ABSTRACT

The initial work of this project involved determining the optimum mesh of grind and frother dosage for Lumwana and Kansanshi ores. This work was conducted at the University of Zambia mineral dressing laboratories based at School of Mines. Further work involved carrying out surface tension, bubble size and froth stability measurements at University of Cape Town's Centre for Minerals Research (CMR) laboratories based at the Department of Chemical Engineering. Finally, water recovery tests were conducted at Lumwana and Kansanshi mine sites.

The optimal mesh of grind for Lumwana and Kansanshi ores were established as 65% and 80% passing 150μm, while frother dosages were established at 60g/t and 80g/t respectively. On flotation kinetics, aliphatic alcohol frother MIBC and higher molecular weight glycol-based formulated frother Betafroth 245 achieved the optimal grade-recovery curves on Lumwana and Kansanshi ores respectively.

There was a general decrease of surface tension as the frother concentration increased. However, all the frothers showed a sudden drop in the surface tension at lower concentration of around 20ppm, indicating that the surfactants tested were more surface active at lower concentrations. Beyond this concentration (20ppm) the surface tension started to level off suggesting that the interface was saturated and the critical micelle concentration (c.m.c) had been reached. Frothers Betafroth 245, Dowfroth 200 and MIBC seemed to give lower critical micelle concentrations. A lower critical micelle concentration is an indication that there is increased adsorption of surfactant at the water-air interface and therefore, such a surfactant had a higher hydrophobicity effect on the flotation performance of the ore, resulting in better flotation results.

Bubble size measurements showed that bubble size decreased as the concentration of frothers increased and that the critical coalescence concentration (CCC) was reached around 25ppm, after which there seemed to be a gradual decrease to the maximum of 100ppm. Beyond the critical coalescence concentration, frothers Betafroth 20, Dowfroth 200, Betafroth 245 and MIBC produced the smallest bubble size distribution. Smaller bubble distribution enhances flotation kinetics (recoveries) and mineral selectivity (concentrate grades). This seemed to support the better performance of the three frothers, on Lumwana and Kansanshi ores, except Betafroth 20 for explained reasons.

Results from froth stability and water recovery tests showed Dowfroth 250 was the most stable frother, and that froth formed was too stable that it recovered high quantities of water and consequently higher entrained gangue (fines) on both ores. The frother Betafroth 245 gave the optimal stability, since its froth was much "drier" and recovered the least quantities of water and therefore less entrained gangue.

These results imply that;

- *Though the chalcopyrite mineral in Lumwana ore is liberated at coarser grind (65% passing 150μm), compared to the chalcopyrite in Kansanshi sulphide ore that is liberated at 80% passing 150μm, the ore (Lumwana) responded well (grades and recoveries) to lower molecular weight frothers such as MIBC and Dowfroth 200, because it contained higher levels of fine gangue (micas).*

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- *On one hand higher molecular weight frothers like Betafroth 245 and Betafroth 20 performed well on Kansanshi sulphide ore and yet not as good on Lumwana ore, because on the other hand the higher molecular weight frothers were forming froths that were to stable due the stabilisation effect of fine gangue.*

- *The response of ores to higher molecular weight frother Dowfroth 250 has showed that in spite giving higher recoveries, the frother gave poor grades on both ores. The poor grades given by Dowfroth 250 can be attributed to formation of highly stable froth enhanced by fine gangue (mica) and gangue entrainment caused by higher water recoveries.*

- *The work has shown that it possible to investigate and establish frothing properties and characteristics of a frother by looking at following properties; (i) surface tension properties, (ii) coalescence (ii) water recovery and lastly (iii) froth stability tests.*

Further work to establish the role pH plays in the hydrophobic effect a frother has on a mineral particle and bubble at one end, and the interfacial surface carrying opposite charge on the other is being recommended.

Key words: Lumwana, Kansanshi, Betafroth, critical coalescence concentration, critical micelle concentration, frother, flotation.

DECLARATION OF ORIGINALITY

This is to certify that the work is entirely my own and not of any person, unless explicitly acknowledged (including citation of published and unpublished sources). The work has not been previously submitted in any form to the University of Zambia or any institution for any other purposes.

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May 2015

CERTIFICATE OF APPROVAL

This thesis of Sidney SONDASHI submitted to the Directorate of Research and Graduate Studies of the University of Zambia through the School of Mines, Department of Metallurgy and Mineral Processing was approved as fulfilling part of the requirements for the award of the degree of Master of Mineral Sciences in Metallurgy and Mineral Processing.

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DEDICATION

This work is dedicated to my wife GORETTIE for her patience and tolerance

ACKNOWLEDGEMENTS

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CAST	centre for advanced separation technology
CCC	critical coalescence concentration
c.m.c	critical micelle concentration
CMR	centre for mineral research
Cu	copper
C1	concentrate 1
C2	concentrate 2
C3	concentrate 3
HMW	higher molecular weight
LMW	lower molecular weight
MIBC	methyl isobutyl carbinol
MSDS	material safety data sheet
Mt	metric tonnes
mt	million tonnes
mtpa	million tonnes per annum
PO	pine oil frother
ROM	Run-of-mine
SAG	semi-autogenous
SEX	sodium ethyl xanthate
SIPX	sodium isopropyl xanthate
S2	second sulphide circuit
TEB	tri-ethoxyl butane
tph	tonnes per hour
UCT	University of Cape Town
UNZA	University of Zambia
ZCCM -IH	Zambia Consolidated Copper Mines – Investment Holding
%TCu	percent total copper
μm	micrometers

CHAPTER ONE

1.0   INTRODUCTION

The advancement in technology coupled with high demand market for commodities has seen increased development of low-grade ore deposits around the world in general, and in Zambia in particular. The treatment of low-grade and complex mineral deposits and high demand for commodities or metals have resulted in the need to have large throughput plants delivering increased productivity, reliability, utilization, together with reduced operational cost. A typical example of increased treatment of low-grade deposits could be appreciated from the point-of-view of the Zambian Copperbelt whereby in the 1960s through to the early 1980s, most of the copper mines treated ores with grades around 2.5%Cu[1]. However, by 2012, some of the old mines including some new operations like Lumwana and Kansanshi mines were treating ores with lean grades as low as 1.0%TCu and less.

The Zambian Copperbelt is one of the world-class copper deposits discovered and developed in the 1920s. The deposit is part of the larger Central African Copperbelt of Zambia and the Democratic Republic of the Congo (DRC) lying some 1500 km from both the Indian and Atlantic Oceans. In Zambia, the deposits were first owned by British and American interests through the British South Africa (BSA) Company and later by Anglo American Corporation. The copper mines in Zambia were nationalised in national interest by the Zambian government in the 1970s, and went through production decline as a result of their remoteness and problems associated with the self-determination of several emerging African countries[1]. Copper production from the Copperbelt mines had dwindled from around 750 000 tonnes in early 1970's to around 260 000 tonnes in 2000, when the mines were on course for re-privatisation[2].

The Zambian copper mining industry has been the mainstay of Zambia's economy since the 1930s, contributing around 10% of the country's GDP and about 80% export earnings. By 2015, copper production from the Copperbelt is expected to reach 1.5 million metric tonnes or almost double the peak achieved during the last boom in the 1970s[3].

The Zambian Copperbelt in this study refers to the area of Copperbelt and North-Western provinces of the Republic of Zambia. Geologically, the Zambian Copperbelt is defined as a region of more than 150 km wide extending from Mwinilunga in the West to the Bangweulu Block in the East, and the entire Central African Copperbelt is 700km, situated along structural trend of the folded and thrust Katangan sediments called the *Lufilian Fold Belt* extending from Angola in the West through the Congo DR and Zambia in the East, though most of the Zambian copper mines were concentrated in the last 200km (the Zambian Copperbelt Province) of this fold arc. Lumwana, Kansanshi and the new Kalumbila deposits are therefore, situated within the Lufilian arc[4].

1.1   Lumwana mine

Lumwana is an open-cast mine situated 65km west of the Zambian North Western provincial capital Solwezi. The mine was commissioned in 2008 by Equinox Minerals. Equinox Minerals was acquired by Barrick Gold Corporation in 2011. The mine's proven and probable reserves were estimated at 299 million tonnes (mt) graded at 0.68% TCu in 2010.

An average of 20 million tonnes of ore a year would be mined to produce an average of 122,000t of copper a year over the 37-year mine life[5].

1.1.1 Ore mineralogy

The Lumwana deposits of Malundwe and Chimiwungo are hosted within the Mwombezhi Dome, a north-east trending basement dome in the western arm of the Neoproterozoic Lufilian Arc thrust-fold belt. The Lufilian Arc is a major tectonic province characterised by broadly north-directed thrust structures and antiformal Basement inliers or domes surrounded by Katangan metasediments, which host the Central African Copperbelt[4].

The copper mineralisation at both Malundwe and Chimiwungo is hosted overwhelmingly within an intensively mylonitised and recrystallised muscovite-phlogopite/biotite-quartz-kyanite schists with disseminated sulphides dominated by chalcopyrite and bornite. The ore schists are intensely sheared and have a higher content of mica. The major gangue minerals in the ore schist are muscovite (50%), quartz (20%), biotite (10%), and kyanite (15%). The sulphide mineralisation at Lumwana mine seem to occupy dilational sites that are associated with mica and quartz. Of the two major deposits, Malundwe is smaller but with higher copper grade and contains discrete zones of uranium and gold mineralisation with occasional sporadic high cobalt[5].

Chimiwungo is much larger and lower in copper grade, but has higher overall cobalt and contains a number of significant high-grade (>0.1%) cobalt zones plus some sporadic uranium mineralization. Malundwe and Chimiwungo deposits are 7 km apart and are being mined sequentially by open-pit methods. The ore bodies are 95% sulphides (with only 5% oxide) and very consistent, hence large-scale bulk-mining methods are being used[5].

1.1.2 Mining and ore processing

Mining of Lumwana ore involves the use of four hydraulic face shovels for waste and ore and two hydraulic excavators (26m³) plus a smaller unit (15m³) for selective ore mining and 26 large AC-drive haul units able to carry 242 tonnes at a time. These units are supported by a fleet of drills, front-end loaders, bulldozers, graders and other ancillary equipment. Trucks from the mine tip directly into a 400 tonne-capacity run-of-mine (ROM) dump hopper. A huge primary gyratory crusher crushes the ROM ore at about 4000tonnes per hour(tph) from a nominal top size of 1,500mm to less than 200mm. Oversize material is deposited on the ROM pad to be further broken by a mobile rock breaker[5].

Ore is reclaimed via apron feeders onto a conveyor belt providing direct feed, at a rate of about 2,500tph (at least 50,000tonnes per day), into the 11.6m x 5.5m SAG mill. The SAG mill trommel undersize discharges into a hopper and is pumped to conventional hydrocyclones, operating in closed circuit with a 7.9m x 12.1m ball mill. The hydrocyclone overflow (p80<280μm) reports to flotation, while the underflow returns to the ball mill[5].

The flotation plant consists of two parallel trains of 160m³ rougher/scavenger cells. The rougher/scavenger concentrate reports to the regrind circuit to further liberate the copper minerals. After regrinding, the concentrate is cleaned in a conventional cleaner/recleaner circuit to reach final concentrate grade. The concentrate is dewatered in a circuit consisting of high-rate thickening followed by pressure filtration to produce a filter cake suitable for transportation to smelters (Figure 1.1). Flotation tailings are thickened and pumped to the tailings dam. Most of the plant water is recovered and recycled from the thickener overflows

and tailings dam return water. Fresh make-up water is supplied from a river-water dam as required[5].
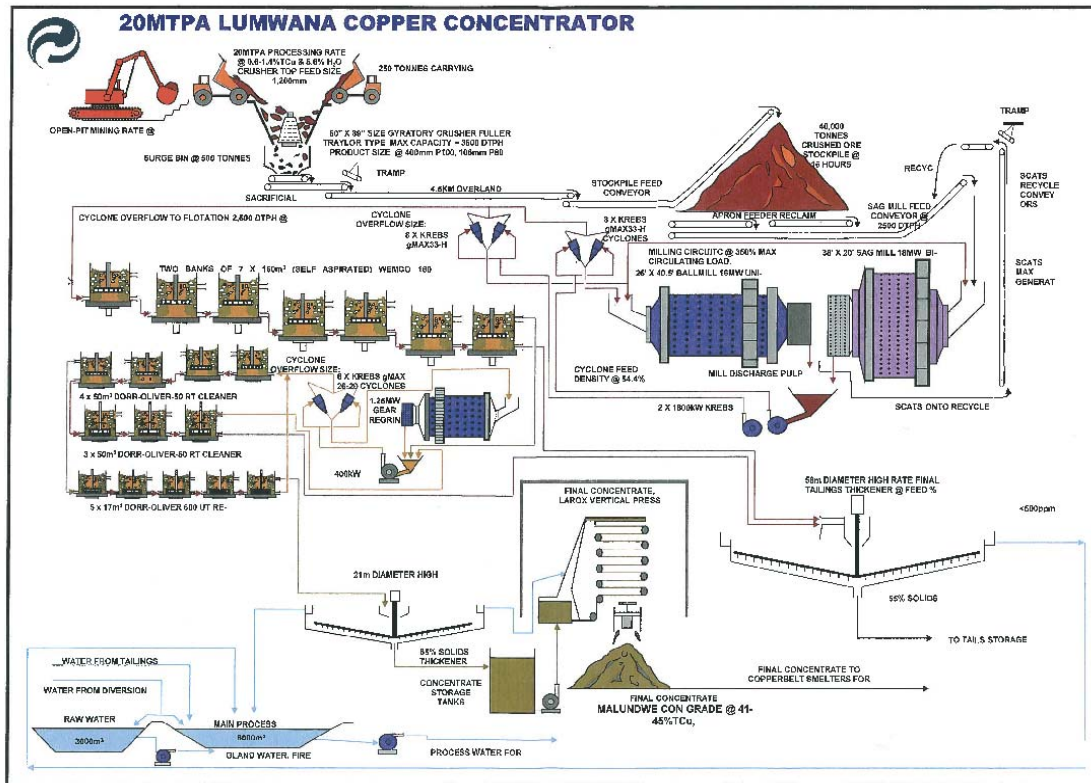
Fig. 1.1: Lumwana process flowsheet: Source: www.mining-technology.com, 2013[5]

1.2   Kansanshi mine

Kansanshi deposit lies within the Dome's Region some 150km west of the main Zambian portion of the Copperbelt province. The deposit is hosted by sediments previously assigned to the Nguba Group (formerly Lower Kundelungu). The deposition of Nguba Group or Lower Kundelungu commenced with a glaciogenic diamictite (Grand Conglomerate) approximately 10km[6].

Kansanshi mine is located nearly 10km north of the Solwezi town and 180km northwest of the Copperbelt town of Chingola. The mine is 80% owned by First Quantum Minerals through its subsidiary Kansanshi Mining Plc. The remaining 20% is held by the Zambian government through ZCCM-IH Plc. The mine began production in April 2005. The proven and probable reserves at the mine then included 74.8 million tonnes (mt) of leachable ore, 75.10mt of mixed float and 154.6mt of sulphide, graded at 2%, 1.04% and 0.81% copper respectively[5].

1.2.1   Ore mineralogy

Mineralisation at Kansanshi is hosted in combinations of veins, vein and fault breccias and replacements developed along the ductile fabric. The ore deposit outlines a well mineralised, north-south striking zone. The zone is characterised by complicated faulting, abundant injection vein networks, development of brecciate units and down-dropped rock structures. Vein-specific copper mineralisation that is either stratiform or concordant is hosted within

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and directly adjacent to mesoscopic veins, in thin bands and veinlets oriented parallel to rock bedding or foliation. It also occurs as disseminated mineralisation related with albite-carbonate alteration. The main veins and vein swarms plunge sub-vertically, perpendicular to the fold axis. Mineralisation within the brecciate zones are common and occurs within the deeply weathered oxidised and supergene enriched layers, but rare in fresh rock hosting most of the sulphide copper. Secondary copper minerals are distributed in a complex manner across these layers. The primary copper sulphide mineralisation is chalcopyrite-dominated and is associated with trace amounts of bornite, minor pyrite and pyrrhotite[6].

Chalcopyrite and pyrite can be observed as breccias infill, as well as inclusions in mineralised vein fragments. Thus it seems clear that faulting and fault reactivation of mineralised veins margins has been an important syn-to-post mineralisation process at Kansanshi. The sulphide zone (deposit) is defined as chalcopyrite (minor bornite) mineralisation hosted in fresh rock. The zone is subdivided into low carbonate sulphide and high carbonate sulphide based upon occurrence in phyllites and schists versus calcareous phyllites schists and marble. The vein mineralisation is characterised by material of quartz-carbonate-sulphide combinations with trace molybdenite in fresh rock, while weathered veins are characterised by oxide copper and ironstone. The oxide mineralisation is largely dominated by chrysocolla. It also hosts malachite, limonite and cupriferous goethite. The mixed zone, a combination of both oxide and primary-style mineralisation, also hosts significant amounts of chalcocite, minor local copper and tenorite[5].

1.2.2   Mining and ore processing

Mining at the Main and North-West open pits is done by conventional open pit methods involving hydraulic excavators and a mining fleet of haul trucks.

Processing of the three ore types, namely leached ore, mixed float and sulphide, is through either an oxide circuit or a sulphide and transitional ore mixed float circuit. Treatment of the sulphide ore involves crushing using a 2000 tonne-per-hour gyratory crusher and milling using a 6.1m x 9.75m ball mill to produce an overflow of p80<150μm that is fed to the 300m^3 rougher/scavenger flotation cells to produce a final copper concentrate after cleaning (Figure 1.2).

1.2.3   Expansion plans

An US$797million expansion is underway to increase the production at the mine from 250,000 to 400,000 tonnes per year of copper by 2015. The expansion being carried out at Kansanshi mine is over three phases. The US$32m phase 1 involved capacity enhancement of the oxide circuit by 20% to 7.2mt. It resulted in a flexible operation that allows easy switch between mixed and sulphide circuits to suit the mining operations. Phase 2, which was completed in November 2013 at a cost of US$200m, increased the annual oxide treatment capacity by 15mt. The mixed ore and sulphide ore are milled together by a second sulphide circuit (S2) following the phase 2 expansion[5].

The third phase of expansion includes construction of a new 16 million-tonne-per-annum (mtpa) sulphide concentrator through a single stage Semi-Autogenous Grinding (SAG) mill, which can be extended up to 25mtpa by adding a ball mill in the future. This phase has been budgeted at US$565m. The new Sulphide concentrator (phase 3) is expected to be operational by 2015. The sulphide ore will be milled by the new phase 3 sulphide concentrator following the third phase of expansion, while the mixed ore will be milled by the phase 2 circuit. The

copper concentrate produced from the phase 3 will be supplied to a new smelter currently being constructed at the mine, under the Kansanshi copper smelter development project[5]. As a result of the ongoing expansions to the process plant, the Kansanshi sulphide ore flotation circuit would only be confirmed after the expansions are completed in 2015.
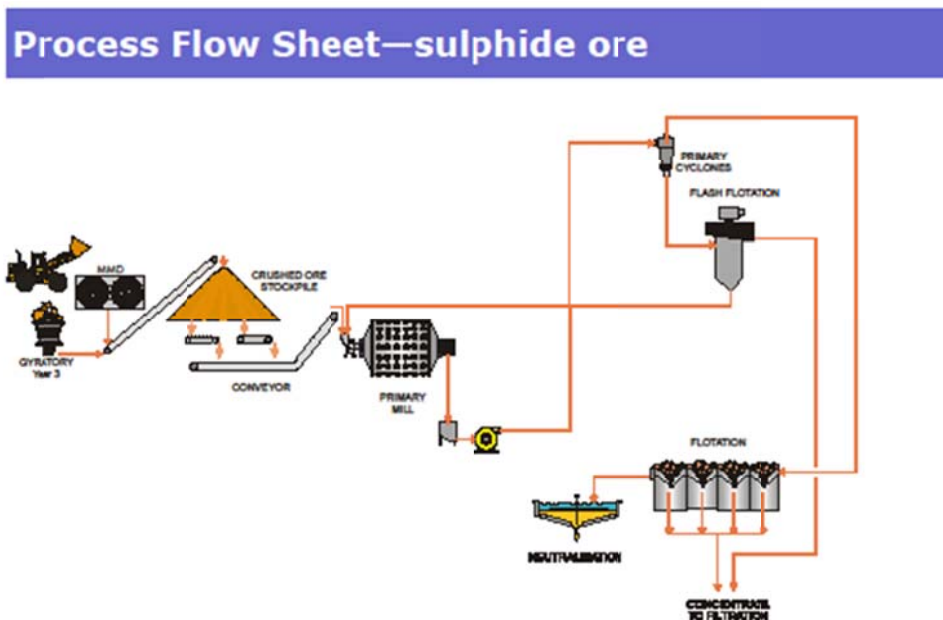
Fig. 1.2: Kansanshi process flowsheet: Source: www.mining-technology.com, 2013[5]

1.3   Current process challenges

From as early as the 1980s[7]to the current times[8], the major changes that have taken place in mining industry in general and copper industry in particular are;

- A general decrease in grade of ores treated coupled with a higher market demand for commodities or metals. As a result the tonnages being treated by individual flotation plants have increased daily tonnes treatment.
- The sizes of equipment used in flotation plants including mining have increased several-fold in order to cope with the demands of throughput. Both autogenous grinding mills and flotation cells have become very large.
- Separation difficulties of these marginal ores (due to intricate interlocking of minerals and variable association and dissemination characteristics) have increased greatly.

These problems have been compounded in that the complex mineralogy has resulted into the use of complicated process flowsheets designed to recover minerals as efficiently as possible[8].The use of complicated process flowsheets entails the employment of large equipment such as large shovels, loaders and trucks in open-pit mining, grinding mills and flotation cells, increased use of plant automation and robust reagents in the processing plants. The use of these large grinding mills and flotation cells has allowed various processing plants to treat large volumes of ore at almost same unit cost. However, the decrease in grade of ores being treated, the increase in size of flotation cell and separation difficulties associated with low grade ores has given rise to new flotation challenges, particularly in flotation chemical regimes.

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Hence, recent trends in mineral flotation processing have established that in most cases, a combination of two or more different collectors may provide some solution to these recent challenges, than does a single collector. Similarly, frother combinations or use of multiple (formulated) frothers has increased drastically due to the realisation that frothers play a vital role in the optimisation of flotation plant concentrate grades, recoveries and circuit control.

Therefore, the aim of this research is to investigate the flotation characteristics of multiple or formulated frothers, on the flotation response of Lumwana and Kansanshi sulphide ores, in comparison to single or tradition frothers.

1.4 Statement of the problem

The treatment of low-grade and complex mineral deposits and high demand for commodities or metals have resulted in the need to have large throughput plants delivering increased productivity, reliability, utilization, together with reduced operational cost. As a result the sizes of all equipment used in flotation plants (including mining) have increased several-fold in order to cope with the demands of throughput. Both autogenous grinding mills and flotation cells have become very large. The separation difficulties of these marginal ores (due to intricate interlocking of minerals and variable association and dissemination characteristics) have increased greatly. Is the use of efficient, effective and more robust flotation reagents helping in resolving some of these problems associated with the use of large cells and the complex mineralogy of low-grade deposits? Is the use of a combination of two or different types of collectors or frothers lead to better metallurgical performance than do single collectors or frothers?

1.5 Significance of study

Since a significant number of copper mines world-wide and almost all flotation plants on the Zambian Copperbelt, are using multiple or formulated frothers, it may be assumed that tradition or single frothers do not perform as formulated frothers in flotation circuits treating low-grade sulphide copper ores and employing larger flotation cells.

While, significant work may have been conducted on flotation circuit control using tradition (single) frothers, such as a polypropylene glycol (Dowfroth series) and methyl isobutyl carbinol (MIBC), very little work has been conducted on formulated frothers in general, and Betafroth frothers in particular, to understand the flotation response of sulphide minerals in the presence of these products.

1.6 Expected impact of study

This study will help in the understanding the behaviour of Copperbelt ores in general and Lumwana and Kansanshi ores in particular, in the presence of formulated and tradition frothers. The study will be able to characterise each frother under evaluation, in terms of its interaction with a collector, water recovery and bubble formation, distribution and froth stability.

1.7 Research purpose

The main purpose of this research work was to make an effort to understand the flotation response of Lumwana and Kansanshi sulphide ores in the presence of formulated (Betafroth) frothers.

1.8   Research objectives

The objectives of this research were to;
1. Optimise grinding time for Lumwana and Kansanshi sulphide ores in order to achieve acceptable sulphide copper concentrates and recoveries.
2. Optimise frother dosages of both formulated and single frothers on Lumwana and Kansanshi ores in order to achieve acceptable sulphide copper concentrates and recoveries.
3. Compare flotation kinetics of formulated frothers to that of single frothers on Lumwana and Kansanshi sulphide ores.
4. Investigate frothing properties and characteristics of the two Betafroth or formulated Betafroth 245 and Betafroth 20 in relation to the single or pure products (i.e. MIBC, Pine oil (PO) from the alcohol family and Dowfroth 200 and 250 from the glycol family).

1.9   Research hypotheses

Based on the statement of the problem, two statistical hypotheses or statements were, therefore formulated.

1.9.1   Null (H$_0$) hypothesis

There is NO significant difference between the flotation results obtained from a single frother and formulated product in the flotation circuit treating Lumwana and Kansanshi low-grade sulphide copper ores.

1.9.2   Alternative (H$_1$) hypothesis

There is a significant difference between the flotation results obtained from a single frother and formulated product in the flotation circuit treating Lumwana and Kansanshi low-grade sulphide copper ores.

1.10   Sampling techniques

The most difficult part of doing reliable ore testing in the laboratory is to obtain a representative sample of the ore to be tested[9]. Therefore, the practice of sampling is one of the most important exercises in achieving results that are representative of the field of study.

1.10.1 Representativeness of sample

The process of selecting a fractional part of the whole relevant group or population is called *sampling*. The basic idea is that by selecting some of the elements (samples) in a population (ore) and focusing research attention on this finite group, one may apply the finding of the study to the whole population of interest. A population element is the single unit of the sample on which measurements and observations are taken. A population, therefore, is the full set of elements or cases from which a sample is taken, to which one can generalise the findings of the study[10].

Sampling design has two-broad categories, namely, probability sampling and non-probability sampling. Non-probability sampling is non-random, subjective and purposive in that the selection of the sample may be based on using criteria other than those associated with

randomness. Probability sampling on the other hand, is based on the concept of random selection. In this study probability sampling of the ore or feed materials was conducted at the respective plant sites. Some of the general concepts associated with probability sampling agreed with the way the ore samples were "cut" from the respective plant sites[10];

- The samples obtained were representative of the population (ore) from which it was drawn,
- The samples were selected randomly from the population (ore)
- Every element in the population had an equal probability of being picked
- It was possible to generalise the findings from the sample to the population (ore)

Hence, probability sampling exists within the positivistic or quantitative paradigm, as it is based on scientific assumptions of developing generalised knowledge about the categories and aspects of ores being treated at the respective plants[10].

1.10.2 The theory of sampling

The theory of sampling explains how the errors can be eliminated or minimised so as to come up with the sample that is close in characteristics to the bulk material as possible. Different types of errors may be caused by characteristics of the material, sampling protocol, sampling equipment used and handling. In addressing these errors, one needs to know the difference between an error and uncertainty. An error is the difference between an observed or calculated value and a true value, i.e. variation in measurements, calculations or observation of quantity due to mistakes are uncontrollable factors, while uncertainty is the lack of sureness about something, i.e. something that is not known beyond doubt[11].

Sampling is dependent on probability, and the more frequently the incremental sample is taken the more accurate the final sample will be. The sampling method devised by Gy is used to calculate the size of sample necessary to give the required degree of accuracy[12]. The formula given by Gy expresses the variance to be expected in the assay value when a given weight of material is taken as a sample from bulk, and the following assumptions are made[13];

1. Normal distribution – it is assumed that if a large number of similar samples were taken from the bulk sample, then the frequency distribution of the assays would follow a normal curve,
2. Equal chance of acceptance - it is assumed that every separate particle and type of component has an equal chance of being selected, and
3. Freedom from bias – it is assumed that the sampling techniques and measurements are free from bias or systematic errors.

It must be noted that in the case of gold, diamond and some sedimentary deposits, the assays frequency distribution is likely to depart from normal and use should be made of the central limit theorem to take samples in such a way that the grouped mean grade will follow a normal distribution. Therefore, basic Gy's formula becomes[13];

$$\left(\frac{\sigma}{a}\right)^2 = \left(\frac{1}{p'} - \frac{1}{p}\right)fgmld^3 \text{ or } \left(\frac{\sigma}{a}\right)^2 = \left(\frac{1}{p'} - \frac{1}{p}\right)Cd^3 \qquad [1]$$

where C = fglm, and

  a = mean metal content of the lot (%)
  σ^2 = variance of the grade distribution
  p' = weight of the sample (kg)
  p = weight of the lot to be tested (kg)
  f = shape factor
  g = size factor
  m = mineralogical index (kg/m^3)
  d = size of the largest piece in the lot.
     This being the aperture which retains 5 to 10% of the original lot (m)
  l = liberation index.

Since $\left(\dfrac{1}{p}\right)$ is too small, the equation [1] can be approximated as;

$$\left(\frac{\sigma}{a}\right)^2 = \left(\frac{1}{p'}\right)Cd^3$$ and when p' is substituted by M, the Gy's basic sampling equation can be re-written as [12];

$$M = \frac{Cd^3}{s^2} \qquad\qquad [2]$$

Where;

  s, is the measure of the statistical error committed by sampling (relative standard deviation of normal distribution curve representing the random assay-frequency data)
  s^2, is relative variance
  C, is sampling constant for material to be sampled (gcm^{-3})
  d, is diameter of the largest particle in the material to be sampled (cm)
  M, is the minimum weight of sample required (g)

As stated earlier C = fglm   [3]

  If we let d_1 = length of the side of the square mesh through which the particle will always pass, and ρ = particle density, then;

  f, (shape factor) $= \dfrac{mass\ of\ particle}{d^3_1\rho}$, and varies from 0 to 1, and normally taken as 0.5 except for gold ores, which is 0.2, while for plate-like minerals (mica) is 0.1.

  g, (the size factor) $= \sum_j \dfrac{D_j}{D}W_j$, where, D_j = size parameter of size range, W_j = the fraction of the total in size range j (wt), and D = maximum particles size, and is dependent on the particle size range, whereby the following values may be used in practice, 0.1 to 0.5 for unclassified material, 0.15 to 0.5 for scalped feed (oversize), 0.2 to 0.5 for deslimed material, and 0.3 to 0.8 for deslimed and classified material. However, in most cases g is taken as 0.25[13].

  l,(liberation factor) $=\dfrac{a^1 - a}{\alpha - a}$, where,

a = the approximate grade of the lot being sampled (% metal),

a^1 = the assay of the richest piece in the largest size fraction (% metal), and

α = the metal assay of the pure mineral being sought (% metal).

with values between 0 for completely homogenous material and 1.0 for completely heterogeneous material, and 0.1 to 0.4 for run-of-mine ore, 0.2 for mixed particles, 0.1 moderately disseminated, 0.05 for finely disseminated, 0.2 for high grade concentrates, 0.4 for low grade concentrates, and 0.1 for tailings[13].

