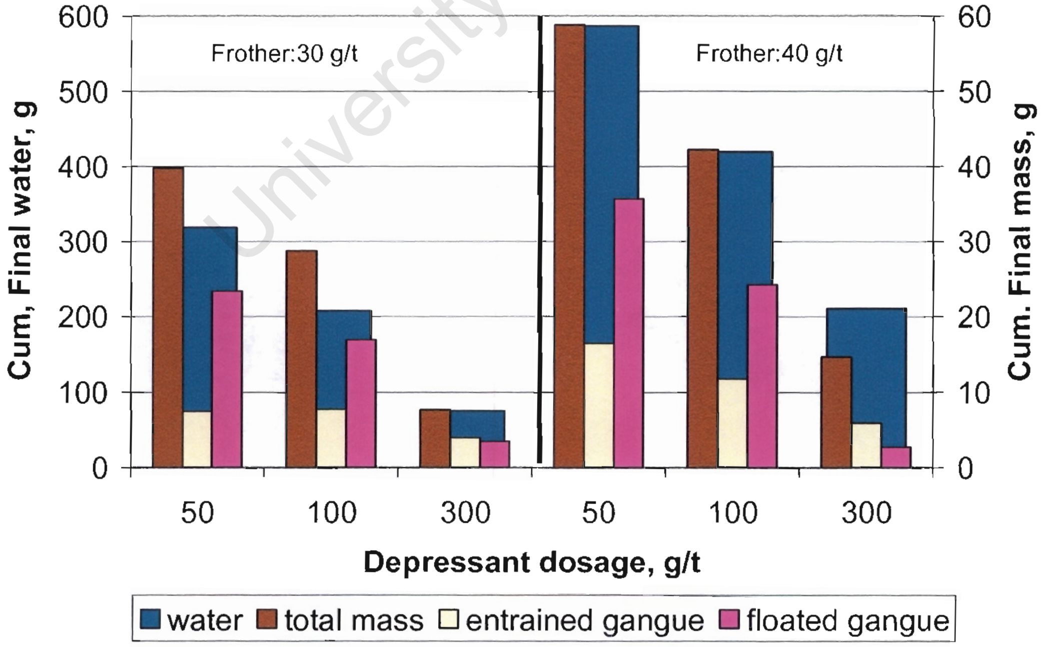

Figure 4-26: Effect of CMC depressant and frother dosages on the final values of water recovery, entrained gangue and floated gangue recovery at 2 cm froth depth

At a depressant dosage of 100 g/t or 300 g/t, the froth recovered less floatable gangue with the CMC than guar depressant. This indicates that the CMC depressant is more effective at high dosages than the guar depressant and visa versa.

At constant depressant dosage, an increase in frother dosage increases the recovery of floatable gangue. These changes occur even though the hydrophobicity and floatability of gangue particles is expected remain the same at a particular depressant dosage. The recovery rates have shown that the increase in recovery with increase in frother dosage reflects a change in the relative rate of flotation of the particles brought about by the increased froth stability. The results show that the effectiveness of depression is affected by the amount of frother present in the system.

Figures 4-25 and 4-26 show that the entrained gangue decreases with increased depressant dosage as a result of the reduced recovery of water. Frother addition increases the water recovery and thus entrainment of solids.

Entrained material is only slightly influenced by the increase in guar depressant addition compared to the CMC depressant. The CMC depressant, Figure 4-26, showed larger decreases in entrained mass due to the larger changes in the of amount water recovered and the froth stability.

These results indicate that increasing frother dosage even at the highest depressant dosage (300 g/t) can reverse the decrease in froth stability caused by depressant addition. The entrainment contribution thus becomes larger as a result of increased water recovery thus reducing the grade.

5 DISCUSSION

This section discusses the observed effects of depressant, frother, and froth depth on grade and recovery of valuable minerals and the recovery of gangue minerals, water and total solids.

5.1 EFFECT OF DEPRESSANT DOSAGE AND TYPE

The increase in depressant dosage to 100 g/t increased the recovery of copper and nickel sulphides. This may be as a result of the slime cleaning action of the depressants on the surfaces of the sulphides and the stabilisation effect of the depressants. The slime cleaning action of depressants was also observed by Edwards et al. (1980) when the addition of CMC modifiers improved the flotation of pentlandite which had been depressed by the presence of slime on its surfaces.

However, higher depressant dosages of 300 g/t decreased recoveries of copper and nickel sulphides indicating that depressants do not only interact with gangue minerals but also with the sulphides. This is in agreement with the finding of Rath et al. (2001) that a guar depressant interacted with the hydroxylated mineral surface of chalcopyrite thereby depressing it.

It might be expected that the nickel sulphides are similarly affected by depressant addition but the results showed that the nickel sulphide was less affected especially at the lower froth depth. Due to its lower floatability, the reduction in the hydrophobicity and competitive recovery of gangue particles increases the rate of recovery of the nickel sulphide.

The sulphide grades were higher for the CMC depressant due to the lower water recovery and a consequent reduction in recovery of entrained gangue. This is attributed to the greater depressing effect of the CMC on the floating gangue at the higher depressant dosages.