Also the values of l can be calculated from an expression; $l = (L/d)^{1/2}$ where d, is the dimension of the aperture which passes 90-95% of the material, and L, is the size in cm at which, for practical purposes, the mineral is essentially liberated[12].

m, (mineralogical composition factor), can be calculated from the expression;

$$m = \frac{1-a}{a}[(1-a)r + at]$$, where, r and t are the mean densities of the valuable

mineral and gangue respectively, and a, is the fractional average mineral content of the material being sampled. This value could be determined by assaying a number of samples of the material[12].

The values of m may vary from 30 for a 90% concentrate to about 107 for a 0.1% tailing. Thus m, is very important than f, g or l and usually approximations in these latter quantities, do not affect the result as do the values of m[13].

From the foregoing therefore, it can be stated that individual make-up of the ore impacts greater influence on the minimum size of the sample required in order to get the required accuracy. For ore of large size, the sample required is much more than in case of fine ore sample. However, while the particle size is of great importance in size of sample required, this is only true for free particles. For locked particles, the most important parameter is not particle size but grain size[14].

CHAPTER TWO

2.0   LITERATURE REVIEW

The declining ore grades, increasing complexity of ore deposits and higher global demand for commodities in general and metals in particular, has resulted in increased daily treatment of ores by individual flotation plants around the world[8]. Increased daily tonnage to the flotation plants has in turn resulted in the use of large equipment in the mining, milling and flotation of these ores. The improvement in technology has allowed various mining operations in general and processing plants in particular to treat large volumes of low-grade sulphide ores at almost same unit cost. The general decrease in grade of ores treated and a higher market demand for commodities or metals, the increase in size of flotation cells and separation difficulties associated with low grade ores, has given rise to new flotation challenges in terms of economic beneficiation of these ores.

Recent trends in mineral flotation processing, has shown that in most cases a combination of two or more different collectors may provide some solution to these recent flotation challenges, than does a single collector. Similarly, frother combinations or use of multiple or formulated frothers has increased drastically due to the realisation that frother plays a vital role in the optimisation of flotation plant concentrate grades, recoveries and circuit control.

Therefore, in order to appreciate the challenges flotation plants are facing in terms of recoveries, concentrate grades and circuit control due to winning of complex and low-grade ores and employment of large flotation cells, it is important to present the literature review in this work by first looking at the theory of froth flotation.

2.1   The theory of froth flotation in general

Froth flotation is the most important method used for concentrating or separating values from low-grade ores. After fine grinding, surface-active chemicals are added to a pulp (ore and water) to enhance differences in physico-chemical surface properties of various mineral species. The pulp is then copiously aerated, and the preferred species clings to bubbles and floats as a mineralised froth, which is skimmed off[15].

Although the froth flotation process is of enormous importance to the world economy, it was developed in the past largely by empirical methods. However, now modern experimental techniques are being used to investigate the mechanism of action of surface-active substances or chemicals that are employed in the froth flotation process[16]. Any substance that has tendency of concentrating on the interfaces is called surface-active agent or simply surfactant. Numerous inorganic and organic surfactants are used in mineral flotation for the purpose of controlling the characteristics of interfaces. These species, whether organic or inorganic in nature which can be adsorbed on any of the five possible interfaces such as liquid/gas, liquid/liquid, solid/liquid, solid/gas, solid/solid are described as amphipatic compounds containing a long-chain hydrophobic group and hydrophilic polar group.

Surfactants can be divided into three classes; (i) anionic types, such as sodium cetyl sulphate, $C_{16}H_{33}SO_4^-Na^+$, in which surface activity resides is an anion, (ii) cationic types, such as cetyltrimethyl-ammonium bromide, $C_{16}H_{33}NMe_3^+Br^-$, in which surface activity resides in the cation, and (iii) non-ionic types, such as cetylpolyglycol ether, $C_{16}H_{33}(OCH_2CH_2)_nOH$[17].

Most surfactants used as frothers in sulphide flotation are non-ionic, i.e. possess a definite permanent dipole, either that of an alcohol or of an ether group[18]. Additionally, surfactants are often named in relation to their technological application, with names such as detergent, wetting agent, emulsifier and dispersant[19]. Surfactants play a two-fold role in froth flotation;

1. Adsorption at the solid/liquid interface making selected minerals hydrophobic in nature, thus acting as *collectors*.
2. Influence the kinetics of bubble-mineral attachment, thus acting as *frothers*.

Therefore, in order to appreciate the role non-ionic surfactants like frothers play in mineral flotation method of ore separation, it is important to further the discussion in this literature review to include the principles of mineral flotation, surface forces and tension, the role of frother in bubble formation and a look at the flotation cell and the role it plays in froth formation and distribution.

2.2   Principles of mineral flotation

Froth flotation is undoubtedly the most commonly used technique in the concentration of ores in general and low-grade ores in particular. The technique is based on making use of differences in the physico-chemical surface properties of different minerals. The differences in the physico-chemical surfaces can also be enhanced by treatment of the minerals with specific reagents called surfactants.

For flotation to take place an air bubble must be able to attach itself to a particle in the mineral suspension known as flotation pulp. For this to happen, the particle should be small enough to adhere and be carried by the bubble to the surface into the froth layer, otherwise the particle will drop-off the bubble, when the bubble starts to rise. This is the more reason froth flotation is only used in the separation of fine particles.

Therefore, froth flotation pulps consist of mixtures of solid particles in an aqueous solution, with small additions of surface active agents and air bubbles. The active agents are either inorganic or organic reagents. Hence in any flotation pulp all three phases, solid, liquid and gaseous are present. The properties of the bulk phases influence and determine the characteristics of the interfaces formed between the adjoining phases.

From the foregoing, it can be deduced that surface chemistry is the basis of froth flotation, and therefore a thorough understanding of the physico-chemical characteristics of solid surfaces is essential to better understand the complex phenomena taking place during flotation. These surface characteristics are determined by the solid crystal properties that hold solids together that is chemical bonding and its atomic and molecular structure. Atomic and molecular arrangement of solid determines the position of the different chemical species and their distance from the surface. In case of sulphide minerals, their surfaces can be classified as sulphur-deficient and sulphur-rich depending on the relative abundance of sulphur atoms[20].

Since froth flotation utilises the differences in physico-chemical surface properties of particles of various minerals, the process can only be applied to relatively fine particles. If the particles are too large the adhesion forces between the particle and the bubble will be less than the particle weight and the bubble will drop its load. For flotation to take place, an air-bubble must be able to attach itself to a particle, and lift it to the water surface. Hence a three-phase system is created, in which the following three interfacial tensions are present as shown in Figure 2.1 below; (i) the gas/solid tension, ($\gamma_{g/s}$), (ii) the solid/liquid tension, ($\gamma_{s/l}$), and (iii)

the gas/liquid tension, ($\gamma_{g/l}$). The three tensions together determine the contact angle concept at the point of conjunction of the three phases. The larger the contact angle, the greater the tendency of the bubbles to adhere to the particles. Therefore, contact angles are used as a measure of the hydrophobicity of mineral surfaces. A finite contact angle means that the work of adhesion of water to the solid is less than the work of cohesion of water to water.

Fundamentally, froth flotation can be viewed as a stochastic (random) event, whereby, P is the probability of particle collection by a bubble (i.e. the flotation probability), and then this can be represented by using the following product of three separate probability terms[21];

$$P = P_c * P_a * P_d \qquad\qquad [4]$$

whereby;

P_c is the probability of collision between the particle and the bubble,
P_a is the probability of adhesion after collision, and
P_d is the probability of detachment.

The first probability, P_c, depends mainly on the hydrodynamic characteristics of the flotation cell. The second probability, P_a, depends on superficial forces, while the third probability, P_d, depends on collision with other particles and on the turbulence of the flotation cell. The basic mechanism of flotation is the adhesion between the particle and the bubble, this stage defines the kinetic characteristics of the flotation process. Therefore, the probability of adhesion between the particle and the bubble after collision can greatly be influenced or enhanced by the addition of surface active substances or surfactants. For completely hydrophobic particle, P_a is equal to 1, while for finer particles, P_d is equal to zero[21].

An air-bubble can only stick to the mineral particle if it can replace a thin water film on the mineral surface. This can only happen if the mineral particle becomes water repellent or hydrophobic. When finally the mineral particles are attached to the air-bubbles and rise to the surface, the air-bubbles can only continue to support the mineral particles if they can form a stable froth, otherwise they will break and drop the attached mineral particles[22].To achieve this chemicals or reagents are used of which the two most important are *collectors* and *frothers*. Collectors adsorb on mineral surfaces, rendering them water repellent or hydrophobic or aerophilic, while frothers help maintain a reasonable stable froth. While it is possible that flotation can take place without any addition of collector, this is known as *collector-less flotation*, to generalise that sulphide mineral surfaces are naturally hydrophobic may be misleading.

Several researchers are cited[23] whereby the concept of collector-less flotation has been redefined, in light of recent electrochemical and surface characterization studies, leading to metal-deficient sulphide surface layers formed after partial oxidation, and therefore concluded that collector-less floatability of sulphide minerals may largely depend on the mineral type and may vary from mineral to mineral depending on the methods (conditions) used to prepare or generate the mineral particle. However, when a frother is added to the flotation pulp, collector-less flotation is more pronounced[20].

In all multiphase systems van der Waals forces are always present and exert a major influence in both long-and short-term range interactions. These interactions include adsorption and adhesion of polyatomic aggregates (non-polar and polar molecules or aggregates such as colloidal particles) to surfaces of solids and to liquids/gas or liquid/liquid

interfaces, which are all readily available in froth flotation. Stability of colloidal dispersion is determined by the balance between the attractive van der Waals forces and the repulsive forces between the charged electrical double layers surrounding each colloidal particle. On the other hand the stability of mineralised (mineral-laden) froth depend on the balance of two van der Waals forces as mentioned above, but since in mineralised froth heterogeneity is greater, three interfaces (solid/gas, liquid/gas and solid/liquid) are participating in their structure instead of two as in colloidal dispersion[7].

Therefore, van der Waals forces may be repulsive or attractive, and the final interaction would depend on relative values of the dielectric constants of the two interacting phases and the intervening third medium. For example, multiphase containing small particles or fines, present in the multiphase may be induced to migrate toward or away from the different types of interfaces as a consequence of the action of van der Waals forces[7].

2.3   Surface forces and contact angles in flotation

The relationship between a mineral surface and the surfactant in a pulp depends on the forces which operate on that surface. The forces tending to separate a mineral particle and the bubble, lead to the development of an angle between the mineral surface and the bubble surface due to the surface tensions.
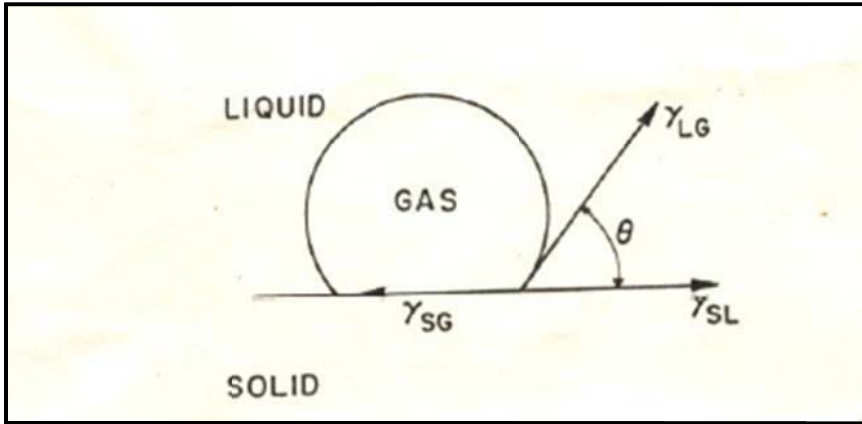
Fig.2.1: Relationship between contact angle and surface tension: Source: Sikamo, 1987[51], after Fuerstenau, 1976

The forces intending to separate a particle from a bubble are known as *tensile forces*. At equilibrium, these forces give a relationship frequently referred to as the Young's modulus equation[19];

$$Cos\emptyset = \frac{\gamma_{s/g} - \gamma_{s/l}}{\gamma_{l/g}}$$

[5]

where,

$\gamma_{s/g}$, $\gamma_{s/l,}$ and $\gamma_{l/g}$ are the surface energies between solid-gas, solid-liquid and liquid-gas respectively, and $\emptyset$ is the contact angle between the mineral surface and the bubble.

On the other hand, the force required to break the particle-bubble interface is called the *work of adhesion*, which is equal to the work required to separate the solid-gas interface and produce separate gas-liquid and solid-liquid interfaces and was derived by Dupre as[7];

$$W_{s/g} = \gamma_{l/g} + \gamma_{s/l} - \gamma_{s/g} \qquad\qquad [6]$$

Combining the two equations [5] and [6] gives

$$W_{s/g} = \gamma_{l/g}(1 - \mathbf{Cos\emptyset}) \qquad\qquad [7]$$

From the equation it can be seen that the greater the contact angle the greater the work of adhesion between particle and bubble and the more resilient is the system to any disruptive forces. The floatability of the any mineral therefore, increases with the contact angle. Minerals with higher contact angles are said to be aerophilic or hydrophobic, that is they have a higher affinity for air than for water[17].

2.4   Surface and interfacial tensions

There is no fundamental distinction between the terms surface and interface, although it is customary to describe the boundary between two phases of which one is gaseous as a *surface* and the boundary between two non-gaseous phases (solid/liquid or liquid/liquid) as an *interface*[19].

At the *liquid/liquid interface* there is an imbalance of intermolecular forces, but of lesser magnitude than the intermolecular forces taking place in the bodies of each of the bulk liquids. The molecules which are located within the bulk of a liquid are on average, subjected to equal forces of attraction in all directions, whereas those located at, for example, a liquid-gas interface experience unbalanced attractive forces resulting in a net inward pull. Hence, as many molecules as possible will leave the liquid surface for the interior of the liquid, leaving the surface to tend to contract spontaneously[19]. Therefore, work must be done to increase the surface area of a liquid. The resistance to increasing the surface area of a liquid is commonly referred to as *surface tension*, γ. Surface tension therefore, is defined as the force acting on a line of unit length in the surface[17].

Therefore, surface tension is a manifestation of the forces of attraction that hold the molecules together in the liquid (or solid) state[24]. For this reason, droplets of liquid and bubbles of gas tend to attain spherical shape, i.e. the form of least surface area. It is these short-range forces of attractions existing between molecules that are responsible for the existence of the liquid state. Hence, it is these short-range intermolecular forces which are responsible for surface and interfacial forces and include vander Waals forces (in particular London dispersion forces) and may include hydrogen bonding in case of water and metal bonding in case of mercury. And it is the surface tension or a more fundamental quantity called *surface free energy* that fulfils the outstanding role in the physical chemistry of surfaces[19].

At the *solid/gas interface*, when a gas comes into contact with a solid, some of it becomes attached to the solid surface, in form of an adsorption layer. As discussed earlier the forces involved in the adsorption of gases and vapours by solids are non-specific or van der Waals forces, and are responsible for *physical adsorption*. On the other hand similar forces involved in liquefaction, or stronger specific forces, such as those which are operative in the formation of chemical bonds result into *chemisorption*[19].

The concept of *wetting* can therefore, be introduced. Wetting simply means the displacement of one fluid by another. Wetting involves three phases, of which two must be fluids (liquid or

gas). In terms of froth flotation, wetting can be displacement of a gas, usually air, by a liquid at a surface of a solid. There are three self-explanatory types of wetting; (i) spreading, (ii) adhesional, and (iii) immersional[19]. However, adhesional wetting is of more prominence in flotation, since a liquid is not originally in contact with the solid and therefore, makes contact and adheres to it. As shown before the work (free energy) of adhesion is given by the Dupre equation in form

$$W_a = \gamma_{s/g} + \gamma_{l/g} - \gamma_{s/l} \tag{8}$$

where the various γ terms represent the interfacial tensions between the phases indicated.

If W_a in this equation is a negative quantity, spreading of the liquid will be spontaneous, and wetting of the solid by the liquid will be complete. However, if W_a is a positive quantity, wetting will be incomplete and the liquid will tend to collect on the surface in the form of drops[12].The extent to which wetting has taken place in these circumstances is conveniently measured in terms of the *contact angle*, which is the angle between the tangent to the gas/liquid interface at the point of contact with the solid at the surface of the solid (see Figure 2.1). Therefore, zero contact angle results when the forces of attraction between liquid and solid are equal to or greater than those between liquid and liquid, and finite contact angle results when the liquid adheres to the solid less than cohere itself. Hence the solid is completely wetted by the liquid if the contact angle is zero and only partially wetted if the contact angle is finite. Complete non-wetting, implies a contact angle of 180°, which is an unrealistic situation since it requires that either $W_a = 0$, or $\gamma_{l/g} = \infty$ (infinite) [19].

Therefore, surfactants act as *wetting agents,* by being adsorbed at the gas/liquid and liquid/solid interfaces where there is an accompanying decrease in the corresponding interfacial tensions. As stated earlier some of the surfactants like frothers are soluble both in water and oil. The hydrocarbon part of the molecule is responsible for its solubility in oil. The polar or –OH group has affinity to water to drag a short-length non-polar chain hydrocarbon chain into aqueous solution with it. If these molecules become located at an air-water interface, they are able to locate their hydrophilic head groups in the aqueous phase and allow lipophilic (hydrophobic) hydrocarbon chains to escape in the air[19] as depicted in Figure 2.2 below.
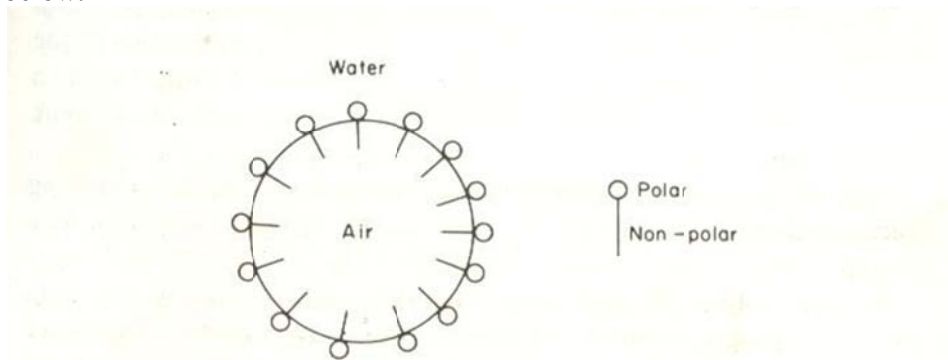
Fig. 2.2: Frother adsorption on the air-water interface: Source: Wills, 1988[12]

Strong surface-active agents (surfactants) consisting of molecules containing both polar and non-polar parts (amphiphilic), adsorbs at surfaces or interfaces in the form of an orientated monomolecular layer or monolayer, termed surface activity. Hence, as stated earlier, surfactants are classified as anionic, cationic or non-ionic according to the charge carried by

the surface active part of the molecule. However, most frothers are non-ionic surfactants, and the advantage of non-ionic surfactants is that the lengths of both hydrophilic and hydrophobic groups can be varied[19].

2.4.1   Relationship between surface tension and micelle forming surfactants

A solution containing a surfactant (frother) exhibits unusual physical properties. In a dilute solution the surfactant acts as a normal solute. At fairly well defined concentrations, however, abrupt changes in several physical properties, such as osmotic pressure, turbidity, electrical conductance and surface tension, take place [19].This behavior of surfactants can be explained in terms of organised aggregates or micelles of the surfactant in which the lipophilic hydrocarbon chains are orientated towards the interior of the micelle, leaving the hydrophilic group in contact with the aqueous medium. The concentration at which micelle formation becomes appreciable is termed the *critical micelle concentration* (c.m.c) [19].

However, above the c.m.c. surfactant molecules associate to form or micelles. The accepted structure of a micelle, according to the liquid-drop model, is an approximately spherical body, with hydrophilic groups on the surface and hydrophobic groups directed towards the interior. Because the surface of a micelle is completely hydrophilic, there is s lesser tendency to adsorb at interfaces above the c.m.c. and this accounts for the levelling of the surface tension-concentration curves as seen in Figure 2.3 below [17].
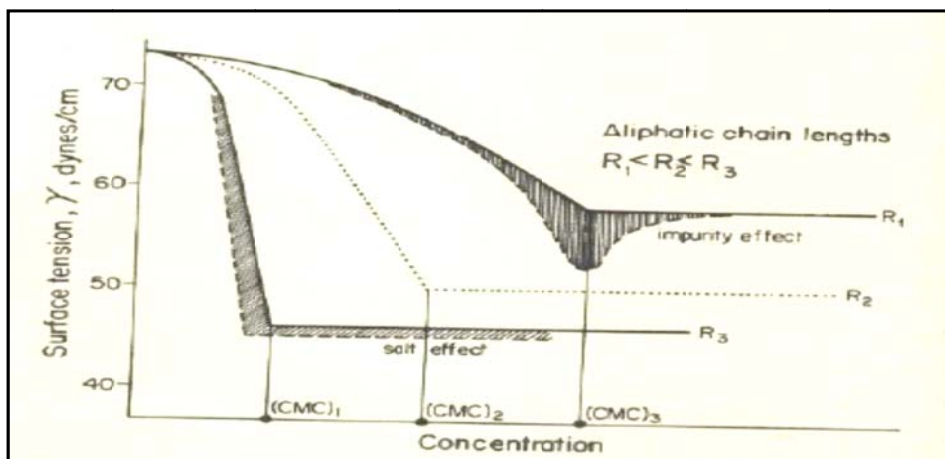
Fig. 2.3: Schematic relationship between surface tension and concentration for micelle-forming surfactant of increasing chain lengths $R_1<R_2<R_3$ for a surfactant containing small amounts of another surface active species (impurity effect) and for a surfactant to which a quantity of a neutral inorganic salt has been added (salt effect); illustrating the lowering of the critical micelle concentration: Source: Leja, 1988[7]

Some of the factors that may be responsible for decrease in the interfacial energy are[19].;

(i)   The intermolecular attraction between the hydrocarbon chains in the interior of the micelle represent an energetically favourable than that which results from alternative hydrocarbon-water attraction.

(ii)   Micellisation permits strong water-water interaction (hydrogen bonding) which would otherwise be prevented if the surfactant was in solution as single molecules wedged between the solvent water molecules. This is the most important factor in

micelle formation and in any adsorption process at an aqueous interface. This is referred to as the *hydrophobic effect*[19].

Micellisation is an alternative to adsorption, whereby the interfacial energy or tension of a surfactant is able to decrease, just like in the case of adsorption. Because micelle formation results from water-water interaction, the attraction of water molecules for a hydrophilic group is greater than that for a hydrophobic group. Therefore, increasing the hydrophobic part of the surfactant molecules lowers the critical micelle concentration (c.m.c.). Lowering of the c.m.c. can also happen by lowering the temperature and/or adding of simple salts or the CH_2 group (in case of ionic or non-ionic surfactants respectively)[19]. For example increasing number of carbon atoms in the hydrocarbon chain leads to drastic lowering of the critical micelle concentration (c.m.c.) when carbon atoms are increased from 8 to 14 in the hydrocarbon chain as one way of increasing the hydrophobicity of the surfactant[7].

Similarly, addition of sodium chloride (NaCl) to an ionic surfactant lowers the c.m.c, within the relevant temperature range and pH, since the repulsion between charged ions at the surface of the micelle is reduced by the screening action of the added ions[19]. This *salt effect* (see Figure 2.3 above) can be considered as evidence of synergistic action existing between the ionic polar groups[7].

Therefore, it is possible for one to draw some assumptions that micellation can be used to determine frother characteristics or properties. The two fundamental frother characteristics that govern selectivity and frothing capacity (stability) are the HLP number (hydrophilic-lipophile balance) and the molecular weight. The HLB number defines the relative water and oil solubility characteristics of the frother. This determines the affinity of the molecule to reside at the air-water interface where it can influence the formation and stability of bubbles. The molecular weight also impacts on the stability of bubbles but has greater influence on factors such as froth drainage and therefore selectivity[25].

2.4.2   Determination of surface tension

The measurement of surface tension helps in understanding the role a frother in particular or a surfactant in general plays in reducing surface tension of liquid in order to promote flotation. There are several methods used for measuring surface tensions and contact angles. These can be classified into *static, detachment and dynamic* methods. Static methods usually offer a greater potential for accurate measurement than detachment methods, especially when solutions of surface-active agents are involved, though detachment methods tend to be the more convenient to operate[19]. Examples of static methods are the capillary rise and plate methods while the detachment methods are ring and drop-volume or drop-weight methods. In this work, the ring method was used to measure surface tension of distilled water containing frothers at different concentrations, since it has been established before that for biological fluids, colloidal solutions and surfactants, surface tension can be determined quickly and with sufficient accuracy [24] by measuring the force required to detach a horizontal ring of platinum wire (radius R) from a surface or interface of liquid as illustrated in Figure 2.4 below.
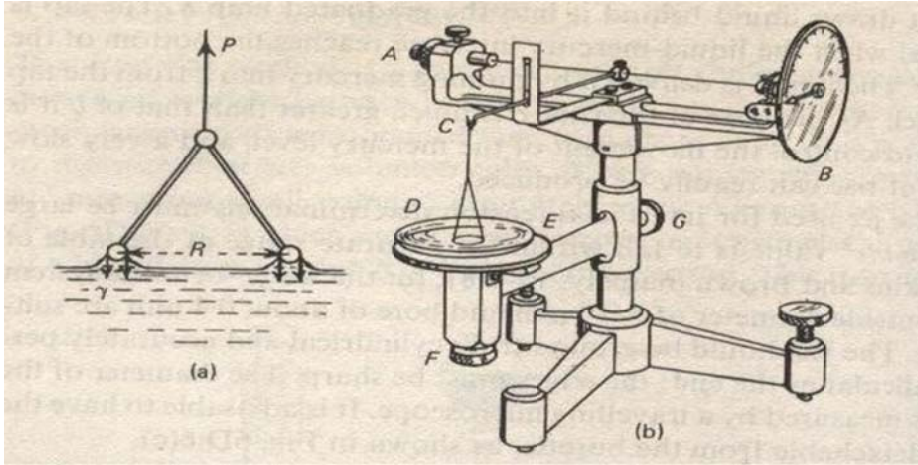
Fig. 2.4: Determination of surface tension by ring method (a) Principle of the method (b) Torsion balance: Source: Levitt, 1973[24]

The force F is given by twice the perimeter of the ring times the surface tension, i.e. F = 4πRγ. The force F must be multiplied by a correction factor β, which varies from 0.75 to 1.1 depending on the dimensions of the ring[17]. The force F is measured by suspending the ring from the arm of a balance. Therefore, detachment force is related to the surface or interfacial tension by the expression[19];

$$\gamma = \frac{\beta F}{4\pi R} \qquad [9]$$

Where F is the pull on the ring, R is the mean radius of the ring and β is a correction factor. To ensure zero and a constant angle, platinum ring is carefully cleaned in strong acid (ethanol) and by flaming it. It is essential that the ring should lie flat in the quiescent surface [19].

2.5   The role of a frother in particle-bubble attachment process

When minerals are rendered hydrophobic by the use of a collector, stability of bubble attachment especially at the pulp surface depends to a considerable extent on the efficiency of the frother. Frothers are heteropolar compounds which decrease the surface tension of the pulp, resulting in increased dispersion of bubbles and increased froth stability[26].

While the primary role of the frother is to help maintain a stable froth on the pulp surface, recent flotation research development has shown that in practice, a frother may play a complimentary role to enhance interaction between minerals and other reagents present in the pulp. In sulphide mineral flotation, however, specific frother may be employed to provide adequate physical properties to the froth, while at the same time interact with the collector to control the dynamics of the flotation process[12].

Therefore, frothers are no longer seen as reagents only producing froth, and that there is now a better understanding of the interaction between collectors and frothers and the influence frothers have on the bubble size and hence bubble surface production rate and flotation kinetic rate. The effect of frother type on the rate constant of various size fractions is well known and there are well-defined optimal particle sizes and rates of flotation for individual frother species. To balance these variables in the multiphase system most flotation plants

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currently use mixtures of frothers[27]. From the foregoing, it is clear that froth-acting surfactants are needed in flotation systems operating under dynamic conditions in flotation cells and consequently have influence on the kinetics of mineral-bubble attachment under these dynamic conditions.

In flotation cells, collisions between ore particles and bubbles cause direct encounters between solid/liquid, air/solid and air/liquid interfaces. These encounters seem to be responsible for a minor proportion of successful attachments of minerals in the pulp. However, an appreciable proportion of the successful encounters are caused by subsequent collision of these micro-bubbles of the air/liquid interface with mechanically-generated bubbles. Two models responsible for bubble-particle collision have been developed[21];

1. *The electrostatic model*. According to this model, the energy for the coupling of the particle with the bubble is due to electrostatic attraction between the particle and an interfacial surface carrying opposite charge.
2. *The hydrophobic model*. According to this model, the particles become hydrophobic after the adsorption of the surfactant, and this allows their adhesion with bubbles.

Once a particle-bubble attachment is achieved, it is important that the adhesion between the particle and bubble be strong enough to survive the disruptive centrifugal forces generated within the mechanical cell. Highly hydrophobic particles with contact angles greater than 90° will destabilise froth as a result of facilitated thinning inter-bubble liquid bridged by the particle[7]. Froth becomes stabilised by hydrophobic solids when they adhere to the air/liquid interface so closely together that the draining of the liquid is restricted. Hence the role played by hydrophobicity of any particle depends on the shape, roughness and size of the particle and type of frother[7,28]. Therefore, the action of any frother in flotation is not only limited to the formation of a stable froth, but also to;

- Favour the formation of much finer air bubbles (i.e. dispersion of air in presence of a frother is much greater). Larger bubbles tend to gobble up other bubbles in the presence of non-uniform bubbles,
- Prevent coalesce of separate air bubbles. Coalescence, being defined as the phenomenon where bubbles grow in diameter by feeding on smaller bubbles,
- Decrease the rate at which air bubbles rise in the flotation to the surface of the pulp.
- Increase the strength of the bubbles and the stability of froth,
- Affect the action of collectors by increasing the hydrophobicity effect of the collector through lowering of the surface tension (lower critical micelle concentration).

In summary, a good frother governs the quality of the concentrate produced, the recovery of the valuable components of the ore and other important factors determining the efficiency of the flotation process. Consequently, the choice of a frother or combination of frothers, for a particular flotation application depends on the frothing mechanism involved. For sulphide flotation it is usual to find two or more frother combinations used in order to compliment the role of the collector in the formation of interaction complexes and to improve flotation efficiency. In most cases a frother containing at least a portion of an alcohol, such as (methyl isobutyl carbinol (MIBC), is the best to match the collector, and higher molecular weight frothers such as the polypropylene glycols, can be added to modify the physical properties of the froth and the bubble size, particularly when coarser particles are to be floated[9].

On the one hand, mineral particles usually carry a charge when suspended in water. This charge may come about due to either intrinsic imbalance in the surface concentrations of ions in the crystal faces exposed to water, or from adsorbed ions [29]. These ions may come about due to surfactants that may be introduced in the pulp[21]. On the other hand, as earlier stated it is to be expected that bubbles in a flotation cell should also carry a charge, arising from adsorbed surfactant (collector) or other materials present in the pulp. When large particles collide with bubbles, these interfacial forces play a minor role in the kinetics of the capture, provided the surface of the solid is hydrophobic. With fine particles, however, it would be expected that the charge on the bubble and the particle may play a major role on the kinetics of capture. The sign and magnitude of the charge on both bubbles and particles could have an important bearing on the rate at which coalescence between the two could occur, i.e. on the flotation rate[21]. Therefore, the importance of bubble charge in relation to flotation can never be over-emphasised.

This charge on the particles and the bubbles can be measured using an *electrophoretic* mobility apparatus. The motion of the particles can be observed under a microscope, and the mobility can be reported in terms of velocity (μm/s) per unit of potential gradient (v/cm). Smaller bubbles are generated electrolytically by controlled pulses from electricity in the liquid taken from flotation cell[29].Therefore, electrophoresis is the movement of a charged surface plus material (i.e. dissolved or suspended material) relative to stationary liquid by an applied electric field. When the material under investigation is in the form of a reasonable suspension or emulsion containing microscopically visible particles or droplets, then electrophoretic behaviour can be observed and measured directly.

Similarly information relevant to soluble material can also be obtained in this way if the substance is adsorbed onto the surface of a carrier, such as oil droplets or silica particles. Particle electrophoresis is also a useful technique for characterising the surface charges. The nature of the surface charge can be investigated by studying the dependence of electrophoretic mobility on factors such as pH, ionic strength, addition of specifically adsorbed polyvalent counter-ions, or surface-active agents and treated with specific chemical reagents[19].

2.6   The role of a flotation cell in froth formation

Flotation machines or cells are the devices used to carry out the flotation process. Towards the end of the 1980s, different flotation machines were being manufactured and many had been developed and discarded in the past, but it is fair to state that two distinct groups had arisen; namely, pneumatic and mechanical machines[12] and lately the tankcell, which is the combination of the two (pneumatic/mechanical) cells. Pneumatic machines either use air entrainment by turbulence in the pulp or by air either blown in or induced, in which case the air must be dispersed either by baffles or some form of permeable base within the cell[16].

Mechanical flotation machines are the most widely used, being characterised by a mechanically driven impeller which agitates the slurry and disperses the incoming air into small bubbles. The most pronounced recent trend in the flotation of base metals has been the move towards larger capacity flotation cells, with corresponding reduction in capital and operating costs.

There are several important features that a flotation machine or cell should possess. Some of these features that must happen simultaneously in the flotation machine are [30]; particle

suspension and dispersion, aeration formation, bubble formation and dissemination, air-particle contacting, quiescent conditions for froth column formation and concentrate removal. Each of these functions requires different cell design and operating conditions for optimum results. Therefore, a chosen design and operating variables should be a compromise favouring the important rate-determining mechanism in focus. In this study however, the feature in focus is the *aeration of pulp*.

Aeration affects the power consumption of the cell as well as the ability of the machine to keep the solids in suspension. When a critical value of the airflow number (defined as $N_Q = Q_A/ND^3$, where Q_A is volumetric flow rate of air at standard temperature and pressure (STP), N is the impeller rotational speed, and D is the impeller diameter) is exceeded, a drastic sedimentation occurs for closely sized particles and a less drastic one with wide range of particle sizes [7]. In the flotation process the aeration and the corresponding size of air-bubbles produced, are of paramount importance. The extent to how much the pulp is aerated depends on size, number and even distribution of air-bubbles in the pulp. Pulp aeration determines the flotation machine output, grades of products, and the reagent consumption. However, best flotation conditions are obtained with optimum degree of pulp aeration.

Mechanical cells can generate the bubble size of 0.8 to 1.0mm in diameter, while in pneumatic cells the air-bubble size can range from 2.5 to 4.0mm in diameter[14]. The amount of air-bubbles in the pulp is directly proportional to volume of air entering the flotation cell and inversely proportional to the speed of air passing through the pulp, therefore[14];

$$V = 100t\frac{Q_A}{Q_B} \ (\%) \hspace{4cm} [10]$$

where

$\quad\quad$ V= total volume of bubbles in a unit of pulp volume as percentage of total effective machine capacity

$\quad\quad$ t= average residence time spent by bubbles in the pulp (seconds),

$\quad\quad$ Q_A= air flow rate (m^3/sec), and

$\quad\quad$ Q_B= effective volume capacity of the chamber (m^3).

It is therefore, essential to introduce a large volume of air into the pulp for high output of flotation machine. By dispersing the air in the cell, keeping sufficient pulp layer and turbulent motions help to keep the air in the pulp for considerable long time. Addition of a frother in a pulp reduces the air intake (self-aerating capacity) of the cell, reduces the average size of bubbles and their ascent velocity, and diminishes the power consumption of the cell [7].In the absence of frother, air bubbles produced by rotating an impeller may coalesce as the air streams impinge on the stator blades[30]. Since, when air or bubble rises it expands, in the presence of a frother the coalescence of bubbles is minimised[31]. Therefore, the use of frothing agents reduces tendency to coalesce, reduces bubble size, and reduces ascent velocity as compared with bubbles of same size without frother. These effects are due to the reagent (frother) adsorbing at the air-water interface and causing the bubble to behave somewhat as a rigid sphere. Without frother, bubbles in the size range 0.5mm to 3mm develop elongated tails which tend to reduce hydrodynamic resistance[30].

As with ore particles, air bubbles have an optimum size distribution. But this optimum bubble size distribution was arrived at empirically over several years, not by measuring bubble size but by monitoring the effects of frother type and concentration on froth depth and persistence.

However, bubble sizes can now be measured, and in normally operated flotation machines can range between 0.1 to 1.1mm, giving an average of 0.5mm.The major factors determining bubble size is frother type, frother concentration and its effect on the surface tension of the pulp water[32].

Therefore, air is a very important variable in flotation control and operation of a flotation circuit because it affects both the pulp and the froth phase. Investigations done on chalcopyrite and pyrite [33]had shown that there is a trade-off between the performance froth phase and pulp phase, in that it is difficult to decide on the optimum air rate for a cell, that gives improved grade at the same time improved recovery. Increasing air in a cell normally reduces froth recovery, while the opposite is also true. Frother, therefore, helps in promotion of both improved grade and recovery. In the pulp phase, frother reduces bubble size by preventing bubble coalescence, and in the froth phase it increases froth stability. While it is a known fact that frother prevents bubble coalescence in the pulp phase, there exists a critical concentration of frother called the *critical coalescence concentration* (CCC), after which any further increase in frother concentration has no effect on the bubble size[33].

The relationship between bubble size and frother concentration was described mathematically and showed that there is an exponential decay relationship between bubble size and frother concentration. This was simplified into[33];

$$d_{32} = d_{lim} + Ae^{-B} \qquad [11]$$

where;

> d_{lim} = limiting bubble size, typically bubble size at concentration>>CCC
> A, B = parameters from fitting with least-squares regression.
> d_{32} = Sauter Mean Bubble Diameter (mm)

In a laboratory flotation cell however, research work [33] has shown that any addition of extra frother above the critical coalescence concentration (CCC) may not be essential, apart from giving smallest possible bubbles in the cell and therefore, maximising the bubble specific area available to particle attachment in the pulp phase, thus improving froth stability in the froth phase. The *UCT bubble size analyser* developed by the University of Cape Town is an excellent tool used to determine bubble size.

While flotation cells are widely used both as laboratory and commercial units as stated earlier, creation of a stable froth is of paramount importance. The creation of a stable froth is promoted by employing a frother in the flotation process. But as will be shown later, fine particles or slimes content in the ore also help to stabilise the froth. In order to appreciate the froth properties of any frother it is essential to subject the same frother to the froth stability tests. These tests can be carried out using the Bikerman flotation column as shown in Figure 3.5. By varying frother concentrations and recording the resulting froth height and collapse rate or reaction time, a lot of information on the frothing properties of the frother can be obtained. The information so obtained can then be used to plot graphs of frother concentration against froth height, and froth height against reaction time. However, for one to understand the performance of any frother, the rate of froth collapse needs to be determined. The rate of froth collapse can be modeled using a modified first order rate equation[34]

$$\frac{dH}{d(t-\phi)} = -kH \qquad [12]$$

Where,

>H is froth height (cm)
>t, is the elapsed time from termination of air flow in the column (second)
>ø is the induction time (seconds), and
>k is the froth "decay constant" (s^{-1}).

Integrating of the above equation [12] from Ho (initial froth height) to H and ø to t, yields a

$$ln[\frac{H}{H_o}] = -kt \qquad\qquad\qquad [13]$$

A plot of $\ln[\frac{H}{H_o}]$ vs (t) may produce a straight line with slope, k, being the froth "decay constant" (rate of froth collapse)[34].

2.7   Current developments and challenges in the flotation processes

The current developments in flotation technology may be considered in various areas. Some of these development areas may be given as new reagent regimes resulting from improved flotation flowsheets, equipment design, increasing size of flotation cell, new methods in process control of flotation process [8]. However, as stated earlier, the major development that has taken place in the last decades as a result of general decrease in grades of ores treated and a higher market demand for commodities has been the increase in the daily tonnes being treated by individual flotation plants. This in turn has had an effect on types of ores being treated and the sizes of the equipment being used in flotation plants.

2.7.1   The development and challenges of large cells

As early as the late 1960s, a good number of copper mines around the world in general, and in the Americas in particular, had started encountering low grade ores and therefore, the trend of treating low grade porphyry deposits [9] had started. By 1975, some of the major International and USA copper operations had started treating these low-grade porphyry ores at a large scale[35], and also started using multiple frothers[9]. During the 1960s, the average flotation cell size was only 2.8m^3. In the 1970s the average size was 8.5m^3 and in the 1980s the average cells size moved to 36m$^{3(35,36,37)}$.

In order to couple with the arising large tonnages during these periods (1970s and 1980s), most flotation plants were made to employ several rows of small flotation cells, of which Bougainville had the largest cells of 18 rows of 36m^3 capacity, simply because the plant was by then a relatively new plant, having been commissioned in 1972. Bougainville in Papua New Guinea was then the world's largest copper concentrator after ramping up to 130 000 tonnes per day from 80 000 tonnes of ore per day throughput, treating at a porphyry deposit [12]. Some of the manufacturers and flotation cells types employed then by different flotation plants world-wide were; Agitair, Callow, Boliden FR, Denver, Fagergren (FAG), Forrester, Maxwell, Macintosh, Mineral Separation, Southwest Air and Outokumpu[35].

By the year 2000, the flotation cell size capacity had reached 200m^3, and in 2004 *FLSMIDTH* Minerals in collaboration with the CAST (centre for advanced separation technology) GROUP plus seven mining schools in the USA, developed a *DORR-OLIVER* 350m^3 SuperCell for the Rio Tinto's Kennecott Copperton Concentrator in Utah State of the USA, in

the flotation of the copper-molybdenum circuit, in order to achieve the 150 000 tonnes of ore per day throughput from a porphyry deposit of 0.6%TCu head grade[38]. By 2011, *OUTOTEC* launched the e500 tankcell with over 500m^3 of active volume, while FLSMIDTH is currently (2012) planning to launch another SuperCell with 600m^3 cell capacity[39,40].
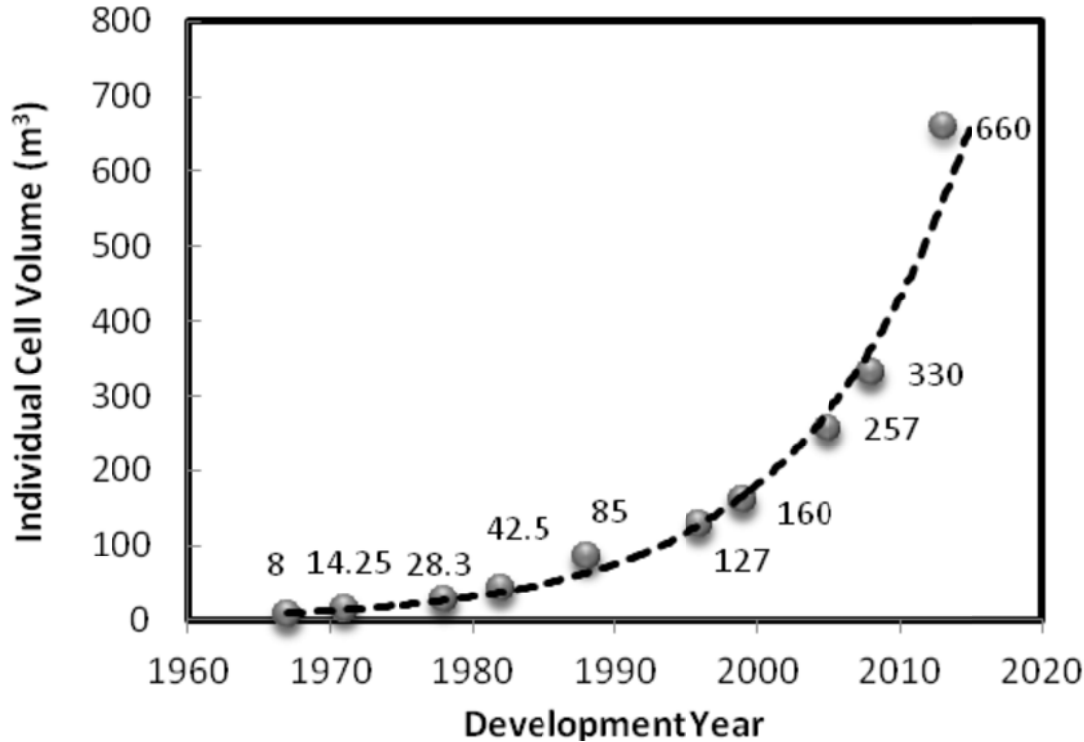
Fig. 2.5: WEMCO flotation machine development timeline: Source: Govender et al, 2013[40]

This innovation in flotation machine technology was being spear-headed by the four major international manufacturing companies, namely; *DORR-OLIVER, EIMCO (WEMCO), OUTOTEC* and *METSO MINERALS*, who gave some of the economic benefits of using larger cells as fewer cells, lower installed power and consumption, better control and smaller footprints. However, researchers say metallurgical benefits of larger flotation cells still need to be fully realised by the industry. Some of the metallurgical problems of large flotation cells for which the manufacturers are trying to resolve are cell mixing, gas dispersion, gangue entrainment and froth flow behaviour [37,41]. While cell mixing, gas dispersion maybe resolved mechanically, the problem of gangue entrainment and froth flow behaviour in large cells may be resolved partly through understanding the role the frother plays in froth flotation. Apart from generation of smaller bubbles, another role of frother in flotation is the formation of strong bubbles and a stable froth, so that hydrophobic particles that are picked up in the cell and brought to the froth can be transferred up to the lip level safely. In large cells this role is of critical importance because failure for a frother to form strong bubbles and stable froth and ensure the efficient transportation of froth or minerals across the surface of the cell could lead to loss of cell recovery.

These metallurgical challenges of large cells are also compounded by separation difficulties encountered by the flotation plants as a result of intricate interlocking of minerals and their variable associations and dissemination characteristics associated with increased treatment of

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low grade ores. Hence, the use of efficient, effective and more robust flotation reagents may help resolve some of the problems of froth flow behaviour in large cells and intricate interlocking of minerals associated with low grade ores.

Therefore, one way to try and resolve these challenges associated with the use of large cells and the complex mineralogy of low-grade deposits is the use of a combination of two or more different types of collectors or frothers that may lead to better metallurgical performance than do single collectors or frothers. While a combination of collectors may be a straight forward case, a combination of two or more frothers may not be so. In case of frothers, therefore, many flotation plants have moved to *formulated* frothers, made specifically for specific flotation plants, based on ore mineralogy and the operating practice of the flotation plant.

2.7.2 *Separation (flotation) challenges of low-grade/complex ores*

The primary purpose of grinding in a concentration plant is the liberation of the valuable minerals from the gangue, and the secondary purpose is reducing the size of the valuable minerals sufficiently enough to enable subsequent concentration process like flotation to take place. Statistically, grinding a rich ore to free a valuable mineral grain gives 80% of the coarsest grains as being free gangue, while only 70% of the valuable minerals were freed. However, when the ore is ground to grain size of a less abundant mineral (low-grade ores), the 80 to 90% is finer than half-grain size and 70 to 80% finer than quarter grain size [42]. This may explain how over-grinding takes place in the milling of low-grade ores prior to flotation due to targeting of the valuable mineral grain size.

This theory is supported by recent works [7] that show that high-grade deposits are usually liberated at coarser sizes and are easier to concentrate by froth flotation. However, such deposits are increasingly becoming depleted, and therefore the treatment of low-grade ores has seen separation difficulties in the flotation of sulphide ores due to over-grinding that is taking place in the milling of low-grade ores [7]. The over-grinding in the mills is taking place due to targeting of the less abundant minerals as a result of increased intricate interlocking and variable association and dissemination characteristics of valuable minerals in the low-grade ores. Intergrowth in ore is the manner in which the valuable minerals are distributed among gangue minerals or host rock. If the intergrowth pattern involves valuable mineral particles of around 300μm, then no major problems of liberation or subsequent separation by flotation may be encountered. But if the mineral particle size is less than 10μm, then the liberation and flotation challenges may be encountered. Similarly if the valuable minerals are highly interlocked and very finely disseminated, their separation or flotation may pose major difficulties [7].

Apart from finely interlocked, intergrowth and dissemination of the valuable minerals in the low-grade ores, other difficulties that may be encountered in sulphide ore deposits may include[7];

- An extensive surface oxidation of individual sulphide grains,
- The co-existence of sulphide and oxidised minerals, as in the case of the Kansanshi ore deposit [5].
- A high degree of interlocking and an extremely fine dissemination of valuable sulphides within the body of massive pyrrhotite or pyrite, as in case of the Kansanshi sulphide ore deposit [5].

- The co-existence of highly hydrophobic minerals, such as, talc, graphite, molybdenite and carbonanecous shale or micas in the case of Lumwana ore deposit [5].
- The co-existence of clayey minerals, especially in non-sulphide ore, producing large quantities of interfering slimes.

Several explanations are given as to why smaller particles are difficult to float. The most common is that fine particles of sizes less than 10μm are virtually too small to float. Several authors [7,43,44] have all come to the conclusions that fine particles acquire insufficient energy of impact to disrupt the water layer existing between the two colliding particulates and that fine particles have negative impact of flotation due to their intrinsic properties, small masses low collision efficiency and higher interfacial free energy, and that finer particles have large specific surface area, which require more time to float and excessive adsorption of reagents.

From the foregoing therefore, in order to deal with fine particles, it may be important to know the characteristics of the fines. It is the variations in the characteristics of these particle surfaces that may be responsible for the flotation problems that may be encountered. The characteristics of the surfaces created are determined by the manner the particles in general and fine particles in particular were generated and hence, some of the mechanisms by which fine particles may have been generated are [7];

(i)   mechanical – creation of surface by impact and attrition – thus very large residual stresses are acquired by the fines,
(ii)   thermal – fines produced by heat decrepitation – heat may be supplied or generated within the system, as heat of wetting of surfaces or heat of adsorption,
(iii)   electrical, magnetic or ultrasonic means – particles produced by using high frequency or high intensity electrical fields – high residual charges cause stable dispersion of fines. Magnetic and ultrasonic fields are also used for dispersion of weakly cemented solids, and
(iv)   chemical – fines produced by condensation of vapours, crystallization from saturated solutions, solvent penetration into cracks and grain boundaries.

Depending on the fines-generation mechanism, there may be large differences in the surface characteristics and consequently, in the flotation behaviour of the fines [28]. This theory is in agreement with collector-less flotation of sulphide minerals given earlier[23], in that apart from depending on the mineral type, flotation of fines may vary from mineral to mineral depending on the methods (conditions) used to prepare or generate the mineral particle [28].

While poor recovery of fine (<10μm) metallic particles by flotation is still under investigations, the poor recovery of coarse particles is readily explained by the inability of bubbles to bouy large particles to the top of the flotation cell [7]. This is more pronounced especially in large cells, where apart from buoyancy, the coarse particle needs to travel across the surface of the cell to the lip of the cell into the launder.

On the other hand, recovery of gangue mineral particles[45], particularly fines during flotation into the froth layer or concentrate, depend; (i) on the carry over off gangue minerals into the froth by attachment to air bubble (true flotation), (ii) suspension of gangue minerals in the water trapped between the bubbles (entrainment).

2.8   Mineral recovery by flotation

As stated before, the recovery of mineral particles into the froth product is generally seen to be caused by two different mechanisms. Hydrophobic particles are lifted to the froth bed due to their affinity for air bubbles, generally induced by addition of some reagents[46], while hydrophilic or water-avid particles are recovered by mechanical transportation or entrainment by water. The particle size dependency of the entrainment of gangue minerals has a strong and disadvantageous effect on the selectivity (or final concentrate grade) in the beneficiation of finer materials [46]. Hence, there are three challenges caused by fine-grain flotation[47]; (i) low recovery due to low flotation rates (ii) low selectivity due to entrainment and hetero-coagulation, and (iii) high reagent consumption due large surface area. Figure 2.6 below depicts mechanism of flotation[48].

Tails

↑

	→ *bubble particle collision & adhesion* →	FROTH PHASE
	→ *entrainment of pulp* →	
Feed→ PULP PHASE	→ *composite particle flotation* →	
		→*Conc*
	→ *slime-coating* →	
	→ *entrapment* →	

↑   *drainage of entrained pulp &*   ↓

← ← ← ← ← ← ← ← ←

shedding of particles due to   bubble coalescence
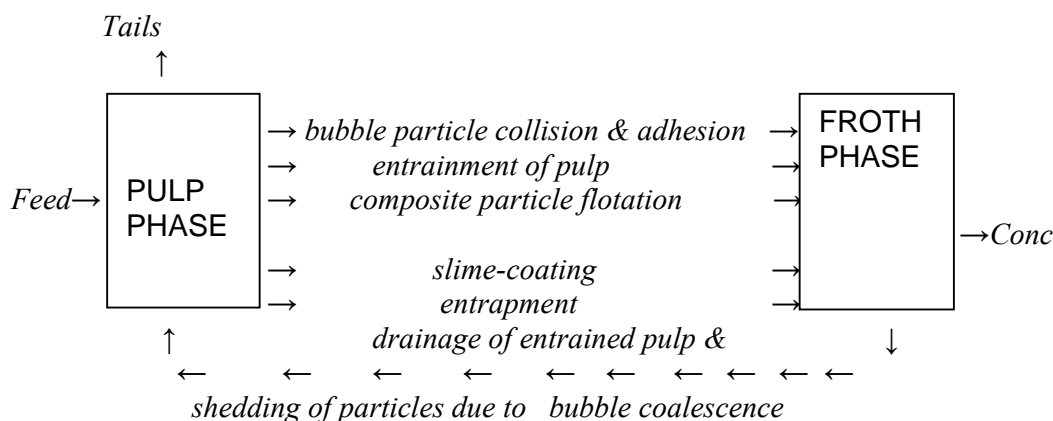
Fig. 2.6: Mechanism of flotation: Source: Osborn and Apling, 1990[48]

When mineral particles are coarse they settle rapidly and have no time to be carried into the froth by entrainment. As they become finer, particles settle more slowly and so have more time to be trapped in the froth and hence they have less tendency to drain away. Clay particles in particular, which are only a few micrometers in size, are more likely to be entrained. For these micrometer particle sizes, the rate of recovery into the froth by entrainment is equivalent to the rate of recovery of water into the froth. Several researchers[45,49] have reported that 20 percent recovery of water in the froth gives 20 percent recovery of fines in the froth too. Therefore, it can be assumed that on one hand that due to large surface area, large cells are less likely to recover finer clay particles in the concentrate depending on the frother used. But on the other hand, since fine particles are known to stabilise froth [43], and therefore it can also be seen that, in larger cells the recovery of fines in order to stabilise the froth may be higher, unless the frother being used can also play the role in stabilising the froth zone.

On one hand, it has been stated [50] that froth flotation can generally be regarded as a first-order process, with respect to the concentration of the floating species in the pulp. The usual method of expressing flotation rate is to plot cumulative percent recovery against time. If the equation was known then it could be re-plotted as a straight line and the slope of the line would be an indication of the magnitude of the flotation rate. The basis used for obtaining the equation of the recovery versus time curve is the law of mass action. This law states that the rate of a chemical reaction is proportional to the active masses of the reacting substance present at any time. This of course implies at constant temperature. This law can be modified for use in flotation by using the terms flotation reaction and floatable species instead of

chemical reaction and active masses [51]. Hence, a simple rate equation for a single floatable species can be given [48] as;

$$\frac{dC}{dt} = -kC^n \qquad [14]$$

where, C, is the concentration of particles, with identical flotation properties in the pulp, and t, is the time of flotation. The rate constant, k, is a function of many parameters or flotation conditions, such as frother concentration, with n, indicating the order of the reaction. If the exponent of C is 1, then the reaction rate is first order. If the exponent of C is 2, then a second order rate reaction exists[51]. Integration of this first order rate equation [14] for C_o, (initial concentration of particles) to C, and from zero to t, yields;

$$ln[\frac{C}{C_O}] = -kt \qquad [15]$$

Hence, a plot of $\mathbf{ln[\frac{C}{C_O}]}$ **vs t** may produce a straight line with slope k, being the rate constant

On the other hand, the use of different frothers produced changes in the flotation rate (K) and recovery (R) values, while in coal flotation earlier work had shown that for all frother types, the finest (<88μm) and the coarsest (>500μm) particles tended to float more slowly than the intermediate size particles. Hence, it has already been shown that the first order rate constant (K) for various industrial flotation cells depends on[9];

$$k = PS_bR_f \qquad [16]$$

where,
P is feed ore floatability, S_b is bubble surface area flux, and R_f is recovery in the froth phase

Alcohol frothers tend to be effective and increase kinetics of finer particles, while polypropylene glycols tend to be more effective on coarser particles, but both giving lower selectivity at higher dosages. From the above equation [16] it can be shown that if P, and R_f, remained constant, then increasing bubble surface area flux, S_b, increases the flotation rate. However, production of smaller bubbles in froth phase increases chance of recovery of finer particles[29]. But the recovery of finer particles always has a detrimental effect on concentrate grade, in that higher recovery of fines is normally associated with high recovery of water in the froth phase, and as earlier discussed, water recovery corresponds directly with gangue entrainment[49].

Hence, as stated earlier, the role of a frother should not only be limited to the formation of a stable froth, but also to (i) prevent coalesce of bubbles, (ii) control the rate at which air bubbles rise in the flotation to the surface of the pulp, (iii) increase the strength of the bubbles and the stability of froth, and (iv) affect the action of collectors, it is therefore critically important to appreciate the action of frothers.

Surfactants such as frothers help in the generation of smaller bubbles. Work done elsewhere[33] has shown that smaller bubbles create larger surface area flux and that frothers help in the formation of a stable froth, thus increasing the efficiency of the flotation process. In practice however, the stability of froth is also dependent on the content of floatable and semi-floatable particles, particularly finer particles, present in the pulp [52]. Therefore,

prevention of coalescence and creation of stable froth also helps in improving the concentrate grade.

Controlling the rate at which air bubbles rise in pulp to the surface determines the mineral recovery or recovery of valuables. The rate at which bubbles are transported through the cell, is largely influenced by operational variables of air flow-rates and froth depth and that bubble size increase through the froth zone is related to higher air residence times and therefore, higher internal coalescence probability, while conditions with lower air residence time showed less internal coalescence. In short, the influence of air flow-rate and froth depth on the bubble motion, coalescence, and air residence time has a bearing on the flotation performance or grade and recovery of the flotation process [53].

From the foregoing it is therefore, important for one to appreciate the action of a frother by understanding its bubble distribution and consequently froth formation and stability. Hence, measurements of bubble distribution froth formation and stability, could be the starting point to understanding of any frother and its effect on mineral recovery and concentrate grade. For example, the Huntsman Performance Products and team [25] have developed a frother, of polyoxyalkylene alkyl ether of low molecular weight in nature and represent a crossover from an alcohol frother to an alkyl ether in terms of chemical class and properties. They claimed that their frother offered a versatile combination of selectivity, hydrophobicity and frothing power and that it is these properties that play an integral part in its selection of any frothing reagent for use on copper ores and that the frother formulation is such that the frother has a portion of a more hydrophobic frother of intermediate strength, suitable as an alternative to alcohol-ester and alcohol-glycol ether frother blends used in copper and copper-gold processing, with improved performance characteristics (see Figure 2.7 below).
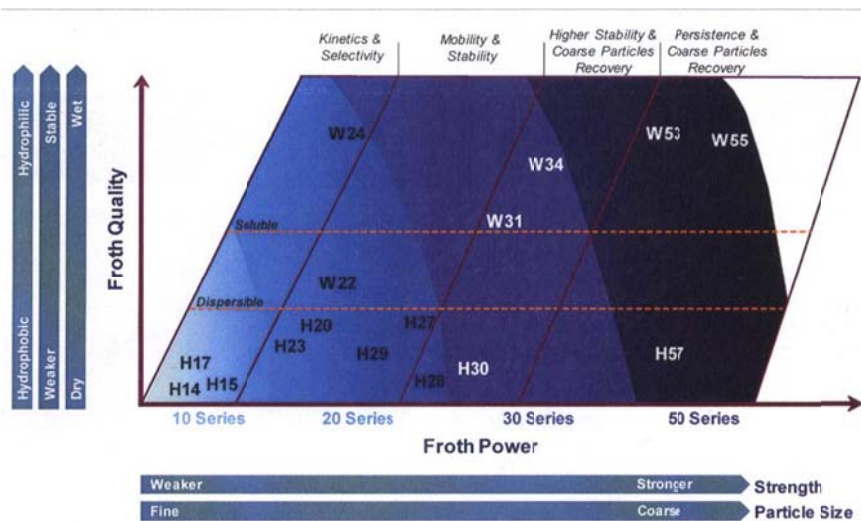
Fig. 2.7: Frother properties: Source: Aston et al, 2013[25]

In conclusion, while the primary role of the frother in froth flotation is to help maintain a stable froth on the pulp surface, recent developments in flotation research has shown that in practice, a frother may play a complimentary role to a collector in enhancing interaction between minerals and other reagents present in the pulp. Therefore, a specific frother may be employed to provide adequate physical properties to the froth, while at the same time interact with the collector to control the dynamics of the flotation process.

2.9   Properties and characteristics of frothers

Most of the developments in froth flotation have been carried out empirically. Hence surfactants used have been the cheapest ones available at that time and in a given locality. The surfactants employed have been usually extracted from vegetable or mineral oils, distilled from coal or wood, or manufactured from complex and impure industrial by-products. For example pine oil was initially used because the plant was readily available in the Western world[7].