Two examples from the results of this investigation will be discussed which could explain the existence of depression effects on the sulphides.

5.1.1 Example 1- the depression of sulphides by guar

Figure 5-1 and 5-2 show the final recoveries of gangue minerals and valuable sulphide minerals obtained with the guar depressant. The runs where the froth recovers equivalent amounts of solids are joined by the red line. As shown in Figure 5-1 the water masses obtained at these two conditions are different. The larger amount of water was obtained with a higher frother dosage even though the depressant dosage was at 300 g/t, indicating the greater effect of frother dosage on froth stability. The floatable gangue contribution was as expected, lower at 300 g/t than at 100 g/t indicating the greater depression at high dosages.

According to the recovery data (Figure 5-2) and the ultimate recovery determinations, the recovery of copper at 300 g/t depressant and 40 g/t frother was lower than the recovery obtained at 100 g/t depressant and 30 g/t frother dosage. Assuming the froth is more stable at the higher frother dosage it was expected that the copper recovery would be higher. However the lower recovery suggests that some depression is occurring.

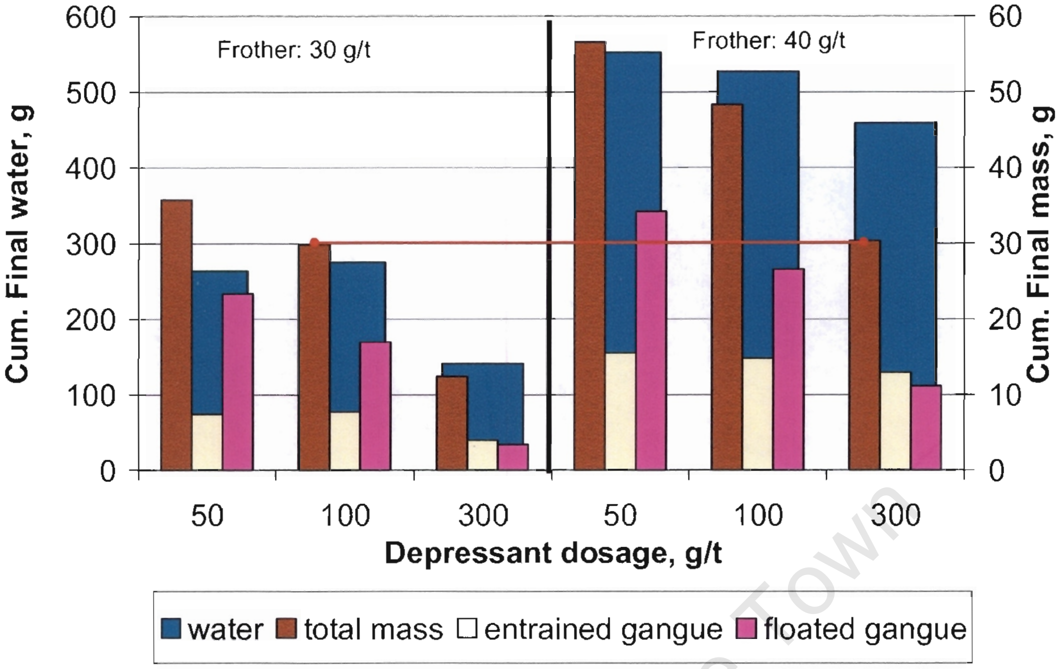

Figure 5-1: Effect of guar depressant dosage at different frother dosages, illustrating gangue contributions to total solids mass at equal solids recovery