As a result there are no standards for purity or quality, either in respect of the starting materials or the final products of reagent preparation, resulting in products or surfactants that are distributed under various proprietary names and trademarks, e.g. Aerofroth, Dowfroth, Betafroth and many more, in case of frothers. The use of trademark flotation reagent has preserved an attitude to flotation as an art and has hindered the understanding of the process for many years. However, it is only recently that the compounds behind the trade names are being disclosed and the utilization of synthetic reagents (like glycols and MIBC) of higher purity has enabled the mechanism of their action to be investigated and characterised[7].

Commercially, frothers can be classified into alcohols, alkoxy-type and polyglycols. Alcohols can be linear aliphatic, represented by MIBC, aromatic, represented by Cresylic acid, and cyclic represented by pine oil, while alkoxy-type and polyglycols are represented by triethoxybutane (TEB) and polypropylene glycol methyl ethers respectively[54].On one hand, frothers can broadly be divided into those that are slightly soluble, generally referred to as *alcohol frothers* and those that are completely miscible with water, mainly *polyglycol frothers*. On the other hand, the other type of frother is the multiple frother, generally referred to as *formulated frother*. As the name suggests, formulated frothers are products made from both alcohols and glycols in various proportions and combinations. The products are made from combinations of water-soluble glycol ethers, non-water-soluble glycol ethers, linear alcohols and branched alcohols of various molecular weights, and are therefore slightly insoluble in water[27].

2.9.1   Properties of partially soluble (alcohols) frothers

An alcohol is defined as a compound formed from hydroxyl groups attached to carbon atoms in place of hydrogen[15]. It is given a general formula of R-OH, where, R signifies an aliphatic radical. An alcohol therefore, is an organic compound in which the hydroxyl functional group (-OH) is bound to a carbon atom. In particular this carbon centre should be saturated, having single bonds to three other atoms. An important class of alcohols are single cyclic alcohols, having a general formula – $C_nH_{2n+1}OH$, of which ethanol (C_2H_5OH), is the most common alcohol, found in alcoholic beverages[55].

Simple alcohols are often referred to by common names derived by adding the word "alcohol" to the name of the appropriate alkyl group. For example a chain consisting of one carbon (a methyl group, CH_3, with an OH attached to the carbon is called "methyl alcohol" or "methanol", while a chain of two carbon (an ethyl group, CH_2CH_3) with an OH group connected to the CH_2 is called "ethyl alcohol or "ethanol". Ethanol and methanol are examples of simple alcohols. Higher alcohols are those containing 4 to 10 carbon atoms, and some what viscous or oily, with fruity odours. Some highly branched alcohols containing more than 12 carbon atoms are solids at room temperature[55].

Alcohols can also be classified into O^o, primary (1°), secondary (2°), and tertiary (3°), based upon the number of carbon atoms connected to carbon atoms that bear the hydroxyl (OH) functional group. Methanol (CH_3OH or CH_4O) is an O^o alcohol[55].

$$RCH_2OH \qquad R-\overset{\overset{\displaystyle R_1}{|}}{\underset{\underset{\displaystyle H}{|}}{C}}-OH \qquad R-\overset{\overset{\displaystyle R_1}{|}}{\underset{\underset{\displaystyle R_2}{|}}{C}}-OH$$

primary   secondary   tertiary
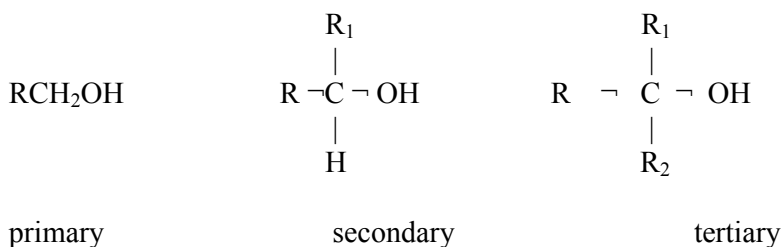
where, R_1 and R_2 $\neq$ R, whereby R is a general symbol given to any alkyl groups that are obtained by removing a hydrogen atom from an alkane.

The OH group attached to a carbon chain drastically changes the physical properties of the molecule owing to interactions via hydrogen bonding, hence referred to as *functional group*[55]. A functional group, therefore, is part of a molecule where most of its chemical reactions occur. It is the part that effectively determines the compound's chemical properties and many of its physical properties as well[55].

In general the hydroxyl group makes the alcohol molecule polar. These groups can form hydrogen bonds to one another and other compounds (except in certain large molecules where the hydroxyl is protected by steric hindrance of adjacent groups). This hydrogen bonding means that alcohols can be used as protic solvents. However, there are two opposing solubility trends; (i) the tendency of the polar OH to promote solubility in water, and (ii) the tendency of the carbon chain to resist solubility in water.

Therefore, methanol, ethanol and propanol are completely miscible in water because the hydroxyl group wins out over the short carbon chains. Butanol with four carbon chain is moderately soluble in water, because of a balance between the two trends. On the other hand alcohols of five or more carbons (pentanol and higher) are effectively insoluble in water, because of the hydrocarbon chain dominance. Also because of hydrogen bonding, alcohols tend to have higher boiling temperatures than comparable hydrocarbons and ethers. Boiling temperature for alcohol ethanol is 78.29^{o}C compared to 69°C for hydrocarbon hexane (a common constituent of gasoline) and 34.6^{o}C for diethyl ether[55].

Alcohols like water can show either acidic or basic properties at the OH group, but with pKa value of around 16-19,(i.e. pKa value being a measure of the strength of an acid on a logarithmic scale)[56], they are in general slightly weaker acids than water, though they are still are able to react with strong bases such as sodium hydrite or reactive metals such as sodium. The salts formed from such reactions are called alkoxides, with a generic formula RO^-M^+.

Alcohols can also undergo oxidation to give aldehydes, ketones or carboxylic acids or they can be dehydrated to alkenes. They can (if activated first) undergo nucleophilic substitution reactions. The lone pair of electrons on the oxygen of the hydroxyl group makes alcohols nucleophilic. As one moves from primary to secondary to tertiary alcohols with the same backbone, the hydrogen bond strength, the boiling point, and the acidity typically decrease. Primary alcohols (R-CH_2-OH) can be oxidised either to aldehydes (R-CHO) for example acetaldehyde, or to carboxylic acids (R-CO_2H), while the oxidation of secondary alcohol

(R_1R_2CH-OH) normally terminates at the ketones (R_1R_2C=O) stage. Tertiary alcohols ($R_1R_2R_3$C-OH) are resistant to oxidation[55]. Below are some of the partially soluble single alcohol frothers;

Aliphatic alcohols – mixtures of C_6 to C_8 alcohols. These are alcohols made from the three types of hydrocarbons namely; *alkanes* – made from crude oil, alkenes - made from cracking of petroleum and other crude oil fractions, and alkynes – made from heating limestone and coke in an electric furnace[57]. MIBC and aliphatic alcohols, generally referred together as *aliphatic alcohols*, were some of the widely used frothers for sulphide ore flotation[57].

MIBC, (methyl isobutyl carbinol), ($CH_3)_2CHCH_2CHOHCH_3$) -is largest volume of aliphatic and alcohol frother currently being used[9].MIBC is a higher boiling point product of butyl alcohol containing 60-65% primary alcohols (2-methyl pentanol), 15-20% secondary alcohols (di-isopropyl carbinol), and 18-20% ketones. MIBC has a density of 0.808 g/ml, freezing point of -90°C, boiling point of 132°C and a solubility of 17.0 g/l in water[58]. The use of MIBC and aliphatic alcohols in froth flotation gives rise to a fine textured froth. Fine textured froth is good for rejection of slimes, and therefore MIBC is good for ores containing slimes[7].

Pine oil and *eucalyptus oil* are some of the natural oils. Pine oil is obtained by fractional distillation (at between 170°C and 220°C) of raw turpentine, which in turn is extracted from crude pine tar with benzene. The product is yellowish in colour and transparent with an odour of turpentine. Pine oil contains at least 44 percent of aromatic alcohols, terpineol, $C_{10}H_{17}$OH, (the most active frothing compound of pine oil), and others are phenols, organic acids boryl acetate. Chemically, pine oil consists mainly of cyclic terpene alcohols, and is therefore an example of cyclic alcohols. It may also contain terpene hydrocarbons, ethers and esters. It has a specific gravity of 0.915-0.935 and boils at 170°C and flashes at 172°C and distillation range is 200 - 235°C[58].

The exact composition of pine oil depends on various factors such as the variety of pine it is produced from and the parts of the tree used. Hence the disadvantage of pine oil is its inconsistent composition. It is difficult to obtain a completely identical reagent from various producers. A typical assay of commercial pine oil is; alpha terpineol 60 -70%, tertiary alcohols 10%, borneol and fenchyl alcohol 10 -5%, and camphor 10 -15%. In flotation, pine oil like other natural oils has collector properties and provides mostly viscous stable-close knit froth. Because of having collector properties, pine oil and other natural oils have made themselves less popular in modern mill operations, in favour of MIBC and other synthetic non-collecting soluble frothers. When used with amyl xanthate, pine oil frother produces strong frothing properties, but in the presence of sulphide minerals, the frother tends to produce little or no froth and only a thick dry film of mineral will float[9].

On the other hand, *eucalyptus oil* frother as the name suggests is obtained from the eucalyptus trees. Eucalyptus oils have greater collector action than pine oils because they are richer in ketones than pine oils[9]. Typical eucalyptus oils available today have specific gravity of 0.921 – 0.923 at 25°C, with a distillation range of 174 – 177°C. The eucalyptus oil frother is widely used in the flotation of oxide copper minerals[14]. And because of its higher collection power, recent studies[59]have showed that eucalyptus oils have potential to be used as collector in fine gold flotation.

Cresylic acids,$CH_3C_6H_4OH$– products of coal tar distillation or derivatives. Cresol or Cresylic acid is produced from distillation (between 190 – 235°c) of raw coal tar from light

creosote oil fraction. Cresol used for flotation has three isomers; paracresol, orthocresol and metacresol containing considerable amounts of neutral hydrocarbons, phenols, oxylol derivatives and higher aromatic hydrocarbons. Metacresol is the most active frother of the three cresol isomers[58]. A typical specification of flotation grade Cresylic acids is: distillation range of 190 – 235°C, density, 1.01 to 1.04 g/ml and solubility in water of 1.7g/l, and boils between 220 -250°C[57]. Cresylic acids are examples of *aromatic alcohols*.

Cresylic acids have the same quality problems associated with pine oil, since these products are all industrial products distilled from impure starting materials (coal tars). In addition they have collecting properties and therefore their use has declined over decades in sulphide ore flotation in favour of MIBC and synthetic non-collecting soluble frothers, though both Cresylic acids and pine oils are still popular in coal flotation[9]. Both pine oil and Cresylic acid had dominated frother use in the first 40 years of flotation, but their world-wide use today is limited[60]. However, Cresylic acid unlike pine oil gives less viscous but stable froth of large bubble size, with the lower boiling fractions producing a more fragile froth and but is more selective[7].

Alkoxy paraffins were developed in South Africa by Powell (1951), and the best known is triethoxybutane or TEB and the Powell Accelerator. Both TEB and Powell Accelerator have similar characteristics of low water solubility, good stability and a strong effect on flotation rate[9].

From the foregoing, it is clear that one of the major properties of alcohol frothers is generally their low solubility in water. This property led to earlier assumption that all effective frothers should have limited solubility and should produce large volumes of froth endowed with appropriate froth stability. But this premise has been reversed by the synthetic or completely soluble (glycols) frothers that have proved that ability to produce a voluminous and stable froth is not synonymous with a satisfactory behaviour of a good frother[9,18].

2.9.2 Properties of completely water miscible (glycols) frothers

An insoluble long chain alcohol can be converted into a soluble non-ionic surfactant by an addition of ethylene oxide to the hydroxyl group of the alcohol, initial reaction being[55];

$$ROH + H_2C \!\!-\!\! CH_4 \rightarrow ROC_2H_4OH$$
$$\backslash \;\; / $$
$$O$$
alcohol   ethylene oxide   oxyethylene ether
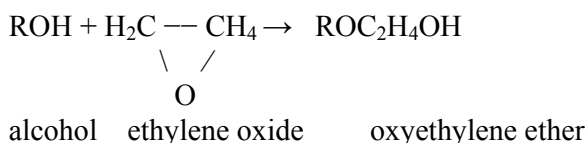
A further reaction with additional ethylene oxide produces polyoxy-ethylene ethers;

$$ROC_2H_4OH + n\,[H_2C - CH_2] \rightarrow R\,(OC_2H_4)_n \bullet OC_2H_4OH$$
$$\backslash \;\; / $$
$$O$$
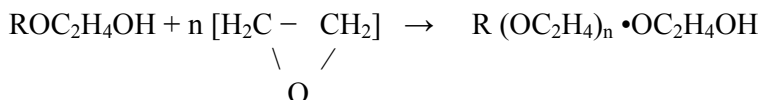
Ethylene oxide will react with any material containing an active hydrogen, thus in addition to alcohols ethylene oxide can react with any amphipatic molecule (surfactant) such as fatty acid, alkyl phenol, mercaptan, alkyl amide, or alkyl amine can be used as a starting material for condensation with ethylene oxide to give non-ionic surfactant[7].

Most of the non-ionic compounds so produced commercially find their applications in formulations of detergents, emulsifiers, cosmetics, food additives and many more applications. But in froth flotation, there are three major polyoxypropylene glycol frothers which find increasing use. These are Dowfroth 450, 250, and 200. They represent compounds of approximate molecular weights 450 g/mol, 250 g/mol and 200 g/mol and are prepared by reacting propylene glycol, $OH - CH_2 - CH_2 - CH_2OH$, with the appropriate number of moles of propylene oxide (three for D250) or condensing propylene oxide on methyl alcohol[9].

Polypropylene glycol ethers are completely miscible in water and were first developed by Tvester (1952)at Dow Chemical Company and Booth (1954) at American Cyanamid Laboratories. Polyglycol ethers were initially produced as by-products of synthetic brake fluids. Polypropylene frothers were initially marketed by Dow Chemical Company under trade name of Dowfroth and by Cyanamid as Aerofroths. Dowfroths are designated by numbers that are proportional to the polymer's molecular weight, thus higher molecular weight products are more powerful frothers, such as Dowfroth 450. As stated earlier, Dowfroth 200, 250 and 450 have molecular weights of approximately 200 g/mol, 250 g/mol and 450 g/mol respectively.   The Dowfroths series are methoxyl polypropylene glycols (polypropylene glycol methyl ethers) with general formula,CH_3-$(O$-$C_3H_6)$ $_n$-OH[9].

Dowfroth 250, with formula *CH_3-$(OCH_2$-$CH)$-OH,* is typical glycol frother used for flotation of copper sulphide ores and is made up by mixing of various propylene glycols. It is a middle to high molecular weight frother (C_3, C_4, C_5 and C_6). Dowfroth 250 is made up of polypropylene glycol methyl ethers [61]. It has the following physical and chemical properties; form: clear liquid, colour: amber to brown, odour: ethereal, boiling point/range (ºC):282, freezing point/range (°C):-50, flash point (°C):143 (PMCC), vapour pressure (mbar):<0.01, density (g/cm³ at 25ºC):0.97, water solubility: miscible in all proportions[61].

Dowfroth 200 is a popular frother used mainly in the flotation of ore containing semi-floatable gangue such as talc and micas, as is the case with many of the platinum deposits found on the Zimbabwean Great Dyke and the South African Bushveld Complex. Because it is a lower to middle molecular weight glycol frother (C_2 and C_3), it gives a fine and fragile or brittle froth, thus increasing flotation kinetics (improving recoveries) and rejecting gangue (producing a cleaner concentrate). Dowfroth 200 is prepared by mixing tri-propylene glycol methyl ether with di-propylene glycol mono-methyl ether and has the following physical and chemical properties; form: clear liquid, colour: colourless, odour: ethereal, boiling point/range (ºC):142–147, freezing point/range (°C):-20, flash point (°C):116 (PMCC), vapour pressure (mbar):<0.01, density (g/cm³ at 25ºC):0.965[62].

As mentioned above, during flotation Dowfroth 200 gives a fine, fragile froth, while Dowfroth 250 gives a slightly more stable froth than Dowfroth 200[7]. Generally, polypropylene glycols produce lasting froth structure that break down readily in the flotation cell launders, unlike the partially soluble frother.

2.9.3   Comparison between alcohol frothers and synthetic frothers

The synthetic polypropylene (glycol) frothers, have several advantages over original industrial products like pine oil and cresol, in that their compositions are much more stable, which makes them easier to control flotation processes and improves process performance. As mentioned earlier, these synthetic frothers including MIBC, are effective in process

control and have replaced natural products in most sulphide ore flotation processing plants and therefore are widely used around the world[60]. In the flotation process control, a synthetic frother has the following advantages over their alcohol counter-parts; (i) its effectiveness as collector is negligible, (ii) it is possible to increase frother dosage without also changing the quantity of collector in the system. This in turn makes the flotation process much easier to control, and (iii) it produces lasting froth structure that break down readily in the flotation cell launders.

Work done on coal flotation[63], but very relevant to sulphide ore flotation too, has shown that alcohol frothers tend to be effective for fine particle recovery than for coarse particles recovery. To recover coarser particles the alcohol frothers and collectors need to be used at higher dosages. However, overdosing of alcohol frother on the one hand lead to a slower flotation rate, because excess frother leads to destabilised froth. On the other hand, high molecular weight propylene glycol frothers and some combinations of glycol-alcohol frothers are more effective for coarse particle flotation than alcohol or lower molecular weight glycol and therefore could be used at lower dosages[9].

On sulphide copper ores, average amounts used for each type of frother or consumption rates of up to 160g/tonne for alcohol or some partially soluble frothers, while those made from polypropylene glycol esters or water miscible frothers have lower consumption rates around 60g/tonne, depending on the ore type[14]. It can therefore be deduced that glycol frother consumption rates are roughly half that of alcohol frother rates. The major reason why glycol frothers give lower consumption rates compared to alcohol frothers is because of the fact that glycol frothers are completely miscible with water. In the plant situation the process water returning to the plant contains certain quantities of residual frother thus reducing addition quantities of fresh frother[33]. Table 2.1 below shows some characteristics of some alcohol and poly-glycol frothers.

Table 2.1: Frother characteristics: Source: Crozier, 1992[9]

Frother	Froth characteristics	Applications/comments
Pine Oil	Viscous stable froth	Recovery problems with sulphides
MIBC	Fine textured froth	Good for fine ores
TEB	Fast-acting effervescent	Secondary frother-good for grades
Cresylic acid	Large bubbles non-selective	Coal/iron ore, cheap cost
Poly-glycols	Compact, long-lasting froth	Selective sulphide flotation

However, regardless of the type of frother (glycol or alcohol), increasing frother dosage to increase recovery always results in poor selectivity, and that the answer lies in finding an optimal frother for both high recovery and good selectivity. This frother, should often be a blend of the various frother classes. And that such a frother blending will give enough benefit to be worth the effort[63].

2.9.4   The background to formulated frothers

The use of multiple (formulated) frothers was supported as early as in the 1960s, by the claim that a reagent can be an effective frother when it has at least six carbon atoms in its non-polar group and that use of frother in combination may give better results[58]. History, has shown that while pine oil and Cresylic acids dominated frother usage in the first 40 years of flotation, today very small amounts are used as single frothers in the flotation of sulphide ores, but in combinations with other frothers such as polypropylene glycols[9].

Table 2.2: The frequency of single frother use in the USA mines, Source: Crozier, 1992[9]

Single frother	1960	1975
Frequency	(%)	(%)
Pine oil	17	15
Cresylic acid	11	2
MIBC	14	29
Higher alcohols	3	0
Polyglycol ethers	21	11
TEB	8	2
Subtotal	74	59

Table 2.2 above shows that overall use of single frothers in US mines decreased from 74% use in 1960 to 59% use in 1975. On the other hand, Table 2.3 below shows that multiple frothers use increased from 18% to 37% in the same period. The driving force was primarily due to improved operating stability and enhanced recoveries and to lesser extent reduced reagent costs arising from the use of multiple frothers[9].

Table 2.3: The frequency of multiple frother use in the US mines; Source: Crozier, 1992[9]

Multiple (formulated) frother	1960	1975
Frequency	(%)	(%)
Polyglycol ethers plus Pine Oil	5	13
MIBC plus Pine Oil	5	5
Cresylic Acid	3	4
Polyglycol ethers	0	11
Pine Oil plus Cresylic Acid	5	0
Polyglycol ethers plus MIBC	0	4
Subtotal	18	37

In case of the Zambian Copperbelt flotation plants, it can be seen from Table 2.4 below that by 1985 almost all frothers that were being used were single alcohol or glycol frothers. The same Table 2.4 goes on to show that by 2012 ore head grades on the Zambian Copperbelt had significantly dropped from the an average of 2.7%TCu in 1985 to around 1.6%TCu. The drop in head grade of the ores was accompanied by increased use of multiple or formulated frothers[64].

Table 2.4: Copperbelt ore grades and frother use in 1985 and 2012, Source: Crozier, 1992[9] & Plant data sheets, 2013

Year	1985	2012	1985	2012
Mine	Ore grade (%Cu)		Frother name	Frother name
Nchanga	3.5	1.5	TEB	Betafroth 245
Nkana	1.9	1.4	TEB	Sasfroth 2040
Mufulira	2.5	1.5	Dowfroth 250	Betafroth 65
Luanshya	1.8	1.4	D14	Pine Oil
Konkola	3.0	2.5	Pine Oil	Betafroth 245
Chibuluma	2.0	2.0	MIBC	Betafroth 100
Chambishi	2.7	1.5	MIBC	Pine Oil
Kansanshi	N/A	0.6	N/A	Aerofroth 68
Lumwana	N/A	0.5	N/A	Interfroth 50
Lubambe	N/A	1.9	N/A	Profroth 200
Average	2.7	1.6	Single frother	Multiple frother

2.9.5   Properties of formulated frothers

As earlier stated, frother formulations can start with the number of carbon atoms in the hydrocarbon chain. Hence, an alcohol with carbon atoms in the alkyl group or chain has a pronounced effect on the froth properties of an alcohol frother up to six or seven carbon atoms, though the properties drop drastically when the alcohol has more than 8 carbon atoms[58]. Some studies[65] have showed that a reaction of a six carbon alcohol with specified amount of propylene oxide gives an unusually strong frother (polypropylene) with an enhanced ability to float coarser particles. Similar work done elsewhere [66] also showed how floatability of galena improved from as low as 10% galena recovery using an alcohol frother with two carbon atoms to as high as 80-90% galena recovery when the number of carbon atoms in the alkyl chain were increased to four and five respectively.

However, further work[65] demonstrated that on the other hand, increasing the branching of the alcohol backbone gradually decreases the effective particle size range floated by the six-carbon propylene oxide product. The work went further to conclude that specific frother chemistry has unique particle size range, and that alcohol frothers were more selective, especially with finer particles. Though alcohol frothers may give higher concentrate grades on flotation of finer ores, they are always slower in flotation rates than the polypropylene glycol frothers, over all mineral particle sizes, especially the coarser sizes. As a result, the benefits of blending frothers to improve overall valuable mineral recovery and concentrate grade becomes obvious[9].

On chemical blends or mixtures, a Europe-based chemical manufacturer, CLARIANT claimed that most of their products are currently being sold as "smart mixtures" or formulations as opposed to pure products because they are designed to do specific jobs as effectively and cost effective as possible. They went further to state that product formulation is more than just science, it is the fine art of developing perfect mixtures and smart products that may help bring out the best in chemicals and outperform the products from which these chemicals are made[67]. Hence formulated products, in physical metallurgy could be compared to *alloys* that are normally made to out-perform the pure products from which they are created.

Similarly, formulated frothers are frothers made from a combination of water-soluble glycol ethers, non-water-soluble glycol ethers, linear alcohols and branched alcohols of various molecular weights and designed for specific flotation plants, based on ore mineralogy and plant operating practice of the processing plant, such as the use of large cells. Hence, formulated frothers are usually customer-made to meet specific requirements of the flotation plant such as ore type, ease breakage in launders, persistence in cleaner circuit, targeting bubble size distribution in flotation cells to maximise particle-bubble contact. Therefore, frother formulation is supposed to help solve product problems, increase yield, cut costs and improve overall plant efficiency[27].

For example, in most cases a frother containing at least a portion of an alcohol (MIBC or pine oil) and a higher molecular weight polypropylene glycol (Dowfroth250), can be a best match to a collector, since it will modify the physical properties of the frother in order to produce a froth with bubbles suitable when coarser ore particles are to be floated[7].Hence, formulated frothers can be classified either as alcohol-based or glycol-based, depending on whether alcohol or glycol is the main constituent of the frother.

Betafroth 20 is a higher molecular (C_7, C_8 and C_9) alcohol-based frother. The frother consists of about 70 percent higher molecular weight aliphatic alcohols, some Cresylic acids and pine oil, with the rest being middle to higher molecular weight polypropylene glycols**.** According to the manufacturer's Material Safety Data Sheet (MSDS), the frother is made up of the following compounds; polyglycol alkyl ether, 2-ethylhexan-1-ol, aliphatic alcohols, dialkyl dithiophosphate, mono-(ethyl-thio)octane and sodium methoxide. The frother has the following physical and chemical properties; form: liquid, colour: honey to colourless, odour: alcohol like–ethereal, freezing point (°C) :<0, flash point (°C):82 (Setaflash CC), density (20ºC):0.93 gm/cm³, water solubility (20ºC) :approx. 25g/l, viscosity (mPa.s 20ºC) :15 (MSDS)[68].

Betafroth 245 is middle to higher molecular weight glycol-based frother with middle to higher molecular weight alcohols (C_2, C_3, C_4 and C_5). Sometimes the frother might have some pine oils and others with a light alcohol such as MIBC depending on the type of gangue encountered. According to the manufacturer, MSDS, the frother has a particular distribution of methyl ethers with a small proportion of sodium methoxide for control of calcium ion activity. The frother Betafroth 245 is prepared by mixing di-propylene glycol mono-methyl ether, tri-propylene glycol mono-methyl ether, polypropylene glycol mono-methyl ether, sodium methoxide and aliphatic alcohols. It has the following physical and chemical properties; form: liquid, colour: dark brown, odour: ethereal, pH:12 – 13.5, melting point (°C):< 0, freezing point (°C):< 0, boiling point (°C):> 130, flash point (°C):140 (PMCC), vapour pressure (mmHg):< 2000, density at 25°C):1, water solubility:> 95%, viscosity (CSt at 20°C):60 (MSDS)[69].

Formulated frothers are supposed to provide superior flotation performance compared to both pure alcohols and pure glycols as a result of the frothers being made from a combination of water-soluble glycol ethers, non-water-soluble glycol ethers, linear alcohols and branched alcohols of various molecular weights. The low molecular weight portion of the formulated frother produces a mobile froth, which directly leads to higher recoveries, compared to the norm. The mid-to-high molecular weight fractions gives froth bubble wall strength and leads to water drain back and thus reduced entrainment of gangue to the sulphide concentrate. The glycol portion gives the frother a water miscible characteristic that leads to lower frother consumptions. The low to middle molecular glycols make the frother mobile and brittle, thus

increasing flotation kinetics (improving recoveries) and rejecting gangue (producing a cleaner concentrate). On the other hand, higher molecular weight alcohols and glycols provide frother strength by giving bubble stability[27].

CHAPTER THREE

3.0   RESEARCH METHODOLOGY

The research design was generally of quantitative nature and involved carrying out several bench scale flotation experiments by testing a total of six frothers (two formulated frothers, two alcohol frothers and two glycol frothers) on Lumwana and Kansanshi mine ores which are predominately chalcopyrite in nature in order to come up with some flotation response of the ores and characteristics of the frothers.

Froth flotation is influenced by a large number of factors. Some of the important chemical factors include collectors, activators, frothers, pH modifiers and depressants. Other factors are water quality, milling media, pulp temperature and the nature of gangue and ore minerals. These factors need to be understood in order to establish their extent of influence on the flotation process in general and in the flotation of copper ore in particular. These parameters which are of critical importance to a particular system have to be optimised for each ore or feed material individually. In this work however, only two parameters (i.e. frother dosage and mesh of grind of the ore) were optimised, while assuming the rest of other parameters remained constant.

3.1   Experimental design

The first set of experiments conducted, were to show the effect of frother dosage and grinding time on the two sulphide copper ores. Due to the large number of experiments to be conducted an experimental design was therefore conducted to determine the number experiments to be carried out. An experimental or factorial design is an important method to determine the effects of multiple variables on a response. Factorial design can reduce the number of experiments one has to perform by studying multiple factors simultaneously. Additionally, it can be used to find both main effects (from each independent factor) and interaction effects (when both factors must be used to explain the outcome)[70]. The first set of flotation experiments were done to show the effects of frother dosage and grinding time on the flotation response of Lumwana and Kansanshi ores in terms of concentrate grades and copper recoveries.Therefore, in order to design this experiment, there was need to determine how many different experiments would need to be performed. From the experimental design it can be seen that there are two different factors, frother dosage and grinding time. For each factor, there exist three different levels, (i.e. three frother dosages and three grinding times). Thus, a 3^2 factorial design experiments were conducted, which gave nine different experiments for each frother to be tested. Since the work involved testing a total of six different frothers, 54 different experiments were conducted (see Appendix II).

The second set of experiments were conducted to show the effect of flotation time on copper recoveries and concentrate grades(i.e. flotation kinetic tests) at the optimised conditions for each ore in order to come up with some flotation kinetics trends. And the final set of experiments involved investigating the frothing characteristics of the six frothers under study. This was achieved by conducting surface tensions measurements, bubble size analysis, froth stability and water recovery tests.

Therefore, a total of six frothers were tested in this work. From the six frothers, pine oil and MIBC came from the alcohol family, while Dowfroth 200 and Dowfroth 250 were from the glycol family. The other two products were formulated frothers, namely, Betafroth 20 and

Betafroth 245. Betafroth 20 is an alcohol-based frother, while Betafroth 245 is a glycol-based frother, meaning Betafroth 20 is made up of more than 50% of alcohols of various molecular weights and Betafroth 245 consists more than 50% of glycols of various molecular weights too.

In first and second set of experiments one percent solution of a single xanthate collector technically known as Betacol 381 (i.e. a mixture of sodium isopropyl xanthate (SIPX) and sodium ethyl xanthate (SEX) in equal proportions) was used. Results obtained from the two formulated frothers were then compared to those obtained from single or pure products (alcohol and glycol frothers) in order to see trends in the flotation response of the ores. All the chemical samples used in the flotation testwork were supplied by Betachem (Pty) Ltd.

3.2   Experimental procedures

3.2.1   *Sample preparation (standard) procedure*

Two separate 100 kg sample representing Lumwana and Kansanshi ores were obtained from Lumwana and Kansanshi mines respectively for the laboratory metallurgical experiments. The samples were received from the respective mines already reduced to less than 6mm in size.

To prepare the sample for metallurgical experiments, coning and quartering procedure was used for each ore sample, to produce six parent samples for each frother type. Thereafter, 1kg sub-samples were produced using the Jones riffle sampler, before further dividing the samples into 0.5 kg sub-samples for use in individual batch scale flotation test. Each 0.5kg sample was milled at 66% solids pulp using 300ml of tap water. The milled ore sample was placed into a 2.0-litre cell for optimisation tests conducted at the University of Zambia and 2.5-litre cell for water recovery tests conducted at the respective mine sites.

3.2.2 *Lumwana and Kansanshi ore flotation optimisation testwork procedure*

All the optimisation flotation tests were carried out at room temperature in a 2-litre flotation cell using the self-induced air DENVER flotation machine set at a maximum impeller speed of 1200rpm. The ore was floated at the pulp pH of University of Zambia main campus tap water of pH 8.0. The frother optimisation work was conducted by testing the six frothers at three different concentrations or dosages of 40g/t, 60g/t and 80g/t, while grinding time optimisation was carried out by milling for 15 minutes, 30 minutes and 45 minutes for Lumwana ore, and 5 minutes, 10 minutes and 30 minutes for Kansanshi sulphide ore, resulting in a mesh of grind of 55%, 65% and 80% passing 150μm respectively. The experiments were carried out as shown below in Figure 3.1;
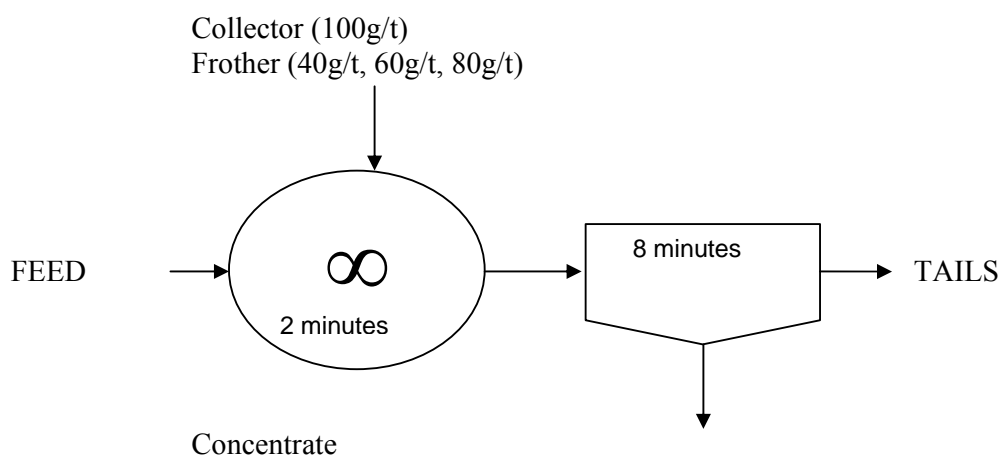
Fig. 3.1: Lumwana and Kansanshi ore standard flotation optimisation flowsheet

The flotation products (concentrates and tailings) were filtered, dried, weighed and analysed for total and acid soluble copper.

3.2.3   Lumwana and Kansanshi ore kinetic flotation testwork procedure

After establishing the optimal flotation conditions for each ore (i.e. 60g/t frother dosage and grind of 65% passing 150µm for Lumwana ore and frother dosage of 80g/t and grind of 80% passing 150µm for Kansanshi ore), further work in terms of determination of flotation kinetics for each frother was conducted. In the flotation kinetics work all tests were conducted in duplicate. Below is the flowsheet showing how the experiments were conducted;
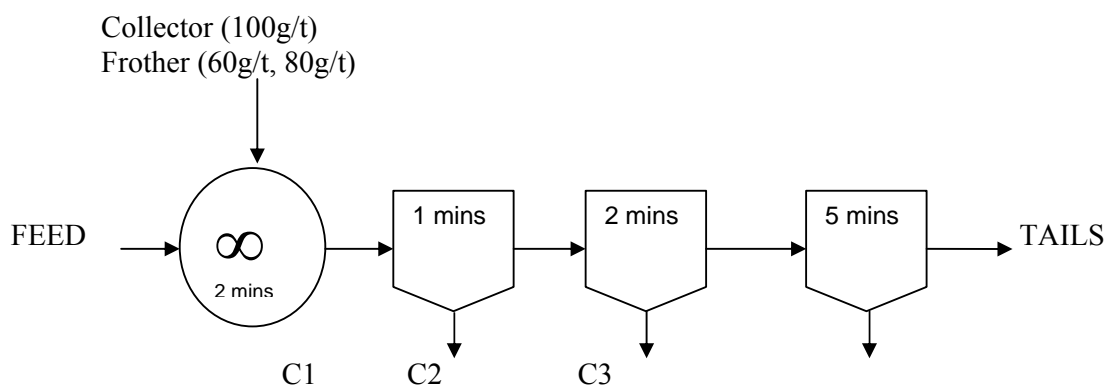
Fig. 3.2: Lumwana and Kansanshi ore standard kinetic flotation flowsheet

The flotation products (concentrates and tailings) were filtered, dried, weighed and analysed for total and acid soluble copper.

3.2.4   Lumwana and Kansanshi ore water recovery flotation testwork procedure

All the water recovery flotation tests were conducted at the respective mine sites; (i.e. Lumwana and Kansanshi mines). For each test, milling was carried out using a 1kg sample and 600ml of water. A WEMCO flotation machine was used at impeller speed of 850rpm. The ores were floated using respective mine process water of nature pH of around 8.0. As in

kinetic flotation testwork, the water recovery tests were also conducted at 60g/t and 80g/t frother dosage and grind of 65% and 80% passing 150µm, for Lumwana and Kansanshi ores respectively. All tests were conducted in duplicate.
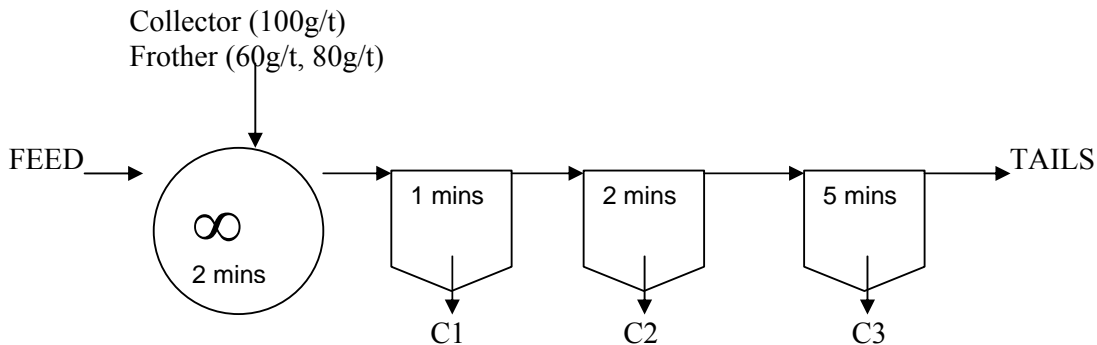

Fig 3.3: Lumwana and Kansanshi ore standard water recovery/kinetic flotation flowsheet

The flotation products (concentrates and tailings) were wet weighed, filtered, dried, weighed again andthen analysed for total and acid soluble copper.

3.3   Experimental equipment

The following are some of the equipment and procedures used to carry out the experiments and tests;

3.3.1   Laboratory ball mill

Laboratory milling was achieved using a 20cm by 18cm stainless steel ball mill with mixed sizes of ball bearings (1.0cm, 1.75cm, 2.5cm and 3.0cm) as standard charge weighing approximately 6.5kg. Each 0.5kg sample was milled at 66% solids pulp by using 300ml UNZA tap water.

3.3.2   Laboratory standard screen sieves

Screening was carried out using the British Standard BSS 410 series. The following sieves with corresponding openings were used; 300, 212, 180, 125, 90 and 63 microns.

3.3.3   Heaters and digesters

A 1g flotation product sample (feed, concentrate and tailing) was heated to $150^{\circ}C$ and digested using 30ml of aqua regia (i.e. a mixture of 3 parts of hydrochloric acid (HCl) to 1 part of nitric acid (HNO_3) for ten minutes or near dryness, before filtration and dilution.

3.3.4   Atomic absorption spectrophotometry (AAS) for elemental copper analysis

The filtrate of each sample was diluted with distilled water to 100ml volume and copper determination was carried out using the atomic absorption spectrophotometry (AAS) using the SPECTRA 50 MODEL at the Geo-chemical laboratory based at the University of Zambia, School of Mines.

3.3.5 Surface tension measurements using the ring method

Two-phase (water-air) measurements of the surface tension at varying frother concentrations were conducted at University of Cape Town, Centre for Mineral Research laboratories using Tensiometer (Figure 3.4) below, interfaced to a computer. Surface tension measurements were taken using the *Tensiometer* at the following frother concentrations; pure distilled water (zero), 6.25ppm, 12.5ppm, 25ppm, 50ppm and 100ppm. The computer software allowed the Tensiometer to take ten readings of each dilution before the mean and standard deviations were automatically calculated. Depending on the value of the standard deviation the tests were repeated (see Appendix VI).

Fig.3.4: Tensiometer – balance for surface tension measurements (UCT)

3.3.6 Froth stability testwork using the Bikerman column flotation cell

Two-phase (water-air) measurements using simulated plant water were conducted using the Bikerman column cell at various frother concentrations. The following frother concentrations were tested; 50ppm, 100ppm, 150ppm, 200ppm and 300ppm. For each test the froth height and collapse rate or reaction time were recorded. Each test was conducted in triplicate and the average was used (see Appendix V).

Fig. 3.5: The Bikerman flotation column (UCT)

3.3.7   Bubble size measurement using the UCT bubble size analyser

The *UCT bubble size analyser,* developed by the University of Cape Town, consists of a glass capillary placed inside a glass column, which is filled with the solution of interest, a detector head which contains two optical detectors mounted at right angles to each other, detector electronics, a microprocessor interfaced to a computer, a peristaltic pump and a gas burette[49].

Fig 3.6: The UCT bubble size analyser (UCT)

Two-phase (water-air) measurements of bubble size distribution using the UCT bubble size analyser as shown in Figure 3.6,at different frother concentrations were conducted. In all experiments synthetic or plant simulated water was used. Synthetic water is water made up in the laboratory by using various salts to simulated quality of plant water. Bubble size measurements were taken at the following concentrations, 5ppm, 12.5ppm, 25ppm, 50ppm and 100ppm. The computer software allowed for four repeats before calculation of the mean bubble size (mm), number of bubbles involved in the measurements and the standard deviation of the data (see Appendix VII).

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

This chapter presents experimental results and interprets these primary findings by linking them to the secondary findings covered in the literature review. The linkage between primary and secondary findings is discussed in such a way as to assess the extent to which the objectives of the study have been attained.

4.1 Mineralogical examination of Lumwana ore

Mineralogical examination of the Lumwana (Chimiwungo) ore sample was conducted at Alfred H Knight (Zambia) Ltd and the ore mineralization was confirmed as being; (i) 85% of the total copper in Lumwana ore was mostly chalcopyrite with lesser amounts of bornite and chalcocite, (ii) 13% of the total copper was acid soluble derived mainly from malachite and chrysocolla, and (iii) the major gangue constituents were quartz and feldspar (62%) and micas at 34%.The copper mineralisation and properties of the two ores were determined as shown below [71];

Table 4.1: Lumwana and Kansanshi copper mineralisation and ore properties, Source: Alfred H Knight, 2013[71]

Mineral Percentage	Lumwana ore (%)	Kansanshi sulphide ore (%)
Chalcopyrite	0.31	0.41
Bornite	0.13	0.01
Chalcocite	0.08	0.01
Covellite	0.01	0.01
Native copper	-	0.01
Malachite	0.06	0.06
Chrysocolla	0.02	-
Total	**0.60**	**0.51**
Ore properties		
Specific gravity (gcm^{-3})	2.80	2.74
Work index (kwh/t)	13.0	8.12

Thin sections of Lumwana ore were examined under a reflecting microscope and the copper mineral (chalcopyrite) was observed to be occurring within muscovite-phlogopite-quartz-kyanite schists. The texture of the ore is mainly foliated-schistose medium to coarse grained. The mineralisation was mainly of biotite, chlorite and seniate schist. Very little copper minerals were seen disseminated within the gangue. This may explain the coarse grind of p80<280µm,the ore undergoes before flotation in the plant situation in order to liberate the copper bearing minerals (Figure 4.1).
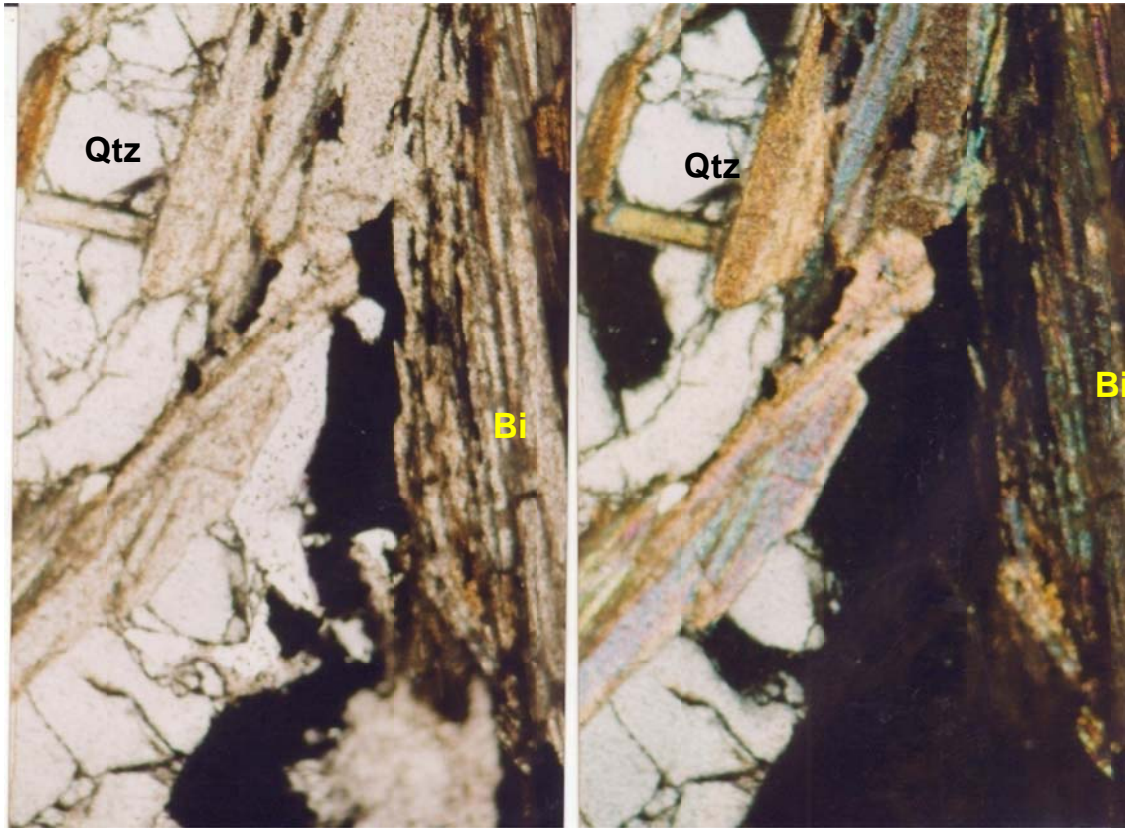
Fig.4.1: Photograph of biotitic schist showing schistose texture - the rock is medium-to coarse-grained, with schistose texture, the schistose texture is shown by the parallel for Lumwana ore.

4.2   Optimisation of the mesh of grind for Lumwana ore

The optimization of Lumwana ore was conducted by firstly determining the mesh of grind of the ore in the laboratory, while bearing in mind that the optimum particle size for Lumwana ore on the flotation plant was only p80<280μm. The ore sample was subjected to grinding times of 15 minutes, 30 minutes, 45 minutes and 60 minutes. The milled samples were, screened using the British Standard BSS, 410 series. The results of the screen analysis obtained (see Appendix I) are presented below;
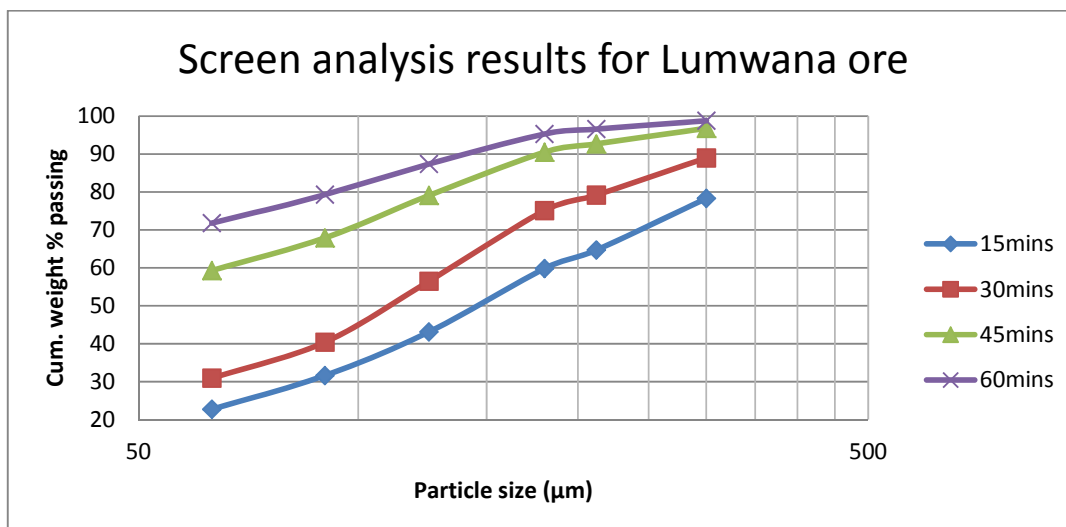
Fig.4.2: Results of screen analysis obtained at different grinding times for Lumwana ore

From Figure 4.2 above, it can be seen that the 15minutes grinding time gave a mesh of grind of 55% passing 150μm (p80<300μm). The 30 minutes of grinding achieved a mesh of grind of 65% passing 150μm (p80<225μm), further milling for 45 minutes gave 85% passing 150μm (p80<125μm), while a mesh of 90% passing 150μm (p90<100μm) was achieved after milling the ore for 60 minutes.

4.3   Flotation response of Lumwana ore to frother dosage and grind

Bench-scale flotation tests were designed and conducted using 15 minutes, 30 minutes, 45 minutes and 60 minutes grinding times and frother dosages of 40g/t, 60g/t and 80 g/t while holding the collector (xanthate) constant at 100g/t. For each test a single concentrate was collected for a period of eight minutes by scrapping the froth off every 15 seconds, after conditioning for two minutes. The flotation performance in terms of copper recoveries and concentrate grades obtained were used to plot graphs below.
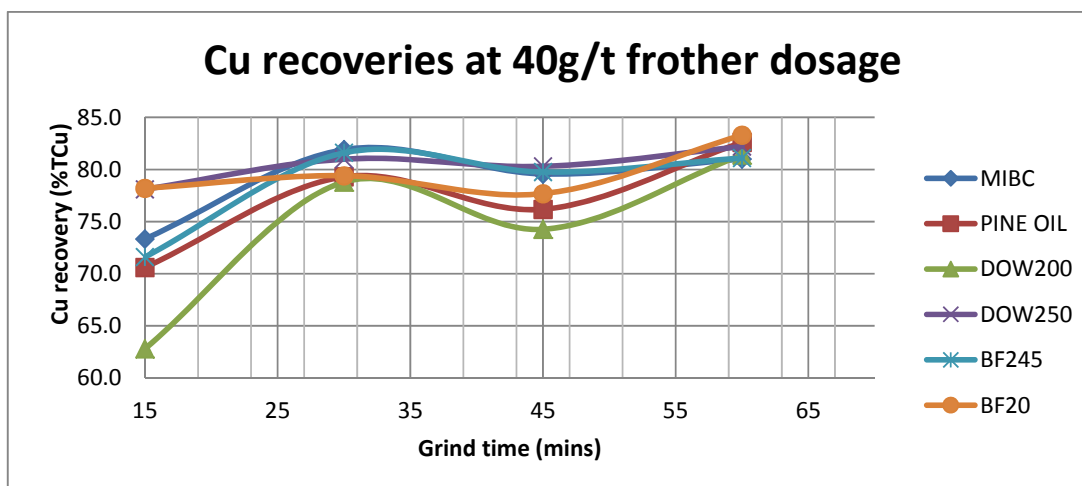

Fig.4.3:   Response of flotation recoveries to grinding time while maintaining a frother dosage of 40g/t on Lumwana ore

From Figure 4.3 above, it can be seen that at frother dosage of 40g/t, the best copper recoveries of 83%TCu (total copper) were obtained at a grind of 90% passing 150μm, using Betafroth 20 and pine oil followed by Dowfroth 250 (82%TCu). The rest of the frothers (Dowfroth 200, Betafroth 245 and MIBC) gave lower recoveries of around 81%TCu each.
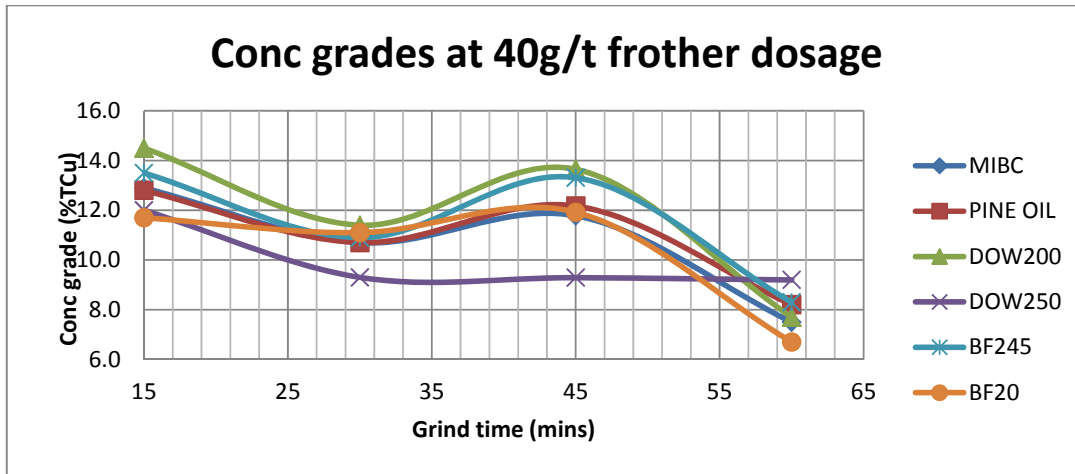
Fig. 4.4: Response of concentrate grades to grinding time while maintaining a frother dosage of 40g/t on Lumwana ore

Figure 4.4 above shows that the highest concentrate grades were achieved using Dowfroth 200, followed by Betafroth 245, while Dowfroth 250 gave the lowest concentrate grades.
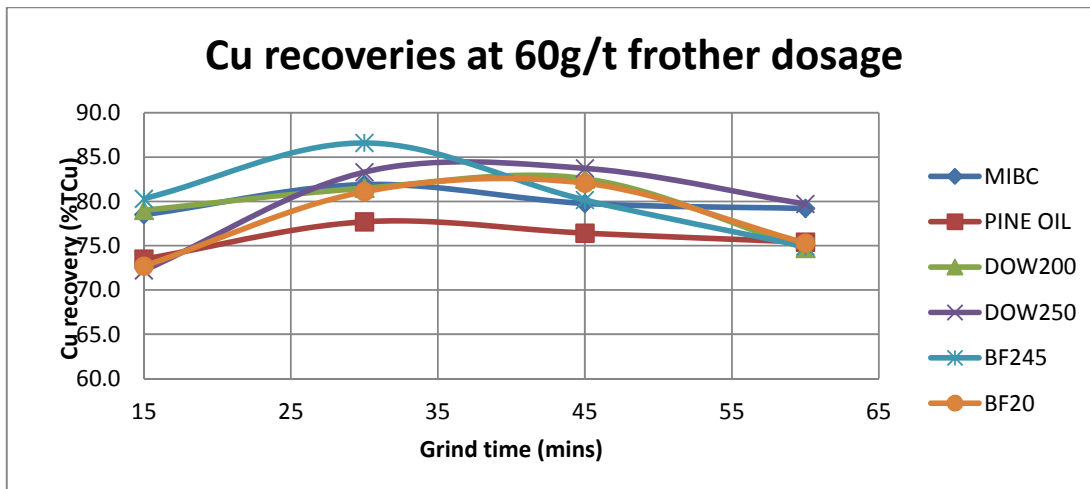
Fig.4.5: Response of flotation recoveries to grinding time while maintaining a frother dosage at 60g/ton Lumwana ore

Figure 4.5above shows that when frother dosage was increased from 40g/t to 60g/t, all six frothers showed a peak in recoveries at grind of 65% passing 150µm. The highest recoveries were achieved when using frother Betafroth 245 (87%TCu), followed by Dowfroth 250 (83%TCu).MIBC and Dowfroth 200 were third, achieving nearly 82%TCueach. Betafroth 20 achieved 81%TCu, while pine oil gave the lowest recovery of about78%TCu.
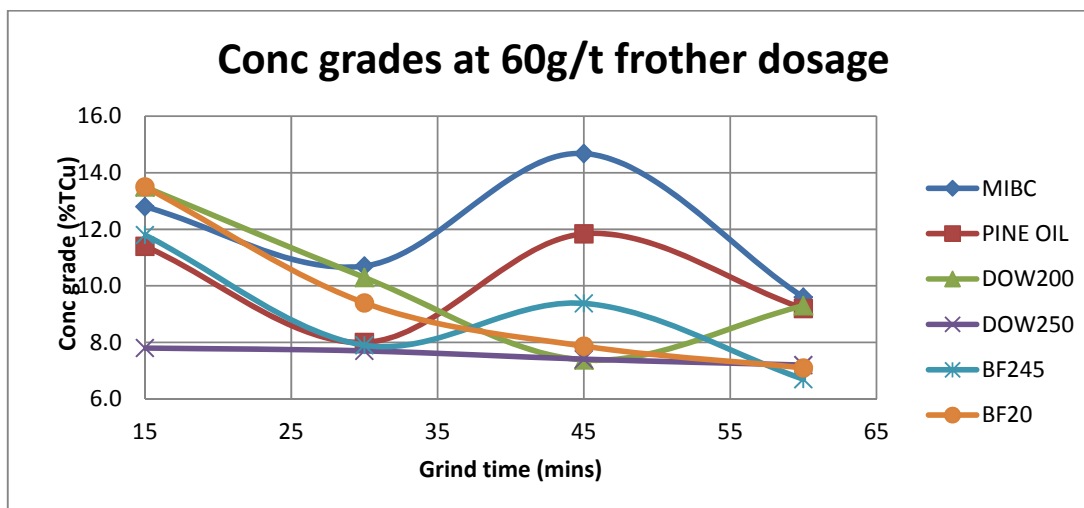
Fig. 4.6: Response of concentrate grades to grinding time while maintaining a frother dosage of 60g/t on Lumwana ore

Figure4.6above shows that the best concentrate grades were achieved using MIBC, pine oil and Betafroth 245, with the highest concentrate grades of 14.7%TCu and 11.8%TCubeing given by MIBC and pine oil respectively, at a grind of 80% passing 150μm. Dowfroth 250 gave the lowest concentrate grades.
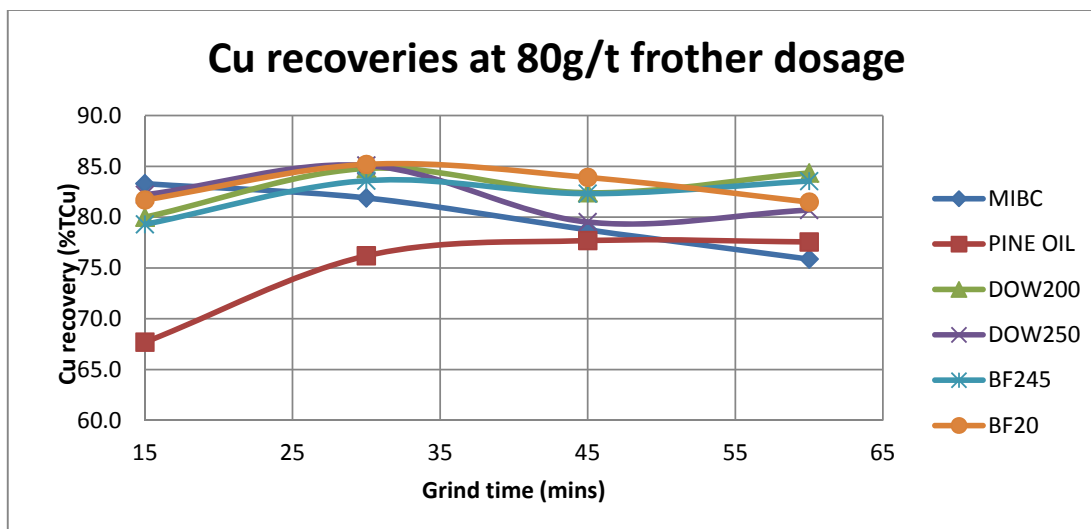

Fig.4.7: Response of flotation recoveries to grinding time while maintaining a frother dosage of 80g/t on Lumwana ore

Figure 4.7above shows that when frother dosage was increased further to 80g/t the highest copper recoveries of 85%TCu each were achieved using frothers Betafroth 20, Dowfroth 250 and Dowfroth 200 at 65% passing 150μm.Pine oil gave the lowest recovery of 76%TCu.
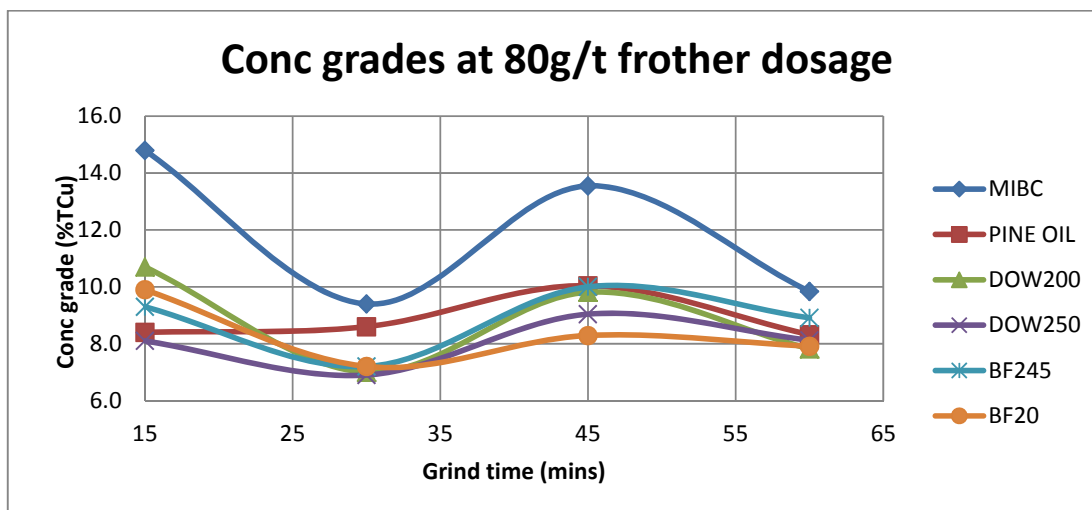
Fig. 4.8: Response of concentrate grades to grinding time while maintaining frother dosage at 80g/t on Lumwana ore