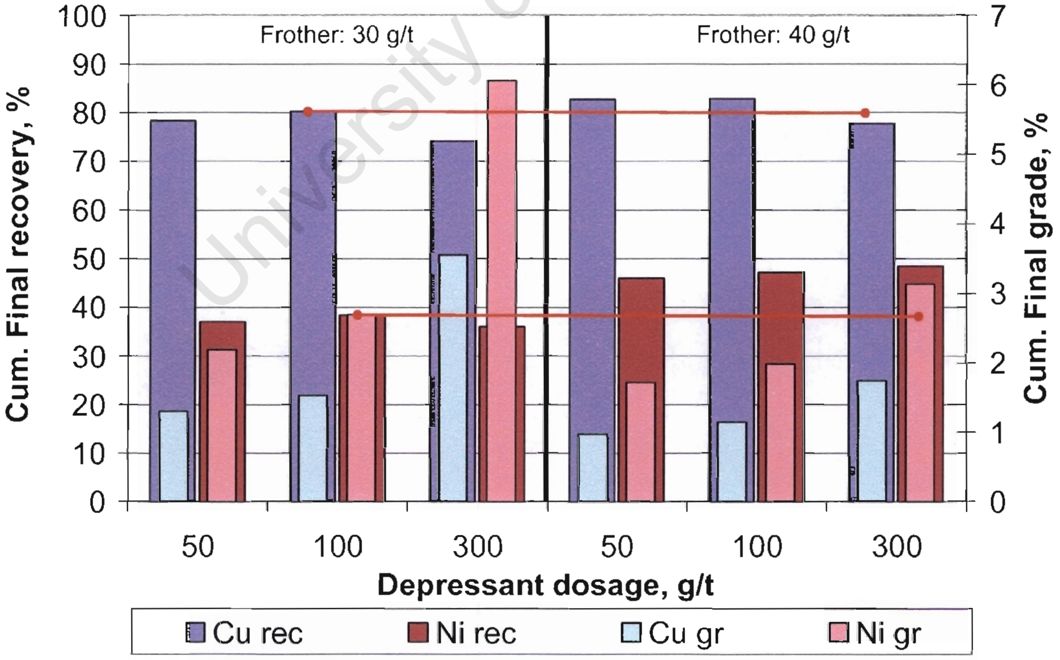

Figure 5-2: Effect of guar depressant dosage at different frother dosages Illustrating copper and nickel grades and recoveries obtained at equal solids recovery

5.1.2 Example 2- the depression of sulphides by CMC

Figures 5-3 and 5-4 illustrate the conditions of depressant and frother, joined by red lines, where the concentrate contained similar amounts of water. Different solid masses were obtained mainly as a result of the differences in the floatable gangue contribution. The recovery of copper as well as its ultimate recovery was again reduced at the high depressant dosage. Since the water recoveries are similar (Figure 5-3) froth stability is assumed to be equal and that the recoveries of copper be similar but Figure 5-4 shows otherwise. These results indicate that the CMC depressant also influences the adsorption surface of the copper minerals at high depressant dosage and depresses the copper sulphides.

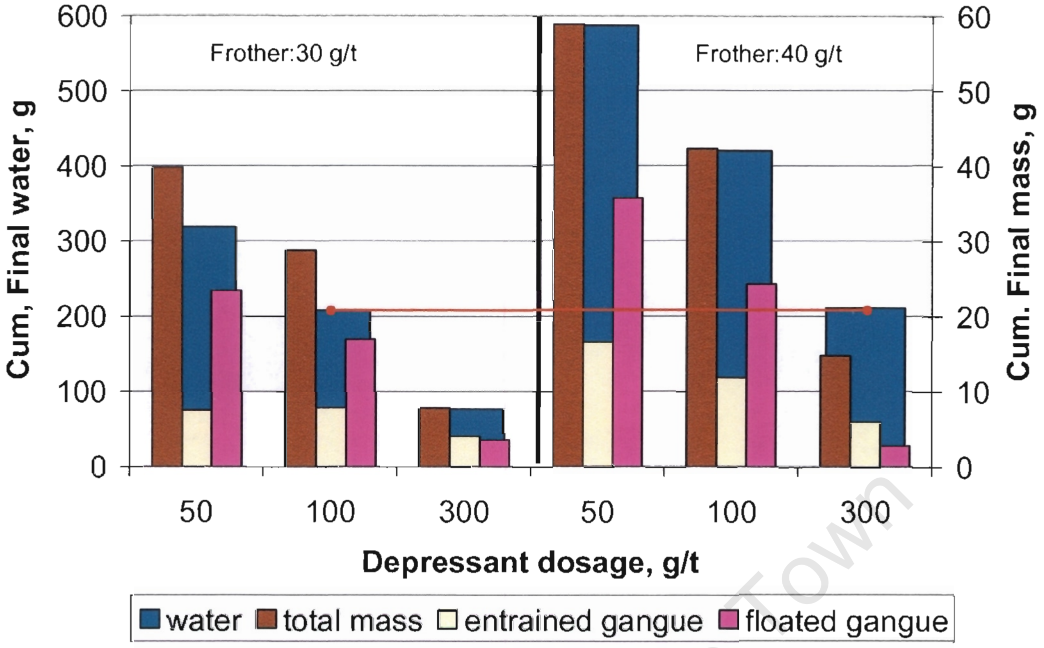

Figure 5-3: Effect of CMC depressant dosage at different frother dosages, illustrating gangue contributions to total solids mass at equal water recovery