Figure 4.8above shows that MIBC gave highest concentrate grades with a peak of 14.8%TCu at 55% passing150μm, followed by Dowfroth 200 and Betafroth 20.Dowfroth 250 gave the lowest concentrate grade.
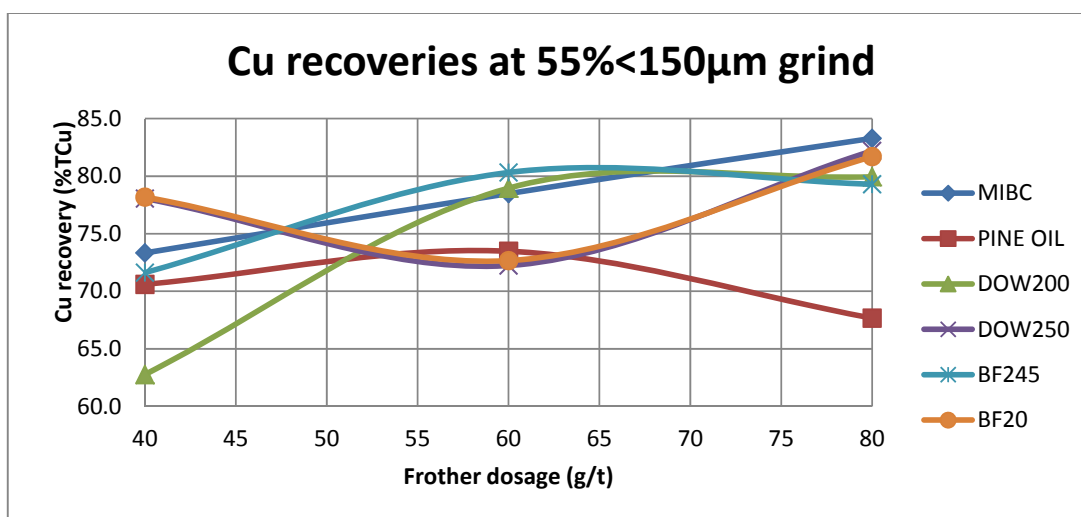
Fig.4.9: Response of flotation recoveries to frother dosage at constant grind of 55% passing 150μm on Lumwana ore

Figure 4.9 above shows that when the grind was maintained at 55% passing 150μm, but frother dosage was varied, the highest copper recovery of 83%TCu was achieved at a frother dosage of 80g/t using MIBC, closely followed by Dowfroth 250 and Betafroth 20,giving 82%TCu each. The lowest recovery of 68%TCu was given by pine oil.
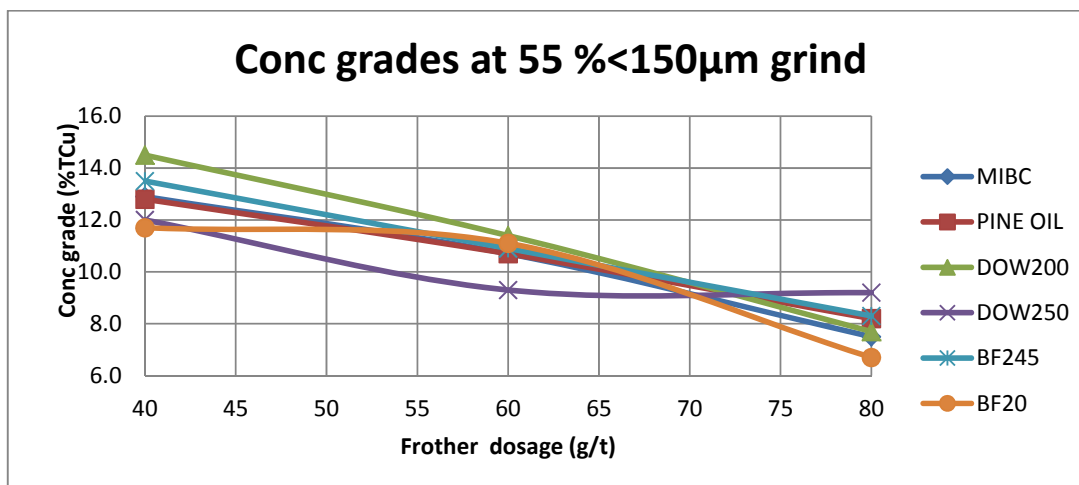
Fig. 4.10: Response of concentrate grades to frother dosage at constant grind of 55% passing 150μm on Lumwana ore

On concentrate grades, Figure4.10above shows that the highest concentrate grades were achieved at a frother dosage of 40g/t using Dowfroth 200 (14.5%TCu), followed by Betafroth 245 (13.5%TCu), MIBC (12.9%TCu), and then pine oil (12.8%TCu). Dowfroth 250 (12%TCu) and Betafroth 20 (11.7%TCu) were last.
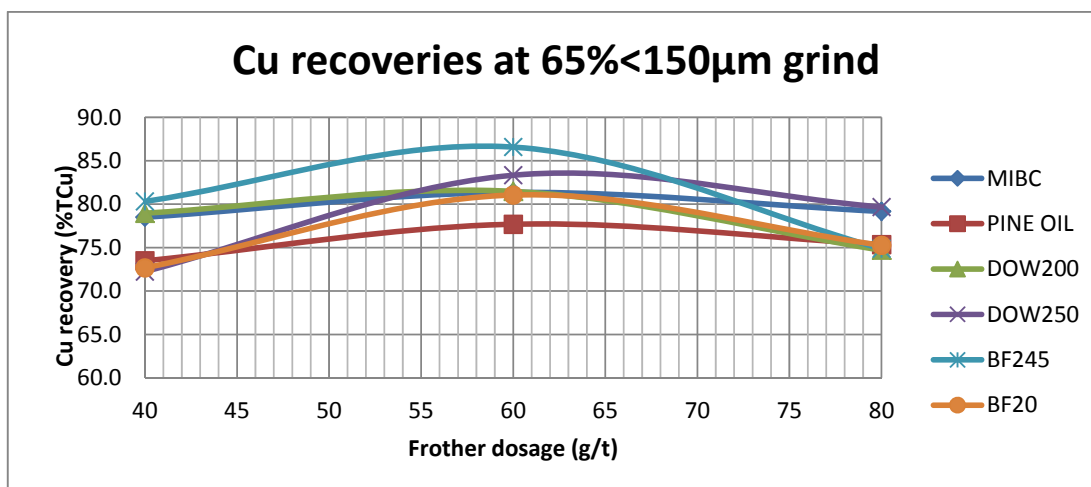
Fig.4.11: Response of flotation recoveries to frother dosage at constant grind of 65% passing 150μm on Lumwana ore

Figure 4.11above shows that at a grind of 65% passing 150μm, the recoveries obtained showed a peak at a frother dosage of 60g/t for all six frothers tested. The highest copper recoveries achieved however, were 87%TCu using Betafroth 245 followed by Dowfroth 250 (83%TCu).MIBC, Dowfroth 200 and Betafroth 20 achieved about 80%TCu each. Pine oil gave the lowest recovery of 78%TCu.
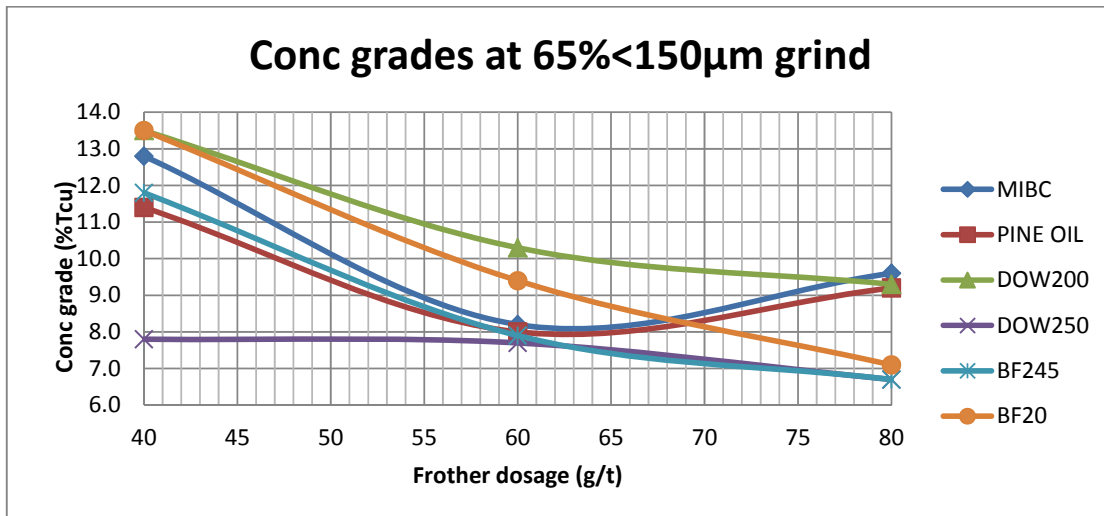
Fig. 4.12: Response of concentrate grades to frother dosage at constant grind of 65% passing 150μm on Lumwana ore

However, on the concentrate grades, Figure 4.12 above shows that the highest concentrate grades were achieved at 40g/t using Betafroth 20, Dowfroth 200, MIBC, pine oil and Betafroth 20. Dowfroth 250 gave the lowest concentrate grades.
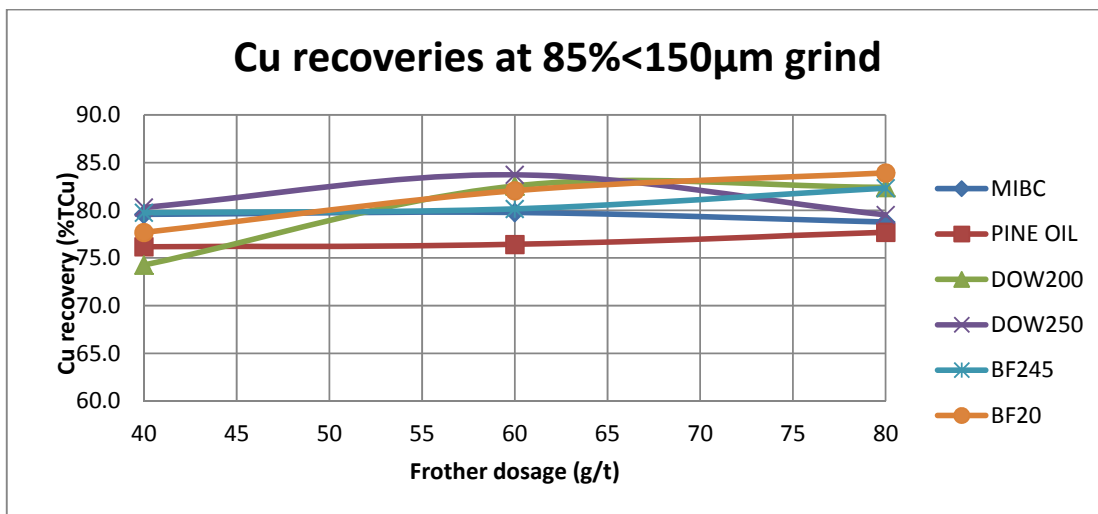

Fig.4.13: Response of flotation recoveries to frother dosage at constant grind of 80% passing 150μm on Lumwana ore

Figure 4.13 shows that at a grind of 85% passing 150μm, the highest recovery of 84%TCu was achieved using Dowfroth 250 at 60g/t, followed by Dowfroth 200 and Betafroth 20 which gave 83%TCu and 82%TCu respectively. MIBC and Betafroth 245 gave about 80%TCu each. Pine oil was last with a recovery of just over76%TCu.
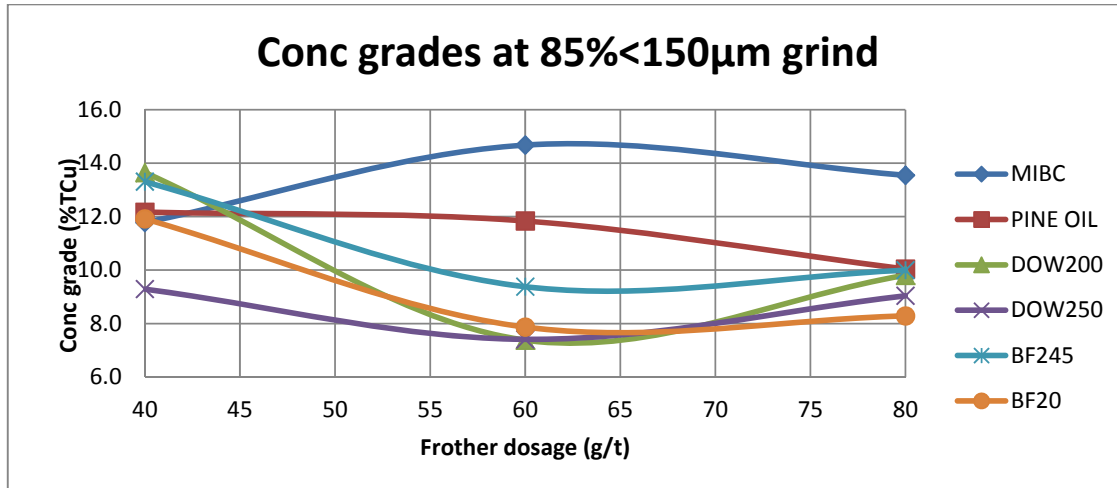
Fig. 4.14: Response of concentrate grades to frother dosage at constant grind of 85% passing 150μm on Lumwana ore

Figure 4.14 shows that at a frother dosage of 60g/t best concentrate grades were achieved using MIBC (15%TCu), pine oil (nearly 12%TCu) Betafroth 245 (about 9.5%TCu). Dowfroth 200, Dowfroth 250 and Betafroth 20 gave lower concentrate grades.
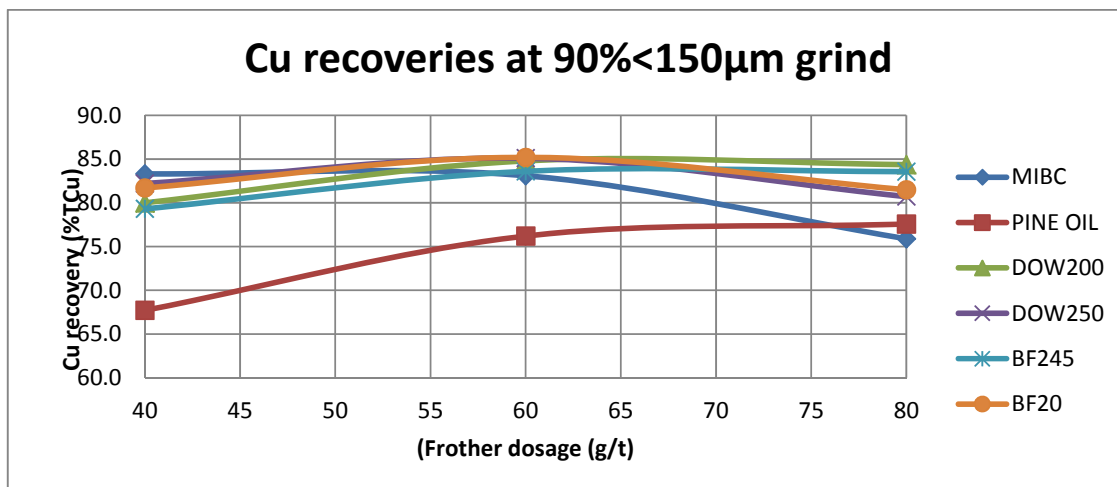

Fig.4.15: Response of flotation recoveries to frother dosage at constant grind of 90% passing 150μmon Lumwana ore

Figure 4.15above shows that at finer grindof90% passing 150μm, except for MIBC, all frothers showed a peak in recoveries at frother dosage of 60g/t, before declining or levelling out when frother dosage was increased further to 80g/t. The highest recovery of 85%TCu was achieved using Betafroth 20 and Dowfroth 250. Pine oil gave the lowest recovery of around 76%TCu.
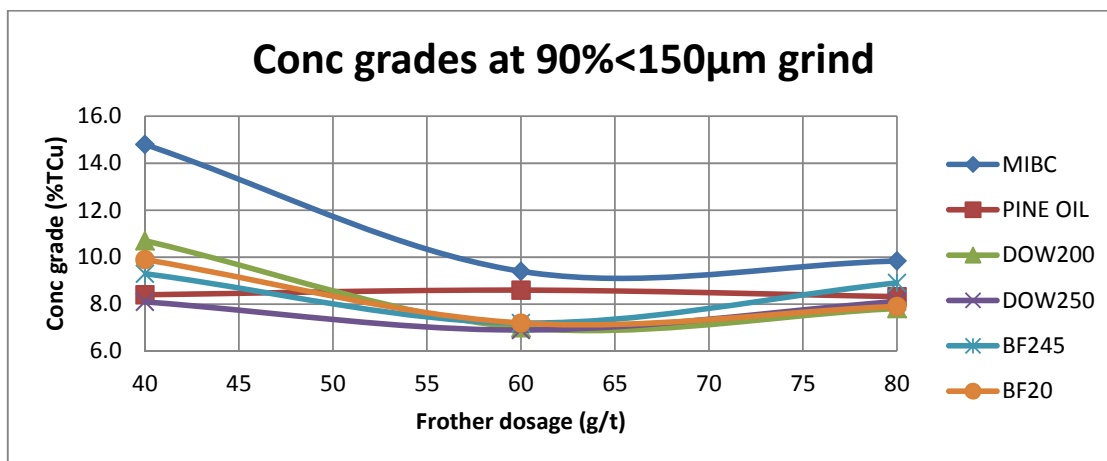
Fig. 4.16: Response of concentrate grades to frother dosage at constant grind of 90% passing 150μm on Lumwana ore

Figure 4.16 shows that at a finer grind of 90% passing150μm, the highest concentrate grades were given by MIBC, followed by Dowfroth 200 at lower frother dosage of 40g/t. The lowest concentrate grades were given by Dowfroth 250 and Betafroth 20.

4.4   Discussion of the response of Lumwana ore to frother dosage and grind

At lower frother dosages, high molecular weight glycol-based frothers (Betafroth 245 and Dowfroth 250) achieved reasonably higher flotation recoveries compared to alcohol frothers (MIBC and pine oil) and lower molecular weight frother (Dowfroth 200). However, at higher frother dosages, the alcohol-based frothers (MIBC, pine oil and Betafroth 20) and lower molecular weight frother Dowfroth 200 showed improved recoveries of close to those achieved with higher molecular weight glycol-based frothers (see Figures 4.17 and 4.18). This is consistent with the work done elsewhere [9] that showed that alcohol frothers tend to be effective and have increased kinetics at higher frother dosages, while polypropylene glycols are effective even at lower frother dosages.
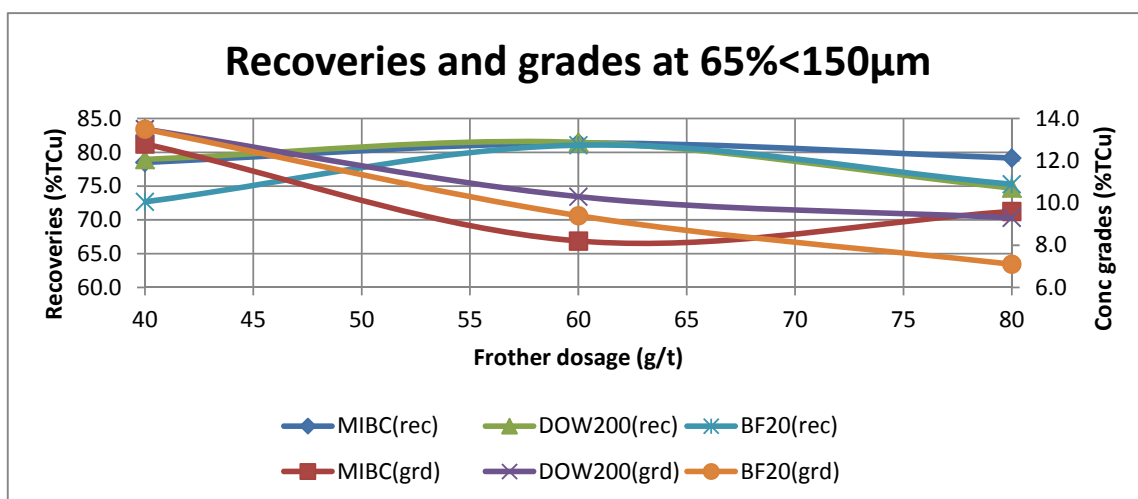
Fig. 4.17: Response of concentrate grades and recoveries at an optimal grind of 65% passing 150μm for MIBC, Dowfroth 200 and Betafroth 20 frothers.
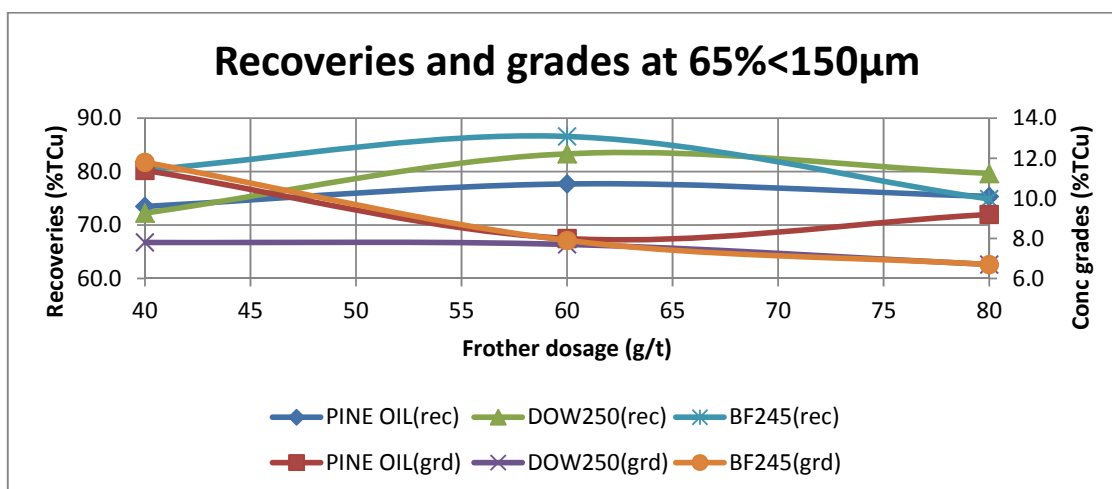
Fig. 4.18: Response of concentrate grades and recoveries at an optimal grind of 65% passing 150μm for pine oil, Dowfroth 250 and Betafroth 245 frothers

When the ore was ground finer, there was a general increase in flotation kinetics, particularly with higher molecular weight glycol-based frothers (Betafroth 245 and Dowfroth 250), though recoveries from other frothers like lower molecular weight polyglycol frother Dowfroth 200, and alcohol-based frothers (MIBC and Betafroth 20) also showed some remarkable improvements. This agrees with the secondary finding [9] that showed that alcohol and lower molecular weight frothers give higher flotation kinetics when used on finer ground ores.
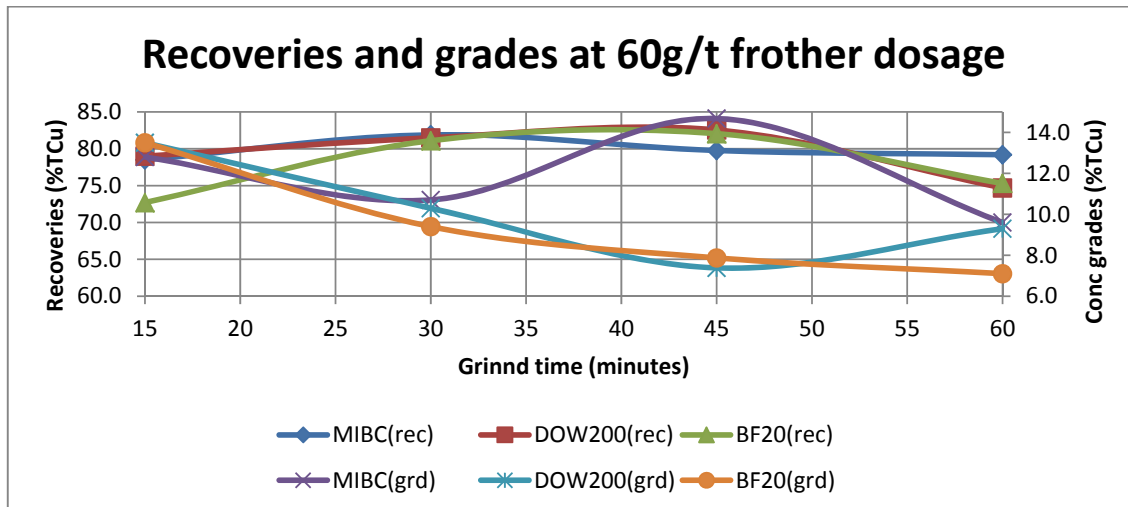
Fig. 4.19: Response of concentrate grades and recoveries to grinding time at optimal frother dosage at 60g/t on for MIBC, Dowfroth 200 and Betafroth 20 frothers
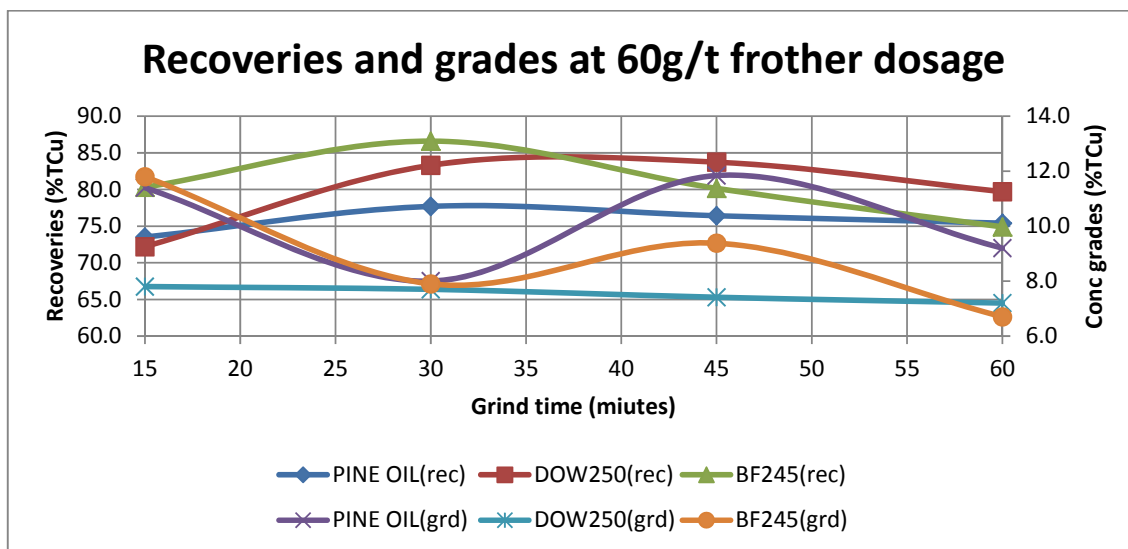
Fig. 4.20: Response of concentrate grades and recoveries to grinding time at optimal frother dosage at 60g/t for pine oil, Dowfroth 250 and Betafroth 245 frothers

However, it was also seen that all frothers achieved the highest flotation recoveries when they were tested at an frother dosage of 60g/t (Figure 4.5) and ground to 65% passing 150μm (Figure 4.11). It can therefore, be deduced that at this point the flotation response of Lumwana ore was at its peak in terms of flotation recoveries. This point can therefore, be defined as the optimum or economic condition for the flotation of Lumwana ore.

On concentrate quality, the best grades were achieved using Dowfroth 200 and MIBC, followed by pine oil, particularly at lower frother dosage and finer grind. This is consistent with behavior of lower molecular glycol frothers (Dowfroth 200 and MIBC) in that the frothers are highly selective but give lower recoveries when used at lower dosages [9].

At higher frother dosages all frothers showed a general decrease in the concentrate grades. However, when the ore was ground finer, some significant improvements in concentrate grades were noticed, especially for lower molecular weight frothers (Dowfroth 200 and MIBC), while improvements given by higher molecular weight glycol-based frothers (Dowfroth 250and Betafroth 245) were marginal (Figures 4.19 and 4.20). The higher concentrate grades given by MIBC and Dowfroth 200 at finer grind is consistent with the secondary finding[7] that showed that lower molecular weight frothers like Dowfroth 200 and MIBC are more selective when used on finer ores even at higher dosages. The two frothers worked well on finer grinds, because they gave a fine textured froth which is good for rejection of slimes, thus improving concentrate quality too. On the other hand, higher molecular weight glycol-based frothers (Dowfroth 250 and Betafroth 245) achieved lower concentrate grades especially at higher frother dosages, because the frothers are too stable and tend to recover significant amounts of fine gangue in order to stabilise their froths [9].

In summary, as the frother dosage was increased, there was a general increase in flotation kinetics (recoveries), but selectivity (grades) suffered. At higher frother dosages there was a decrease in concentrate grades regardless of the type of frother. However, as the ore was ground finer both flotation kinetics and selectivity improved, particularly for lower molecular weight frothers (Dowfroth 200 and MIBC). This holds well with the secondary

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findings[63] that showed that regardless of the frother type (alcohol or glycol), increasing frother dosage to increase recovery always results in poor selectivity (grades), and that alcohol frothers are more effective on finer particles, while glycol-based frothers are more effective on coarser coarse particles [9].