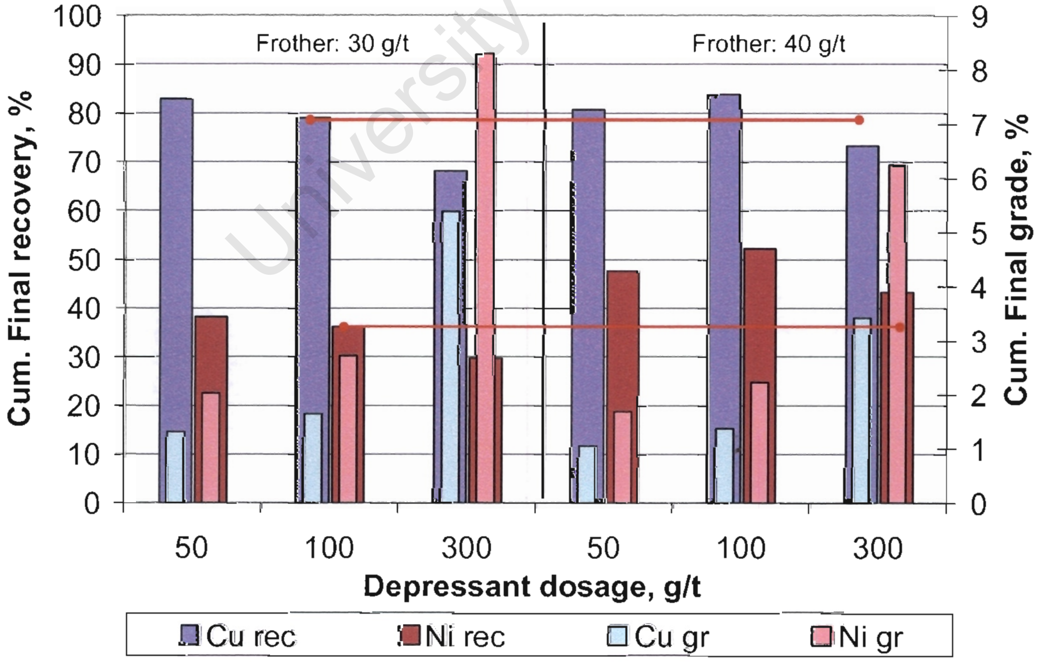

Figure 5-4: Effect of CMC depressant dosage at different frother dosages, Illustrating copper and nickel grades and recoveries obtained at equal water recovery

The decrease in floatable gangue with increased depressant dosage was expected since according to Steenberg and Harris (1984), Jenkins and Ralston (1998) and Rath et al. (1995) the adsorption densities of depressant on talc particles increases with concentration of depressant used. The fact that a guar depressant is more effective than a CMC depressant as found by Steenberg and Harris (1984) and Rath et al. (1997) corroborates the results of this study at low depressant dosage of 50 g/t. At 100 and 300 g/t dosage the CMC depressant becomes more effective. The effectiveness of a CMC depressant at these conditions is probably due to its froth destabilising effects.

Destabilisation is caused by CMC's dispersing effect on particles as mentioned by Livshits and Dudenkov (1965) and Lovell (1976) who found dispersed hydrophobic particles destabilising the froth. Lovell (1976) also found that increased particle size due to coagulating modifiers caused stabilisation. This could explain why the guar depressant may have lower destabilising effects at higher dosages compared to the CMC depressant.

The water recovery increases from 50 to 100 g/t depressant dosage and decreases at 300 g/t dosage. The initial increase may be due to stabilising effect of the depressants. The decrease of water recovered at high depressant dosages comes about as a result of the decrease in stability caused by the reduction in stabilising hydrophobic particles in the froth. The decrease in stability may be due to the increase of the drainage rate of liquid from the lamellae as the air-water interface thins and bubbles tend to come into contact and burst producing a reduction in the water recovery.

The CMC depressant decreases the amount of water more than the guar depressant, suggesting that is causes greater destabilisation of the froth. It was found by Robertson (2003) that a dispersing depressant increases the hydrophobicity of sulphide particles by slime cleaning increasing their froth destabilising effect as well as the rate at which they float.

It is known that particles with contact angles greater than 90 degrees destabilise the froth. Dippennar (1978) suggested that when such a particle is between the bubbles the contact angle of the resulting three phase film would be less than the equilibrium contact angle. Thus the movement of this boundary to attain the equilibrium contact angle causes the film surrounding the particles to rupture causing destabilisation.

Recovery by entrainment decreased with increasing depressant dosage. Entrainment is strongly related to water recovery (Engelbrecht and Woodburn, 1975; Warren, 1985) thus a decrease in water recovery by increasing depressant dosage also decreases the entrainment of particles.

5.2 EFFECT OF FROTHER DOSAGE

At the low frother dosage of 30 g/t there was little difference in the effects of the guar and CMC depressants on the recovery of floatable gangue. Increasing the frother dosage increased the recovery and rate of flotation of copper and nickel sulphides, water, floatable and entrained gangue recovered. This is mainly a result of an increase in froth stability. According to Gaudin (1957), the froth stability is brought about by the ability of the adsorbed frother species to prevent bubble coalescence. This coalescence is prevented by increasing the stability of the hydrated layer surrounding the bubbles thus preventing bursting of the layer (Klassen and Mokrousov, 1963).

Previous studies have indicated that at higher frother dosages, the average bubble size in the pulp and the froth decreases (Harris, 1982). The probability of bubble-particle attachment is thus increased as well as the ability of the froth to carry mineral particles to the surface.

At lower depressant dosages the floatable gangue recovery increases with frother dosage. This may be a result of increased froth stability enhancing the rate of flotation of the slow floating gangue. This does not necessarily imply a reduction in the depressant ability. At the lower depressant dosage it implies that the frother increases the flotation of the slow floating gangue which has not been depressed. At 300 g/t with guar (Figure 5-1) it would imply that the depression of gangue is not complete but at 300 g/t with CMC (Figure 5-3) the floatable gangue does not increase significantly with a frother increase from 30 to 40 g/t. This agrees with the above discussion where the CMC depressant is more effective in depression at 300 g/t than the guar depressant.

5.3 EFFECT OF FROTH DEPTH ON STABILITY AND FLOTATION

The increase in froth depth is expected to regulate the recovery by entrainment. Unfortunately the results of this investigation show, the recovery of valuable minerals is reduced with an increase in froth depth as in Figure 5-5, even though the grades are improved. This is attributed to the increased drainage of liquid causing the thinning of bubble leading to coalescence which results in larger bubbles which eventually burst and reduced the bubble surface area according to Moys (1978). The detachment of hydrophobic minerals from the froth with increased froth depth was also found by Engelbrecht and Woodburn (1975) for pyrite. Engelbrecht and Woodburn (1975) suggested that the recovery decreased due to the overload of particles on the bubbles as the bubbles coalesce and also due to the resultant preferential shedding of particles from the froth.

Deeper froth depths have the effect of reducing the amount of water recovered in the froth as illustrated in Figure 5-6. As a result of increased drainage of water, the bubbles coalesce (Ross, 1997) and the froth becomes less stable. The consequences of this are the decrease in the amounts of water and solids recovered in the froth as shown in Figure 5-6.

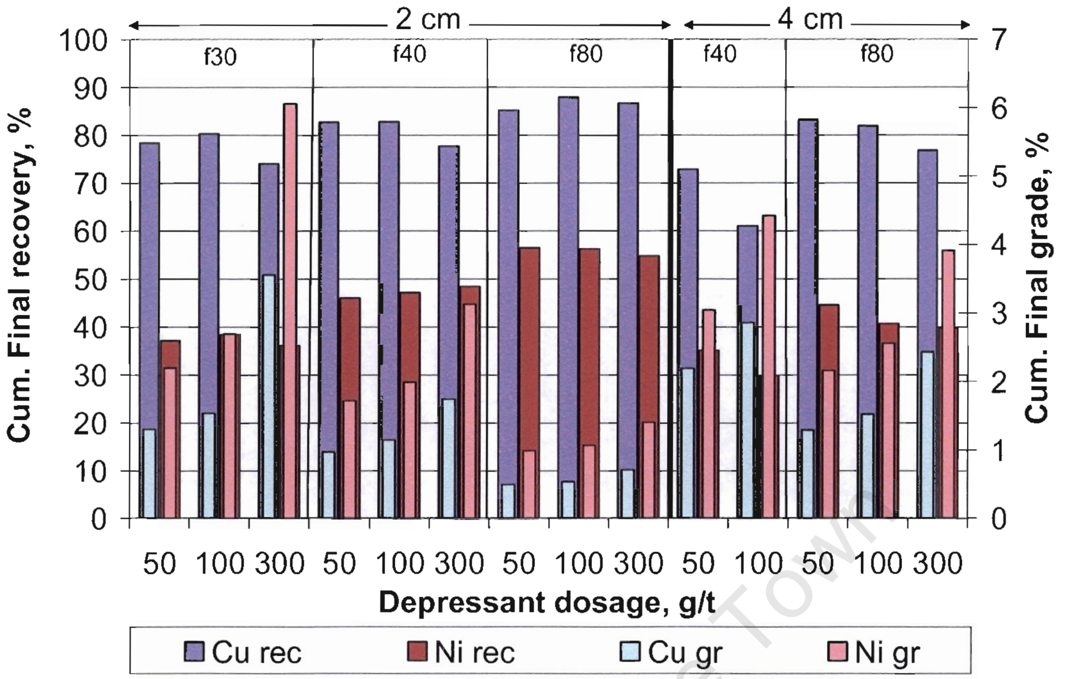

Figure 5-5: Effect of froth depth on final copper and nickel grades and recoveries at increasing depressant dosages with different frother dosages