4.5   Flotation kinetics of Lumwana ore

Further work in terms of determining the flotation kinetics of each frother was conducted. The testwork involved collecting three concentrates from each test at intervals of one minute, two minutes and five minutes and scraping off the froth every 15 seconds. Each test was carried out four times, and the average results obtained (see Appendices III) were used to plot graphs in Figures 4.21 and 4.22 below.
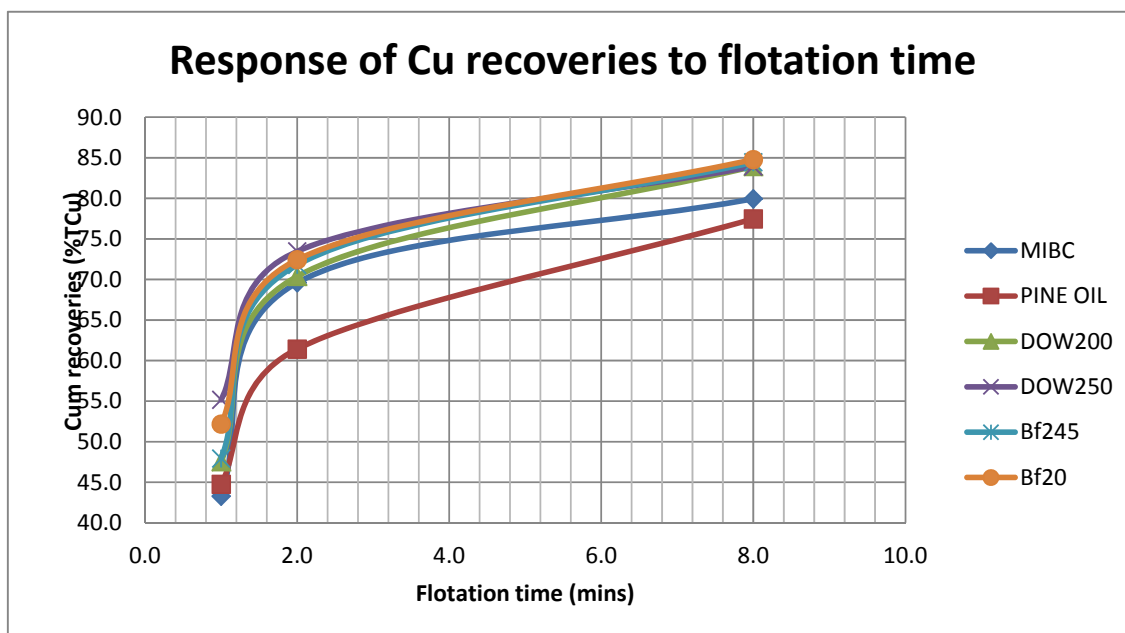
Fig. 4.21: Flotation kinetics of Lumwana ore showing flotation recovery as a function of flotation time at optimal condition of 65% passing 150µm and frother dosage of 60g/t

Figure 4.21 shows that Dowfroth 250 and Betafroth 20 achieved the fastest flotation rates reaching 55%TCu and 52%TCu respectively in the first minute, followed by Betafroth 245 (48%TCu) and Dowfroth 200 (47%TCu). The lowest kinetics in the first one minute came from MIBC giving only 42%TCu recovery. After two minutes of flotation, Dowfroth 250 (74%TCu) maintained with fastest kinetics followed by Betafroth 20 and Betafroth 245 giving 72%TCu each. The lowest flotation kinetics came from pine oil with 61%TCu recovery only. However, after floating for last five minutes, the highest recoveries of 85%TCu were achieved using Betafroth 20, followed by Dowfroth 200 and Betafroth 245, Dowfroth 200 84%TCu. MIBC and pine oil achieved 80%TCu and 78%TCu respectively.
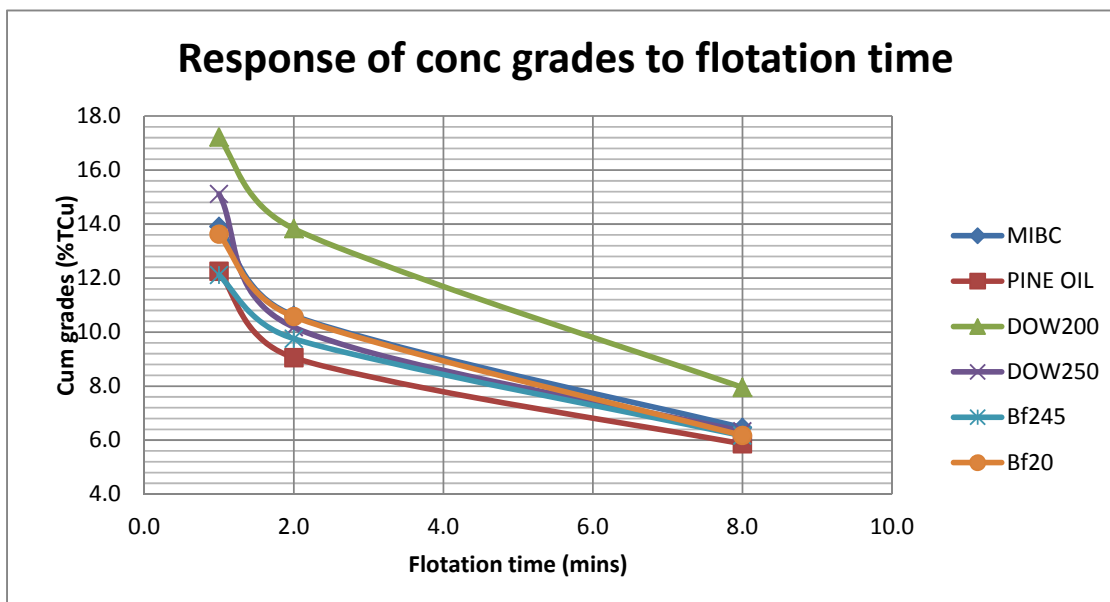
Fig. 4.22: Flotation kinetics of Lumwana sulphide ore showing concentrate grades as a function of flotation time at optimal condition of 65% passing 150μm and frother dosage of 60g/t

On concentrate grades, Figure 4.22 shows that frother Dowfroth 200 gave the highest cumulative concentrate grade of nearly 8%TCu followed by MIBC (6.5%TCu). Betafroth 245, Betafroth 20 and Dowfroth 250 trailed with about 6.3%TCu each. Pine oil gave lowest cumulative grade of about 5.9%TCu.

However, when flotation recoveries (Figure 4.21) and concentrate grades (Figure 4.22) were expressed in a relationship, the following graphs (Figure 4.23) were obtained.
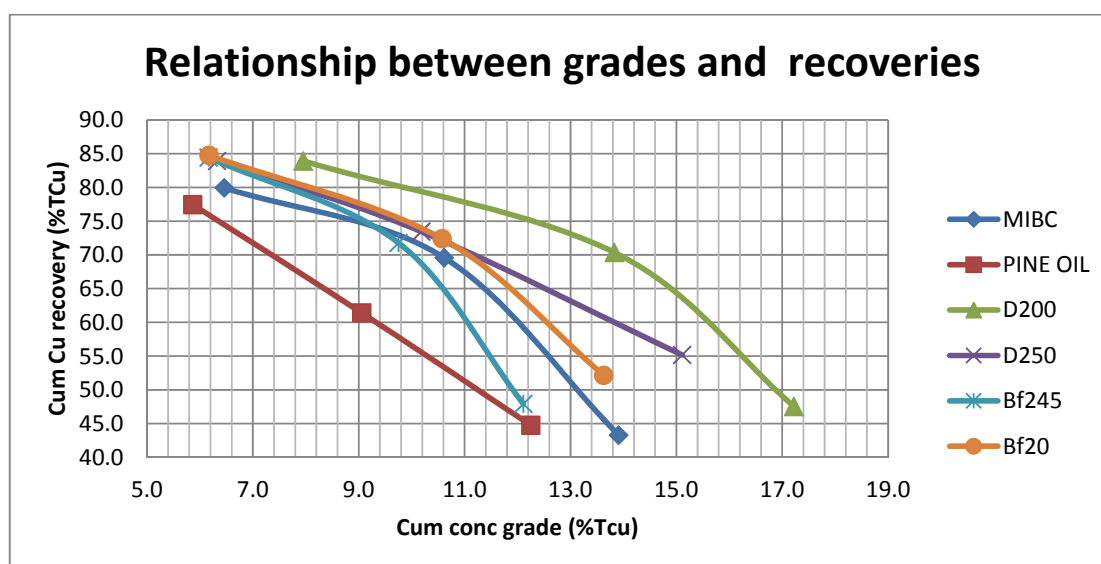
Fig. 4.23: The relationship between concentrate grades and flotation recoveries for Lumwana ore

The grade-recovery curves in Figure 4.23 above show that when Lumwana ore was ground to 65% passing 150µm and frother dosage of 60g/t was used, the best results (concentrate grades and copper recoveries) were achieved using a lower molecular weight glycol frother Dowfroth 200.

4.6   Discussion of the flotation kinetics of Lumwana ore

When tested on Lumwana ore, all frothers showed a sharp rise in flotation kinetics (recoveries) in the first concentrate (C1). Dowfroth 250 and Betafroth 20 gave the highest kinetics in the first minute of flotation respectively. The slowest flotation kinetics in the first minute came from MIBC. However, in the second minute of flotation, Dowfroth 250 followed by Betafroth 245 and Betafroth 20 gave the fastest kinetics. As discussed earlier, the faster kinetics given by Dowfroth 250 and Betafroth 245 frothers could be attributed to the fact that these two frothers are strong higher molecular weight glycol-based frothers that exhibit higher kinetics initially compared to alcohol frothers and lower molecular weight frothers [9].

After floating for last five minutes, recoveries achieved with all the six frothers increased gradually from second (C2) to the final (C3) concentrate, with Betafroth 20 remaining superior, closely followed by Betafroth 245, Dowfroth 200 and Dowfroth 250 as shown in Figure 4.21. As stated earlier, higher molecular weight glycol based-frothers tend to be more robust in flotation of coarser minerals, particularly when the mineral particles are liberated at a relatively coarser grind like in the case of Lumwana ore.

However, when flotation kinetics tests conducted at UNZA were compared with tests conducted at Lumwana mine site (Figure 4.24), they showed that higher overall kinetics were achieved using MIBC followed by Dowfroth 250. Dowfroth 200 gave the lowest flotation kinetics.
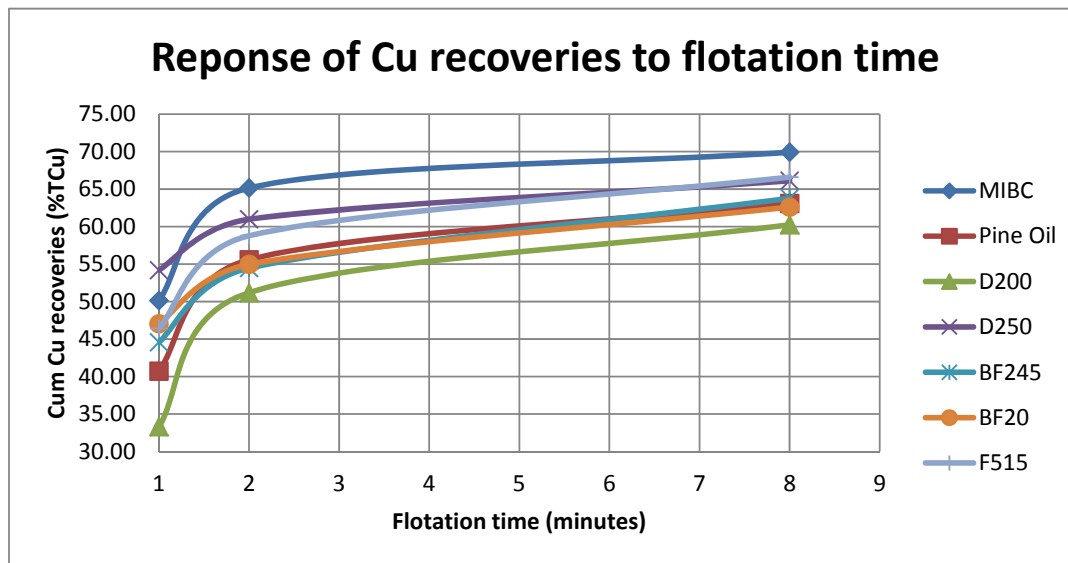
Figure 4.24: Flotation kinetics of Lumwana ore during water recovery testwork (cumulative copper recoveries)
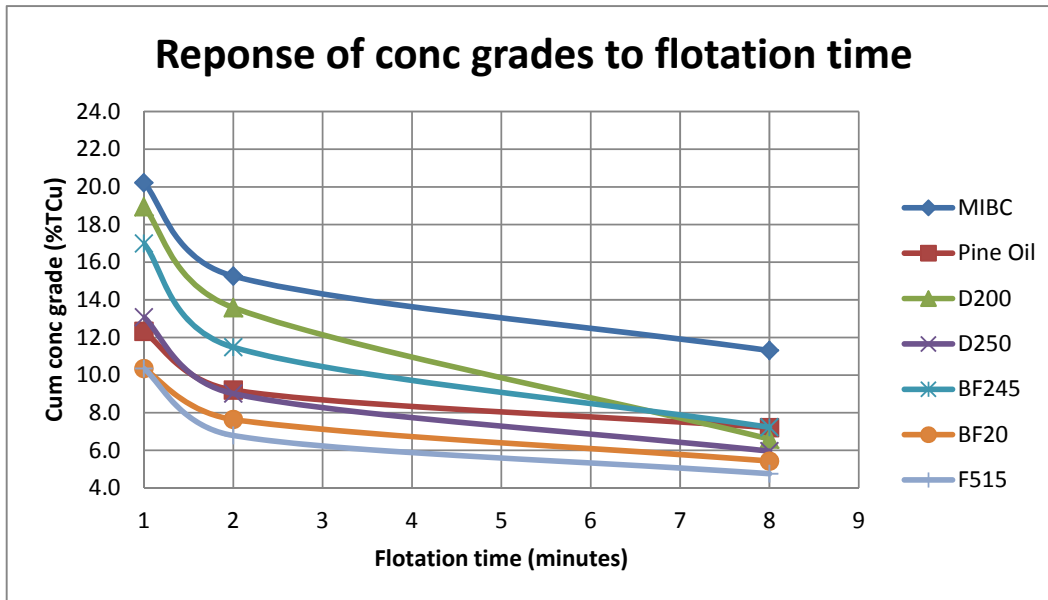
Fig. 4.25: Flotation kinetics of Lumwana ore during water recovery testwork (concentrate grades)

On concentrates, Dowfroth 200 followed by MIBC produced concentrates of highest quality (Figure 4.25). The good concentrate grades achieved with Dowfroth 200 and MIBC, on one hand could be attributed to rejection of fine gangue like micas in Lumwana ore, while on the other hand fine gangue (micas) tend to contribute to poor selectivity for higher molecular weight glycol-based frothers like Dowfroth 250 particularly at higher dosages. It can therefore, be seen from Figure 4.24 above that though both frothers (Dowfroth 250 and Betafroth 20) exhibited very high flotation kinetics, the two frothers also gave out concentrates with the lowest grades as shown in Figure 4.25. The cleaner concentrates produced by frothers MIBC and Dowfroth 200 as earlier stated evidence enough[9] low-molecular weight frothers (MIBC and Dowfroth 200) tend to give finely distributed well-knit froth, which allows the rejection of fine gangue producing a concentrate of high quality.

This finding can further be supported by the lower amount of water recovered by the two lower molecular weight frothers (MIBC and Dowfroth 200) compared with higher water recovered by higher molecular weight frothers (Dowfroth 250 and Betafroth 245) as shown in Figure 4.56, whereby Dowfroth 200 and MIBC are shown to have recovered the lower amounts of water, while Dowfroth 250 and Betafroth 20 are shown to have recovered the highest amounts of water, translated into higher levels of gangue entrainment.

Relationship between conc grades and flotation recoveries
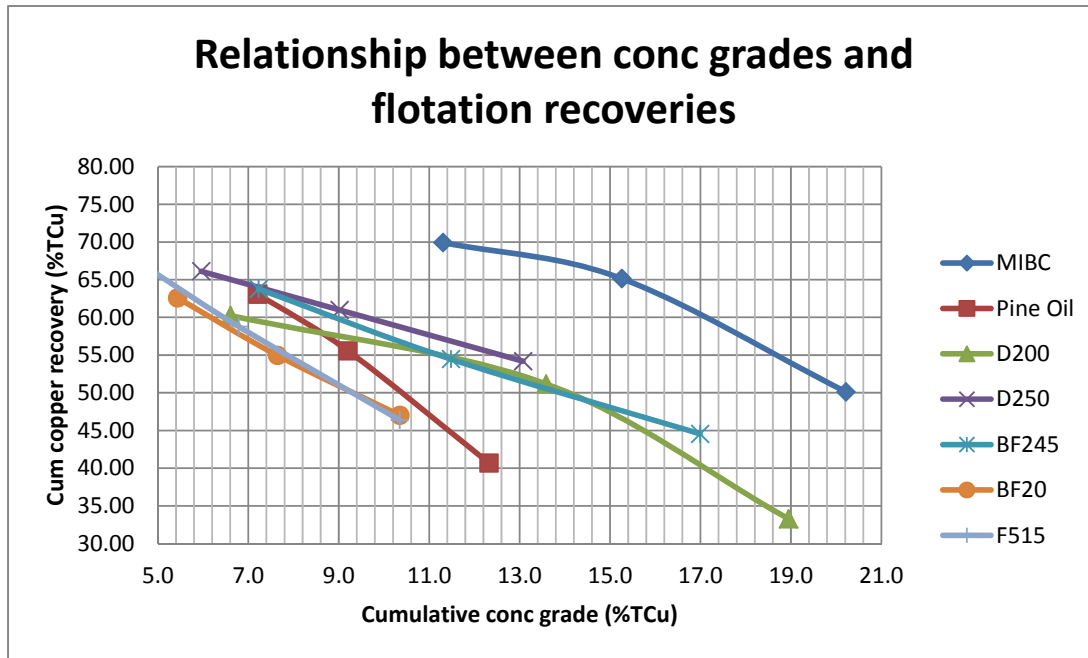
Fig. 4.26: Flotation kinetics grade-recovery curves for Lumwana ore during water recovery testwork

Figure 4.26 above shows average grade-recovery curves, confirming the superior flotation performance of MIBC, while Dowfroth 250 and Betafroth 245 came out second and third respectively. The lowest grade recovery curves were given by Betafroth 20 and Lumwana plant standard frother F515.

4.7 Mineralogical examination of Kansanshi sulphide ore

Mineralogical examination of Kansanshi sulphide ore sample was conducted at Alfred H Knight (Zambia) Ltd and the ore mineralization was confirmed as being[71]; (i) 88% of the copper was drawn mostly from chalcopyrite, with minor amounts of bornite, (ii) 11% of the copper was acid soluble derived mainly from malachite, and (iii) the gangue was composed of mostly quartz and feldspars (77%) some micas (12%) and carbonates (6%). Table 4.1 shows copper mineralisation and ore properties of Lumwana and Kansanshi mine ores respectively[72]. Kansanshi or copper mineralisation is as shown in Figure 4.27.

Thin sections of Kansanshi sulphide ore were examined under reflected light microscope and the ore texture was found to be of polygonal graino-blastic with triple point junctions. Gangue mineralisation was mainly of calcite associated with tremolite. The copper (chalcopyrite) was observed to occur as disseminated mineralisation with albite-carbonate alteration. The ore showed medium to fine grains, leading to finer grinding in order to liberate the copper bearing minerals (Figure 4.27).
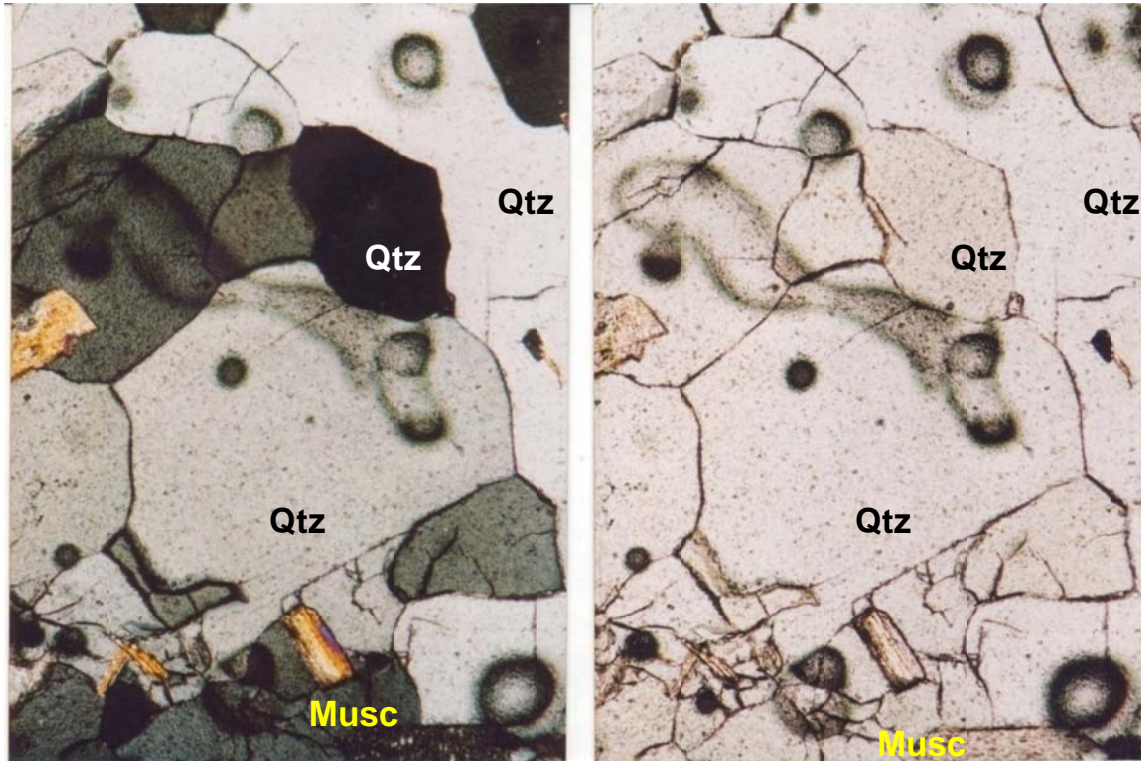
Fig.4.27: Photograph of quartzite showing grano-blastic polygonal texture - the rock is fine-to-medium-grained for Kansanshi sulphide ore.

4.8   Optimisation of the mesh of grind for Kansanshi sulphide ore

The optimization tests for Kansanshi ore in the laboratory were conducted by firstly, determining the mesh of grind for ore. Standard grinds were conducted in the laboratory keeping in mind that the mine's milling plant operates at a particle size p80<150μm. The ore sample was subjected to grinding times of 5 minutes, 10 minutes, 15 minutes, 30 minutes, 45 minutes and 60 minutes. The milled samples were screened using the British Standard BSS, 410 series. The screen analysis results obtained (Appendix II) are presented below;
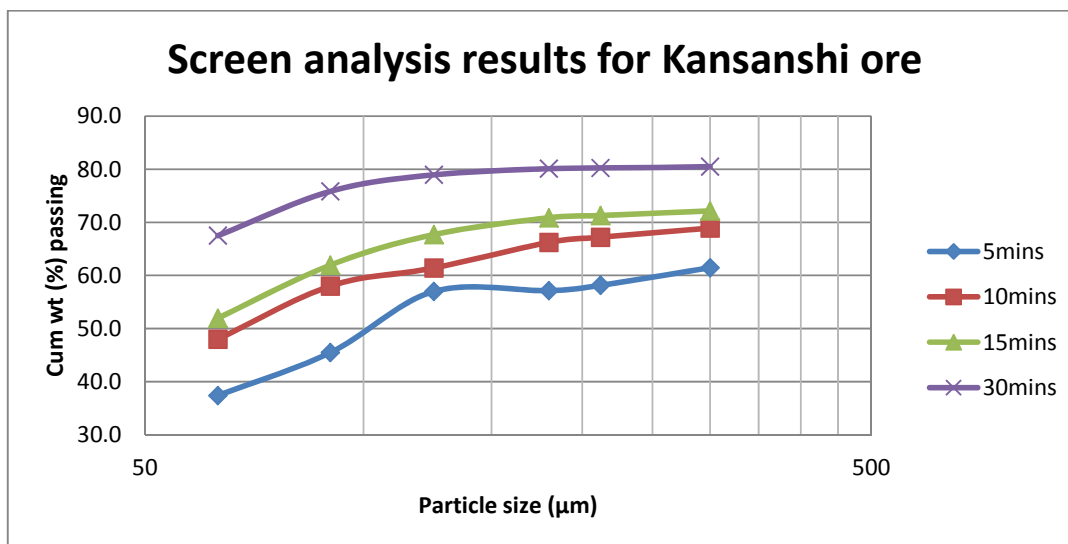
Fig.4.28: Results of screen analysis obtained at different grinding times for Kansanshi sulphide ore

From Figure 4.28, above it can be seen that five minutes grinding time gave just about 55% passing, 10 minutes of grind gave 65% passing, and 15 minutes of grind gave nearly 70% passing, 30 minutes of grind gave 80% passing 150μm respectively.

4.9   Flotation response of Kansanshi sulphide ore to frother dosage and grind

Bench-scale flotation tests were carried out using 5 minutes, 10 minutes and 30 minutes grinding times and frother dosages of 40g/t, 60g/t and 80 g/t while holding the collector (xanthate) constant at 100g/t. For each test a single concentrate was collected for a period of eight minutes, after conditioning for two minutes, by scrapping the froth off every 15 seconds. The flotation results obtained (Appendix II) were used to plot graphs below.
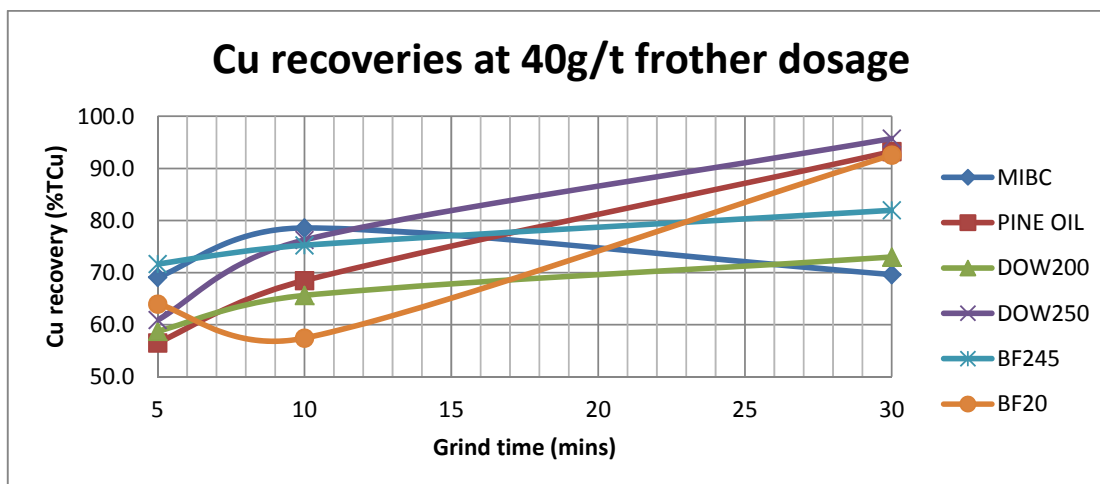
Fig. 4.29: Response of flotation recoveries to grind time while maintaining frother dosage at 40g/t on Kansanshi sulphide ore

Figure 4.29 above shows that when frother dosage was held at 40g/t while grind time was varied, the highest copper recovery of 96%TCu was achieved using Dowfroth 250 at a grind

of 80% passing 150µm, followed by Betafroth 20 and pine oil at 93%TCu each. Dowfroth 200 and MIBC and gave the lowest recoveries of around 70%TCu.
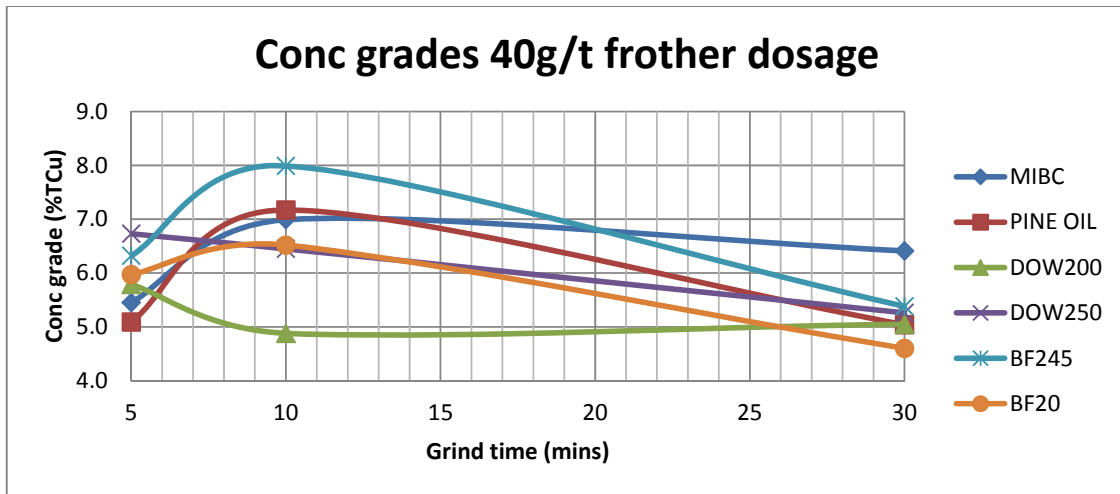
Fig. 4.30: Response of concentrate grades to grind time while maintaining frother dosage at 40g/t on Kansanshi sulphide ore

Figure 4.30 above, shows that the highest concentrate grade of 5%TCu was given by Betafroth 245 at 65% passing 150µm, followed by MIBC and Pine oil. Dowfroth 200 gave the lowest concentrate grade.
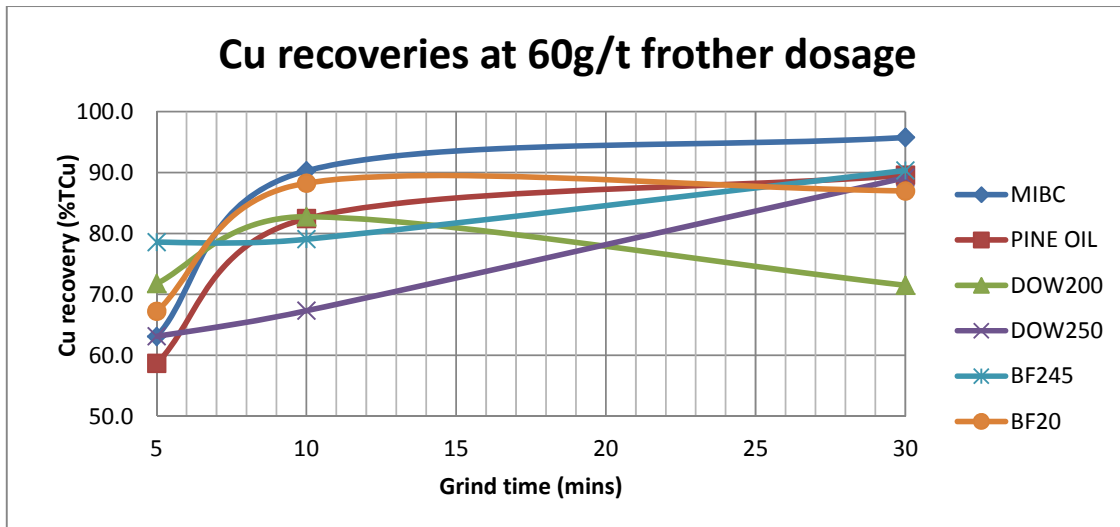
Fig. 4.31 Response of flotation recoveries to grind time while maintaining frother dosage at 60g/t on Kansanshi sulphide ore