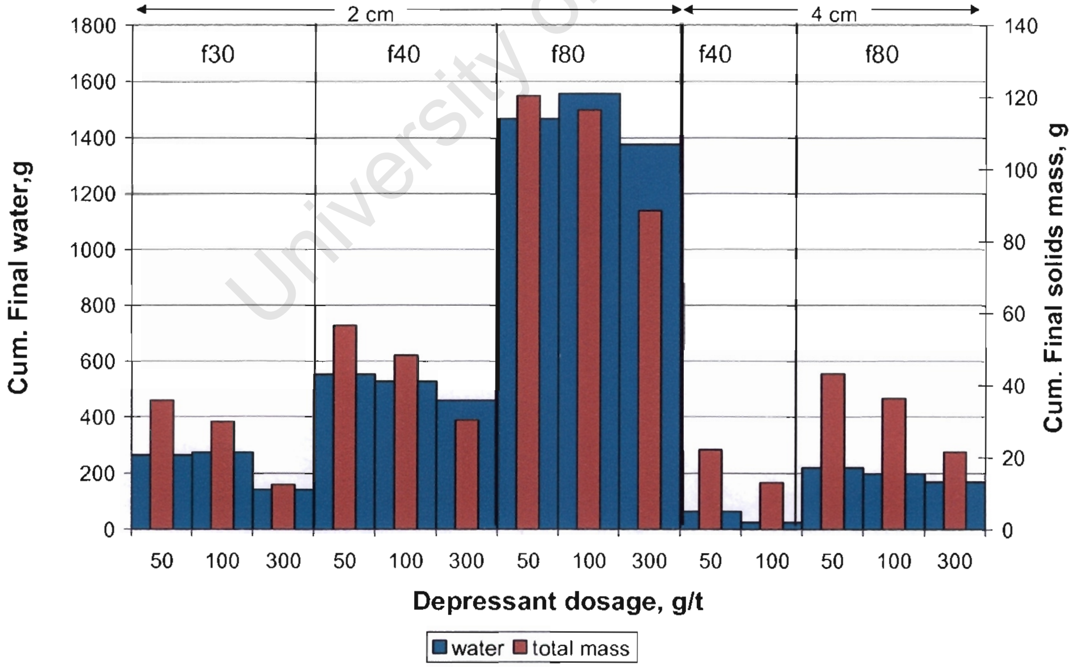

Figure 5-6: Effect of froth depth on the final water and solids recovery at increasing depressant dosage with different frother dosages

5.4 DEPRESSANT-FROTHER INTERACTIVE AND COUNTERACTIVE EFFECTS

Figure 5-7 illustrates the interactive and counteractive effect of frother dosage on the change in mass recovered brought about by change in depressant dosage. When depressant dosage increases, the solids recovered decreases but are increased by an increase in frother dosage.

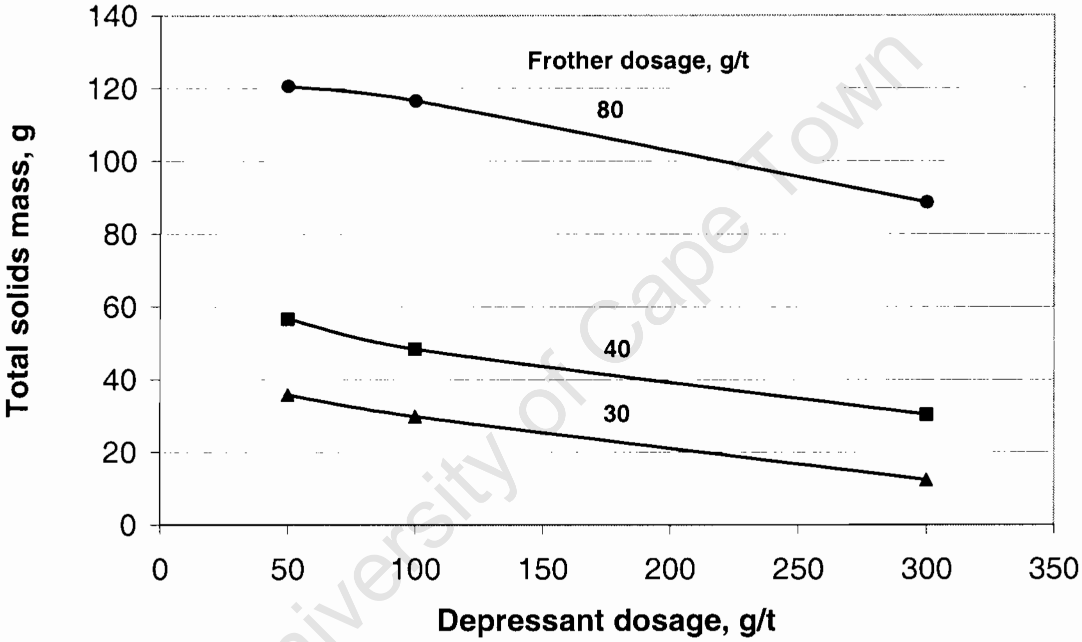

Figure 5-7: Effect of depressant dosage on the total solids recovery as a function of frother dosage

In Figure 5-5 it may be seen that a reduction in copper recovery by depressant dosage is countered by increased frother dosage.

The effects of depressant and frother on recoveries could be used to maximise the recovery and grade of the valuables. By increasing frother an increase in the recovery of valuable minerals is achieved at all depressant dosages. It has been found that even at higher depressant dosages where the recovery of sulphides is affected the most the increase in frother dosage readily reverses the effect on valuable mineral reduction.

The rate of recovery determined from the Klimpel equation shows that even when the rate of recovery of sulphides decreased with depressant dosage an increase in frother dosage caused a net increase in the rate of recovery. This shows that the frother dosage has greater significant effects on the rates of recovery. Frother increase results in the recovery of gangue minerals by entrainment and thus the reduction in the grades of the concentrate. A balance between the frother dosage and depressant dosage is required which provides a cost effective solution to the overstabilisation of froth by hydrophobic talc particles.

5.5 EVALUATING THE ENTRAINMENT FACTOR

The entrainment factor used to calculate the entrainment contribution was applied on the assumption that the entrainment is affected only by water and particle effects and not by the froth characteristics. At 80 g/t frother there was an unexpected increase in the floatable gangue recovery even at the 300 g/t depressant dosage where most of the floatable gangue has been depressed. At this high frother dosage the entrainment factor used does not hold. It is expected that with the high froth stability, the contribution to mass be mostly the entrained solids. Another factor should be developed for such conditions where the froth is highly stable. Also the entrainment factor was developed for a froth depth of 2 cm and may not hold at 4 cm froth depth as a result of the changes in the structure of the froth. The results obtained show that the entrainment of particles is also influenced by changes in the characteristics of the froth phase.

6 CONCLUSIONS

6.1 EFFECT OF INCREASED DEPRESSANT DOSAGE

Increasing depressant dosage from 50 to 100 g/t increased the recovery of copper and nickel sulphides. This can be attributed to the slime cleaning action, although not directly measured, of both guar and CMC on the sulphides' surfaces. A further increase in the dosage to 300 g/t, of both CMC and guar reduced the recovery of copper and nickel sulphides suggesting that at high dosages, the depression of sulphides occurs due to the adsorption of depressant onto sulphide surfaces.

In the flotation of Merensky ore depressants are added to decrease the amount of floating gangue particularly talc. As expected, the reduction in floatable gangue increased with depressant dosage.

The amount of water and the recovery of entrained gangue material decreased with increasing depressant dosage contributing to increased grade. This is due to the decrease in froth stability which could be attributed to the removal of hydrophobic gangue material or the increase in hydrophobicity of sulphides.

6.1.1 Differences between CMC and guar effects

There was little difference between guar and CMC at 30 g/t frother. Differences between the two depressants were obtained at 40 g/t frother. At the lower depressant dosage of 50 g/t the guar depressant was more effective at reducing floatable gangue recovery while at the higher dosages 100 g/t and 300 g/t the CMC depressant became more effective. The reason may be that the CMC as a result of its charged nature induces the dispersion of particles at higher dosages resulting in froth destabilisation.

Less water and thus entrained gangue was recovered by CMC at 100 and 300 g/t than the guar depressant. This may be attributed to the dispersion and slime cleaning action effect of the CMC depressant which reduces the froth stability and allows the water to drain back to the pulp more freely.

6.1.2 Difference between copper and nickel

Nickel sulphides were less affected by the high depressant dosage as a result of the slow floating nature.

6.2 EFFECT OF INCREASED FROTHER DOSAGE

Increasing frother dosage at constant depressant dosage increases recovery and decreases grades of copper and nickel sulphides. Recoveries of water, floatable gangue and entrained gangue increased with frother. This was attributed to the increased rate of flotation and the stability of the froth allowing it to successfully carry more particles to the froth surface.

6.3 EFFECT OF FROTH DEPTH

Increased froth depth decreased the recovery of valuable minerals but increased the grades. Higher froth depths increase the drainage of liquid from bubbles and cause froth destabilisation.

6.4 INTERACTIVE AND COUNTERACTIVE EFFECTS OF DEPRESSANT AND FROTHER DOSAGES

Depressant and frother dosages have interactive and counteractive effects on the flotation performance. The extent of decrease in the copper and nickel recovery and floatable gangue mass with depressant dosage is reduced by increased frother dosage even at the 300 g/t dosage of depressant. The increase of the recoveries with frother is also reduced by increasing depressant dosage. This investigation has shown that high flotation performance is obtained at medium depressant dosage and a high frother dosage.

The decrease in the recovery of copper and nickel sulphides by depressant increase can be reversed and countered by increased frother dosage. The problem is the water increase as a result of increased frother dosage is larger than the decrease in water brought about by depressant increase. Therefore the recovery of entrained material is greater and the grade is reduced. Smaller optimised increases in frother dosage might be utilised to counter a reduction in the recovery of values brought about by depressants whether due to a decrease in froth stability or hydrophobicity of the surface and this should be investigated further.

7 REFERENCES

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8 APPENDICES

Appendix 1: Floatation procedure

The experiments were performed as outlined below:

1. A 1kg sample of dry ore and 500ml synthetic plant water were placed into a stainless steel rod mill and milled for 15 minutes at 90 rpm mill rotational speed to achieve a grind of 60% passing 75 μm.

2. The milled slurry was then transferred to a 3 litre batch flotation cell and the volume was made up to 3 litres by using synthetic plant water.

3. A feed sample was taken from the cell using a syringe.

4. The collector was added at 80 g/t ore and conditioned for 2 minutes.

5. A depressant at the specified dosage was added and also conditioned for 2 minutes.

6. A specified dosage of Dow250 was added and conditioned for 1 minute.

7. The air at a flow rate of 7 L/min was then turned on and the froth allowed to build up. Four concentrates were collected at 2, 6, 12 and 20 minutes of flotation.

8. At the end of the 20th minute, two tailings samples were taken after each experiment.

9. Concentrates were weighed and water recoveries were calculated for each sample.
10. All feed, concentrate and tails samples were filtered dried and weighed.

Appendix 2: Statistical analysis of Klimpel constants

The statistical analysis was carried out at 95% confidence interval. Note that the trends that are indicated as not significant in these tables could be significant at lower confidence levels. The p-value given is the measure of how much evidence there is against the hypothesis that the values investigated are the same at 95% confidence interval.

Table 1: Significance of trends observed on the recovery at infinite time Rinf

Effect of	On	Conditions	p-value	Effect
Increased guar	R inf of Cu	2 cm	0.0136	decrease
Increased guar	R inf of Ni	2 cm	0.0214	increase
Increased guar	R inf of Flt G	2 cm	0.0000	decrease
Increased guar	R inf of Cu	4 cm	0.0052	decrease
Increased guar	R inf of Ni	4 cm	0.0621	none
Increased guar	R inf of Flt G	4 cm	0.0013	decrease
Increased frother	R inf of Cu	2 cm, guar	0.000008	increase
increased frother	R inf of Ni	2 cm, guar	0.00000002	increase
increased frother	R inf of Flt G	2 cm, guar	0.00000003	increase
increased frother	R inf of Cu	4 cm, guar	0.0004	increase
increased frother	R inf of Ni	4 cm, guar	0.0354	increase
increased frother	R inf of Flt G	4 cm, guar	0.0002	increase
d and f interaction	R inf of Cu	2 cm, guar	0.0051	exist
d and f interaction	R inf of Cu	4 cm, guar	0.0231	exist
d and f interaction	R inf of Ni	2 cm, guar	0.0001	exist
d and f interaction	R inf of Ni	4 cm, guar	0.8725	none
d and f interaction	R inf of Flt G	2 cm, guar	0.000000004	exist
d and f interaction	R inf of Flt G	4 cm, guar	0.5637	none
Increased CMC	R inf of Cu	2 cm	0.4610	none
Increased CMC	R inf of Ni	2 cm	0.0001	decrease
Increased CMC	R inf of Flt G	2 cm	0.0071	decrease
Increased frother	R inf of Cu	2 cm, CMC	0.0077	not clear
increased frother	R inf of Ni	2 cm, CMC	0.0013	increase
increased frother	R inf of Flt G	2 cm, CMC	0.8318	none
d and f interaction	R inf of Cu	2 cm, CMC	0.0172	exist
d and f interaction	R inf of Ni	2 cm, CMC	0.000022	exist
d and f interaction	R inf of Flt G	2 cm, CMC	0.0066	exist

Therefore the smaller the p-value i.e. if it is less than 0.05, the more significant is the effect being investigated. As there was so much interaction and highly significant effects of frother dosage, it was necessary to conduct a one-way

ANOVA at each of the frother dosages to ascertain the trends observed with changes in depressant dosage as shown in the Tables 1, 2 and 3.

Table2: Significance of trends observed on the rate constant, k

Effect of	On	Conditions	p-value	Effect
Increased guar	k of Cu	2 cm	0.5810	none
Increased guar	k of Ni	2 cm	0.0003	increase
Increased guar	k of Flt G	2 cm	0.0415	not clear
Increased guar	k of Cu	4 cm	0.6549	none
Increased guar	k of Ni	4 cm	0.0032	increase
Increased guar	k of Flt G	4 cm	0.8968	none
Increased frother	k of Cu	2 cm, guar	0.000002	increase
increased frother	k of Ni	2 cm, guar	0.0000005	increase
increased frother	k of Flt G	2 cm, guar	0.00004	increase
increased frother	k of Cu	4 cm, guar	0.0008	increase
increased frother	k of Ni	4 cm, guar	0.0002	increase
increased frother	k of Flt G	4 cm, guar	0.0188	increase
d and f interaction	k of Cu	2 cm, guar	0.0008	exist
d and f interaction	k of Cu	4 cm, guar	0.1119	none
d and f interaction	k of Ni	2 cm, guar	0.0003	exist
d and f interaction	k of Ni	4 cm, guar	0.0040	exist
d and f interaction	k of Flt G	2 cm, guar	0.0023	exist
d and f interaction	k of Flt G	4 cm, guar	0.7357	none
Increased CMC	k of Cu	2 cm	0.0050	decrease
Increased CMC	k of Ni	2 cm	0.0253	decrease
Increased CMC	k of Flt G	2 cm	0.0003	decrease
Increased frother	k of Cu	2 cm, CMC	0.0086	increase
increased frother	k of Ni	2 cm, CMC	0.0008	increase
increased frother	k of Flt G	2 cm, CMC	0.0043	increase
d and f interaction	k of Cu	2 cm, CMC	0.2703	none
d and f interaction	k of Ni	2 cm, CMC	0.9217	none
d and f interaction	k of Flt G	2 cm, CMC	0.0586	none

Table 3: Significance of effect of increased depressant dosage

Effect of Increased	Frother dosage g/t	Froth depth cm	Copper R inf	p-value	Nickel R inf	p-value	Flt G R inf	p-value
guar	30	2	none	0.5161	none	0.1800	decrease	0.0055
guar	40	2	decrease	0.0022	none	0.3147	none	0.0872
guar	80	2	decrease	0.0392	decrease	0.0066	decrease	0.0000797
guar	40	4	decrease	0.0433	none	0.1447	decrease	0.0174
guar	80	4	decrease	0.0339	none	0.2769	decrease	0.0038
CMC	30	2	none	0.1233	none	0.5729	decrease	0.0234
CMC	40	2	none	0.1103	none	0.3347	decrease	0.0222
CMC	80	4	decrease	0.0180	none	0.2112	decrease	0.0130