When frother dosage was held at 60g/t, Figure 4.31 shows that the highest copper recovery of 96%TCu at 80% passing 150µm, was achieved using MIBC, followed by Betafroth 245 and pine oil at 90%TCu each. Dowfroth 250 and Betafroth 20 gave 89%TCu and 87%TCu respectively. Dowfroth 200 gave the lowest recovery of 72%TCu.
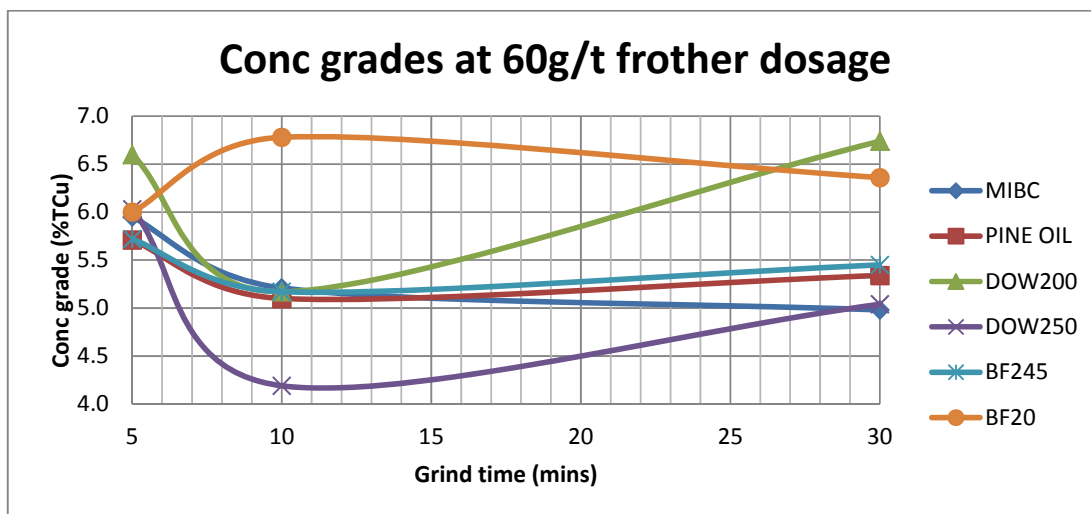
Fig. 4.32: Response of concentrate grades to grind time while maintaining frother dosage at 60g/t on Kansanshi sulphide ore

Figure 4.32 above shows that at 80% passing 150µm, Dowfroth 200 gave the highest grades, followed by Betafroth 20. MIBC and Dowfroth 250 gave the lowest concentrate grade of 5%TCu each.
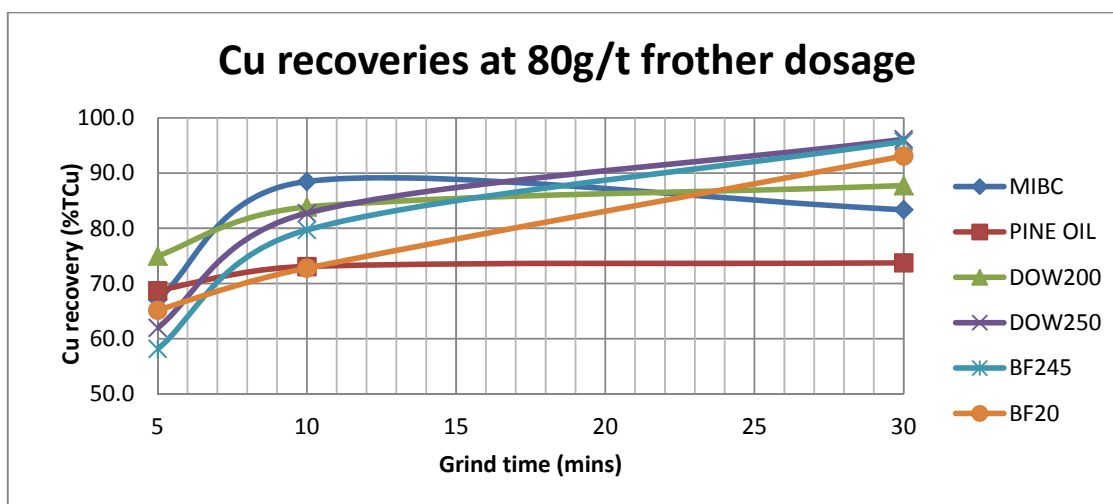
Fig.4.33: Response of flotation recoveries to grind time while maintaining frother dosage at 80g/t on Kansanshi sulphide ore

Figure 4.33 shows that when frother dosage was increased from 60g/t to 80 g/t, frothers Dowfroth 250 and Betafroth 245 gave the highest copper recoveries of 96%TCu each at grind of 80% passing 150µm, followed by Betafroth 20 (93%TCu), Dowfroth 200 (88%TCu) and MIBC (83%TCu). Pine oil achieved the least recovery of 74%TCu.
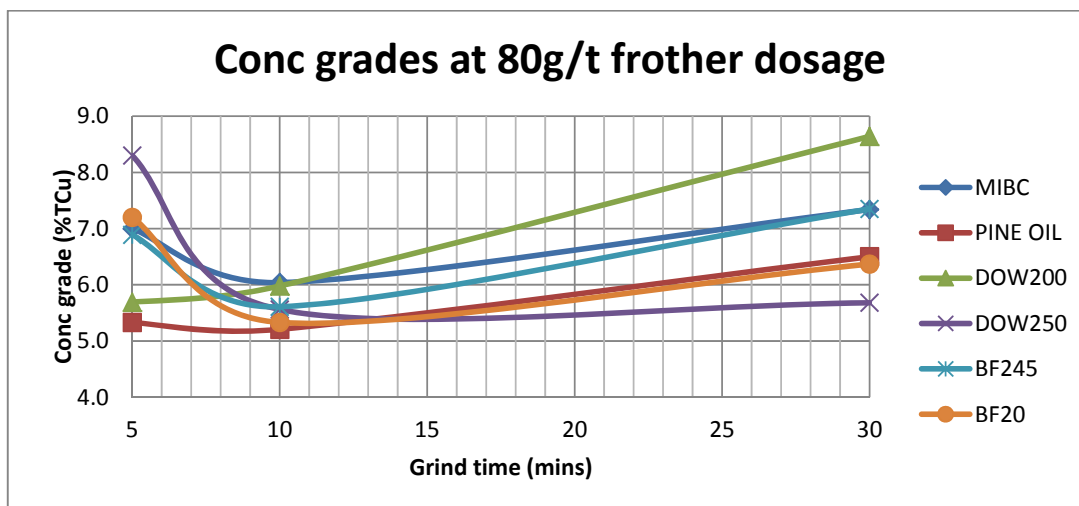
Fig. 4.34: Response of concentrate grades to grind time while maintaining frother dosage at 80g/t on Kansanshi sulphide ore

On concentrate grades, Figure 4.34 above shows that higher concentrate grades were achieved using Dowfroth 200(8.5%TCu) followed by MIBC and Betafroth 245. Dowfroth 250 and pine oil gave the lowest average grade of around 5%TCu.
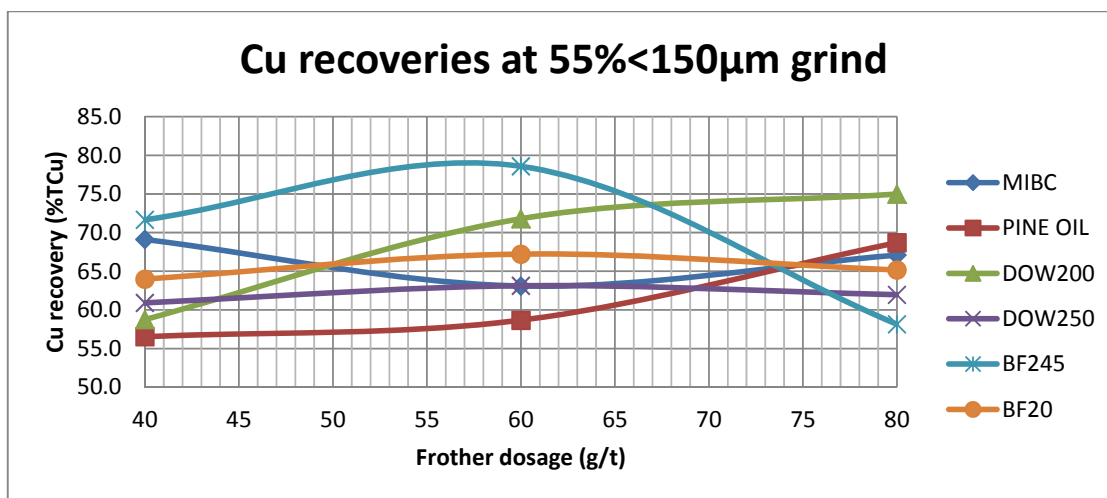
Fig. 4.35: Response of flotation recoveries and concentrate grades to frother dosage at constant grind of 55%passing 150μm on Kansanshi sulphide ore

Figure 4.35 above shows that the highest copper recovery of nearly 80%TCu at frother dosage of 60g/t was achieved using Betafroth 245 at a froth dosage of 60g/t, followed by Dowfroth 200. Betafroth 20 was third with nearly 70%TCu recovery. Pine oil gave the lowest recovery of 61%TCu.
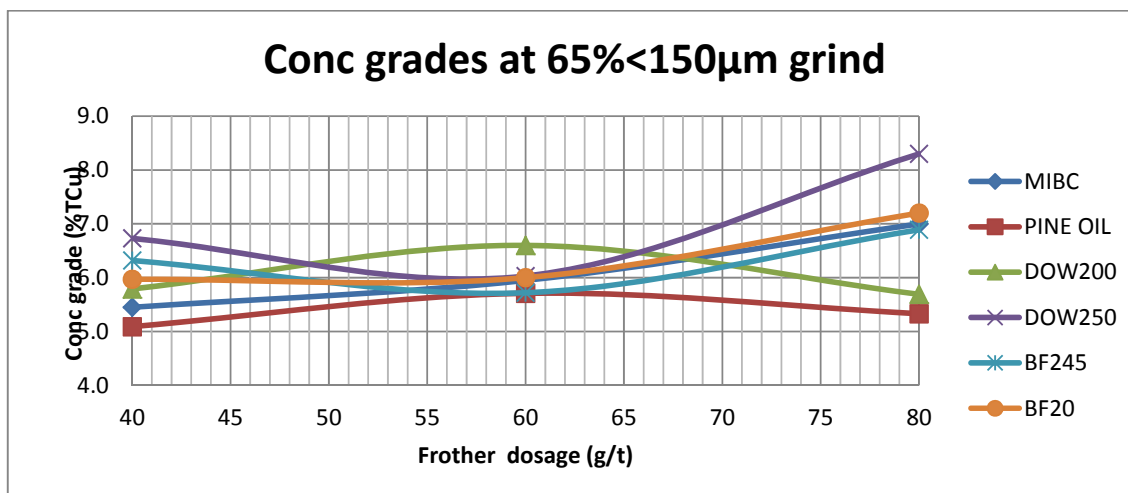
Fig. 4.36: Response of concentrate grades to frother dosage at a constant grind of 55%passing 150μm on Kansanshi sulphide ore

On the concentrates, Figure 4.36 above shows that highest concentrate grades were given by Dowfroth 250 at frother dosage of 80g/t, followed by Betafroth 20, MIBC and Betafroth 245. The lowest concentrate grades were given Dowfroth 200 and pine oil.
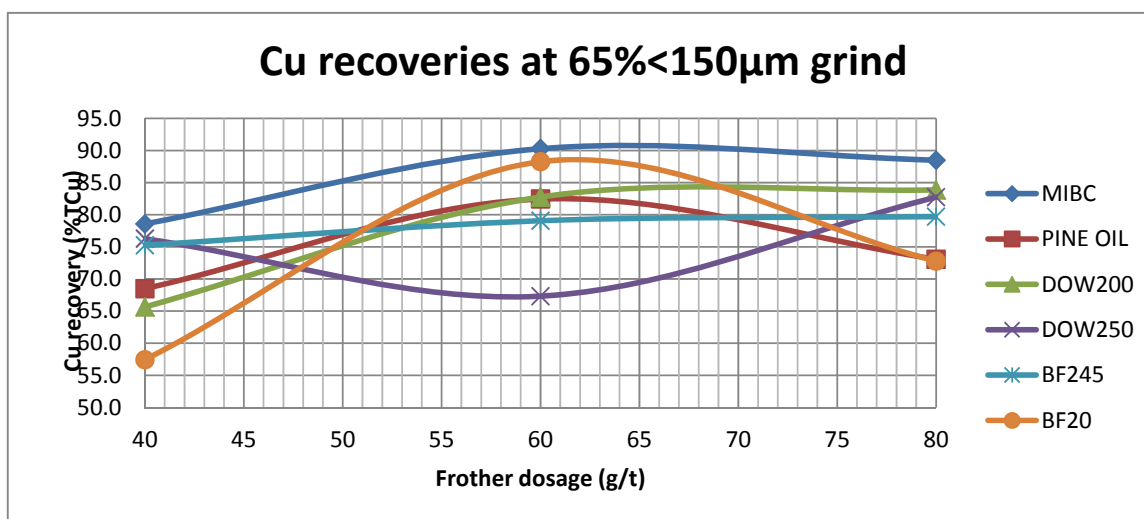
Fig. 4.37: Response of flotation recoveries to frother dosage at a constant grind of 65% passing 150μm on Kansanshi sulphide ore

Figure 4.37 above shows that MIBC gave the highest coppery recoveries of 86%TCu at a frother dosage of 80g/t, followed by Dowfroth 250 and Dowfroth 200 achieving nearly 85%TCu each and Betafroth 245 (78%TCu). The lowest average recovery of about 73%TCu was given by Betafroth 20 and pine oil.
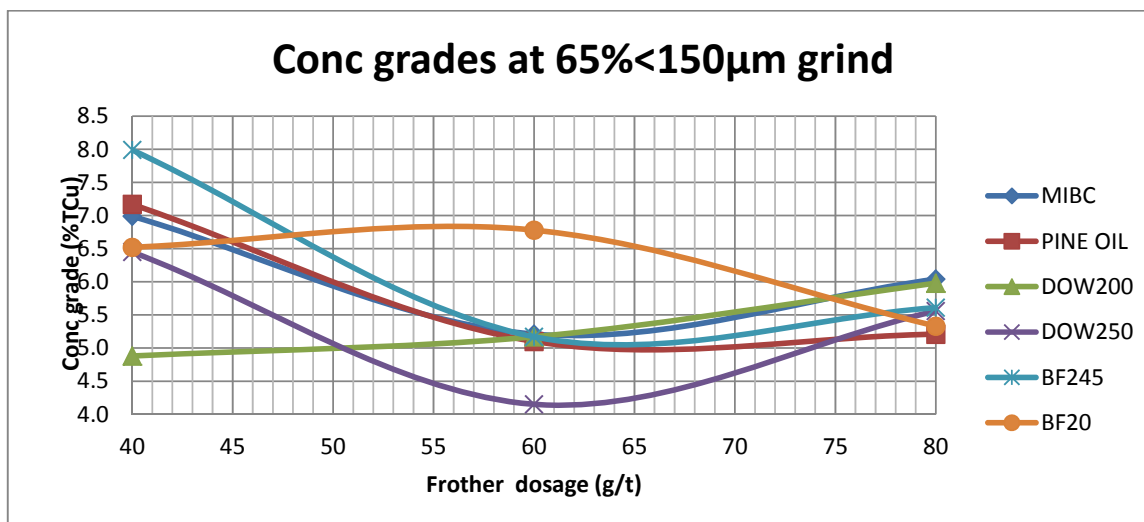
Fig. 4.38: Response of concentrate grades to frother dosage at a constant grind of 65% passing 150µm on Kansanshi sulphide ore

Figure 4.38 shows that highest concentrate grades were achieved using Betafroth 245 (8%TCu) at 40g/t frother dosage, followed by pine oil, MIBC and Betafroth 20. Dowfroth 200 gave the lowest concentrate grade of just under 5%TCu.
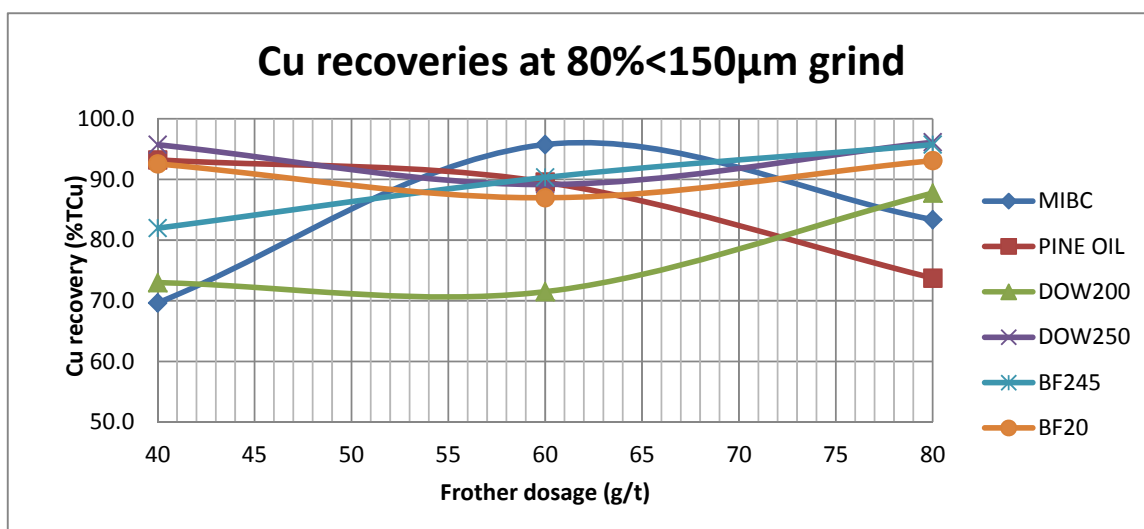
Fig. 4.39: Response of copper recoveries to frother dosage at a constant grind of 80% passing 150µm on Kansanshi sulphide ore

Figure 4.39 above shows that when Kansanshi ore was ground finer to 80% passing 150µm, the best recoveries of 96%TCu each were achieved using Dowfroth 250 and Betafroth 245 at 80g/t frother dosage, followed by Betafroth 20 (93%TCu), Dowfroth 200 (88%TCu) and MIBC at 83%TCu respectively. Pine oil gave the lowest recovery of 74%TCu.
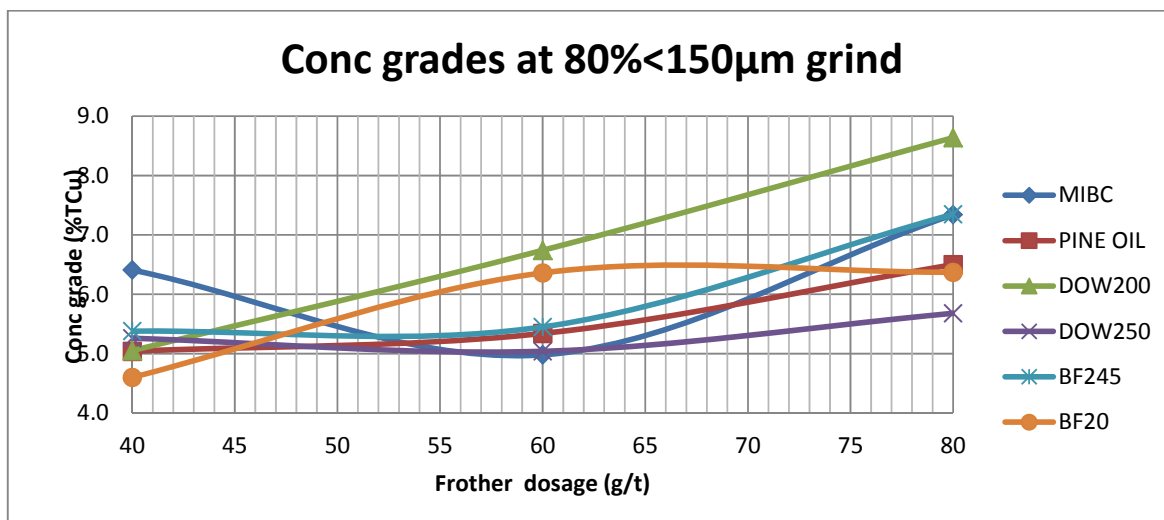
Fig. 4.40: Response of concentrate grades to frother dosage at a grind of 80% passing 150μm on Kansanshi sulphide ore

Figure 4.40 above shows that at a frother dosage of 80g/t, Dowfroth 200 (8.7%TCu) gave the highest concentrate grades, followed by Betafroth 245 and MIBC, giving nearly 7.5%TCu each. Dowfroth 250 gave the lowest grades.

4.10   Discussion of response of Kansanshi ore to frother dosage and grind

At lower frother dosages higher recoveries were only achieved at a finer grind, particularly for higher molecular weight products like Dowfroth 250 and Betafroth 245. This again is consistent with the secondary findings[63] in that high molecular weight glycol frothers are capable of giving reasonable recoveries even at lower frother dosages, especially when the ore is finer.
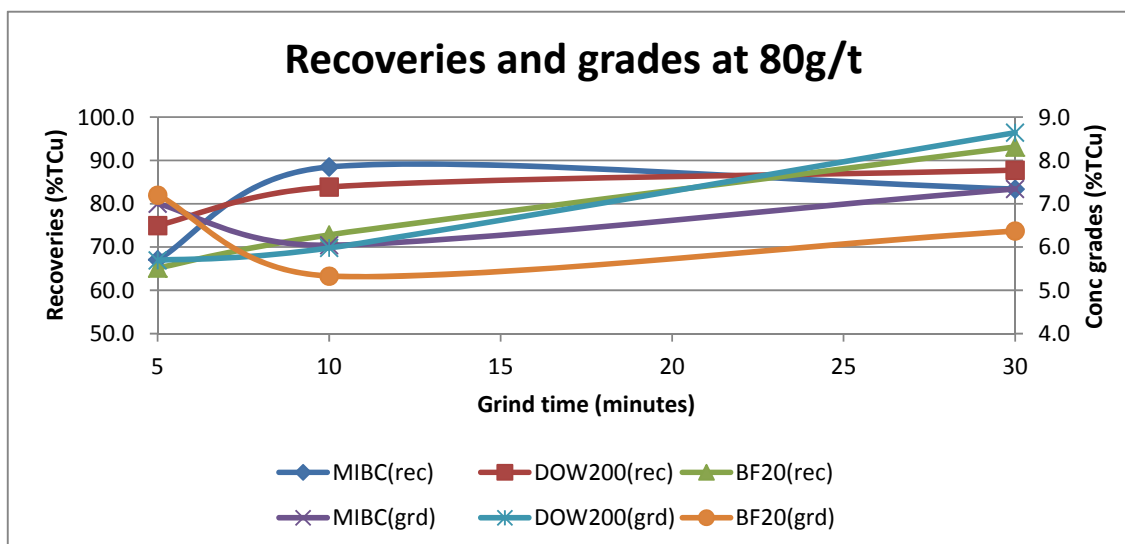
Fig. 4.41: Response of concentrate grades and recoveries of Kansanshi ore to grinding time at an optimal frother dosages of 80g/t for MIBC, Dowfroth 200 and Betafroth 20 frothers
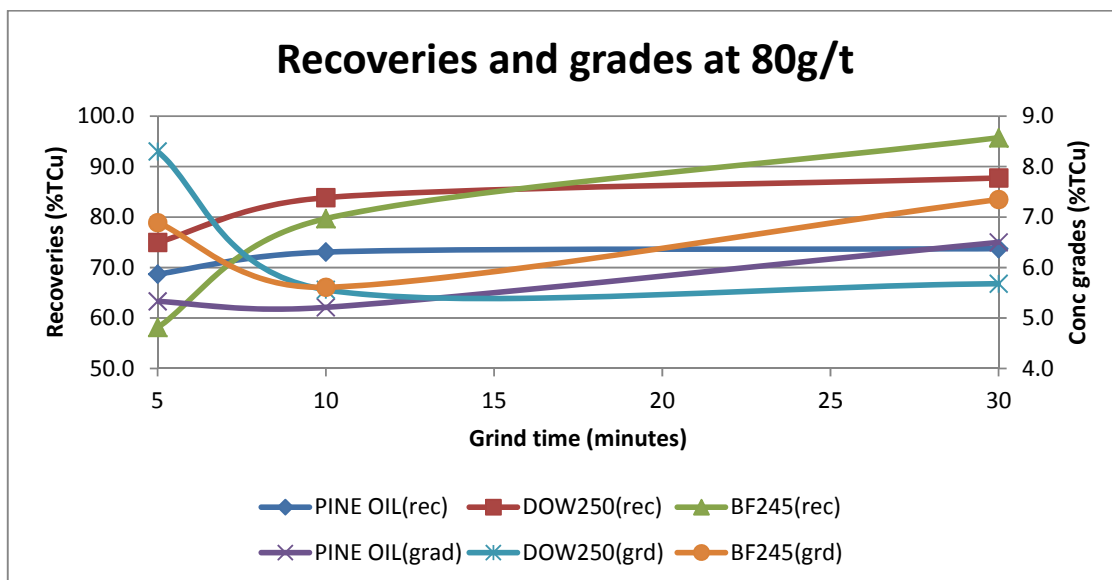
Fig 4.42: Response of concentrate grades and recoveries of Kansanshi ore to grinding time at an optimal frother dosages of 80g/t for pine oil, Dowfroth 250 and Betafroth 245 frothers

On the other hand, when the frother dosages were increased all frothers achieved reasonably higher recoveries. However, performance of alcohols and lower molecular weight frothers was better, in terms of recoveries and concentrate grades, at higher dosages and finer grind than they did at lower frother dosage and coarser grind (Figure 4.43). Higher flotation recoveries achieved with Dowfroth 200 and MIBC was consistent with the behaviour of low molecular weight glycols and alcohol frothers at higher frother dosage and finer grind [7,9], though the results were still inferior to those achieved with higher molecular weight frothers (Betafroth 245 and Dowfroth 250).
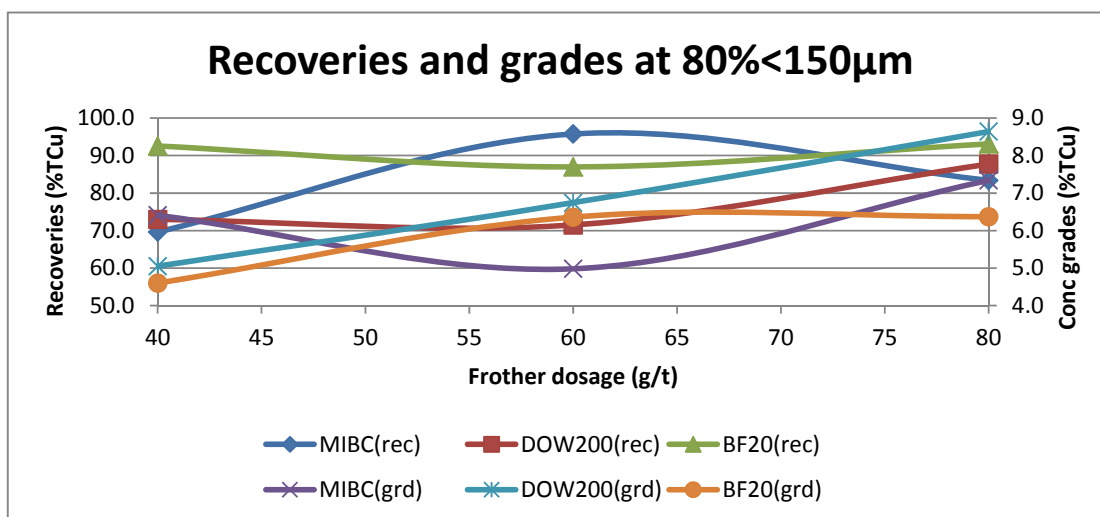
Fig. 4.43: Response of concentrate grades and recoveries to frother dosage at an optimal grind of 80% passing 150μm for MIBC, Dowfroth 200 and Betafroth 20 frothers
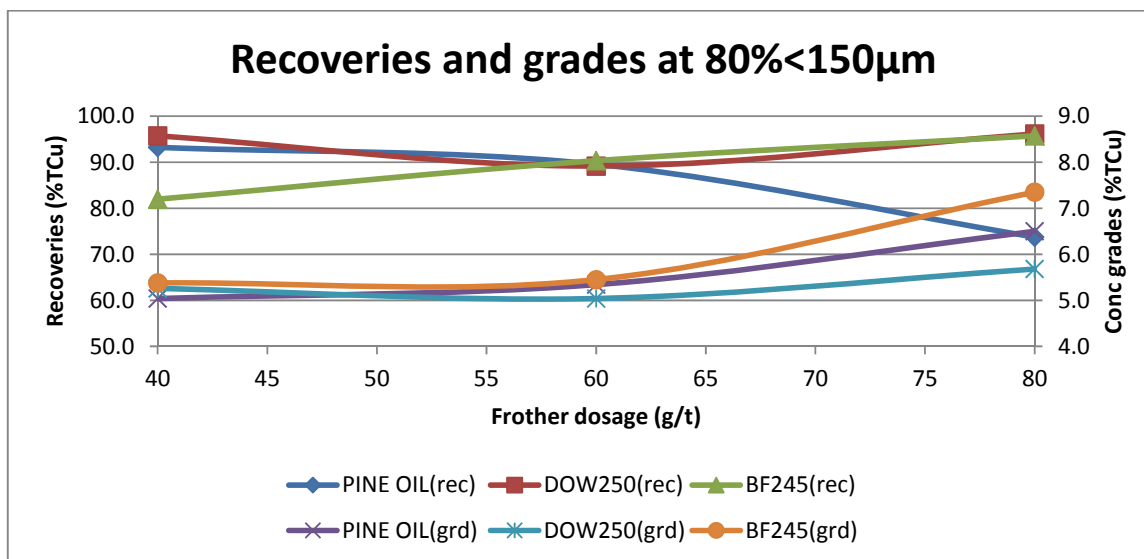
Fig. 4.44: Response of concentrate grades and recoveries to frother dosage at an optimal grind of 80% passing 150µm for pine oil, Dowfroth 250 and Betafroth 245 frothers

On the quality of the concentrates produced, the highest concentrate grades were achieved when lower molecular weight frother Dowfroth 200 followed by alcohol MIBC were used, particularly at finer grind. Unlike on Lumwana ore, Betafroth 245 gave some of the highest concentrate grades on Kansanshi ore compared to lower concentrate grades given by higher molecular weight glycol-based frother Dowfroth 250. This can be attributed to the finding that showed Lumwana ore unlike Kansanshi ore contains appreciable levels of semi-floatable gangue, which made both of these strong frothers give concentrates of poor grades on Lumwana ore. However, as established earlier Dowfroth 250 is also too stable a frother compared to Betafroth 245, and that the frother ends up recovering significant amounts of fine gangue on both ores. From the foregoing, Dowfroth 250 exhibited poor selectivity when used on both ores, especially at higher frother dosages and finer grind (Figure 4.44).

4.11   Flotation kinetics of Kansanshi ore

From the results shown in the graphs above it can be deduced that for Kansanshi sulphide ore, the best results (grades and recoveries) were achieved when all the frothers (to lesser extent pine oil) were used at higher frother dosage of 80g/t and finer grind of 80% passing 150µm. This point can therefore, be referred to as the optimised flotation conditions or simply economic conditions for the flotation of Kansanshi sulphide ore.

Therefore, further work in terms of determination of flotation kinetics using the six different frothers was conducted. The testwork involved collecting three concentrates from each test at intervals of one minute, two minutes and five minutes and scraping off the froth every 15 minutes. The tests were conducted four times. The average results obtained (Appendix III) were used to plot graphs below.
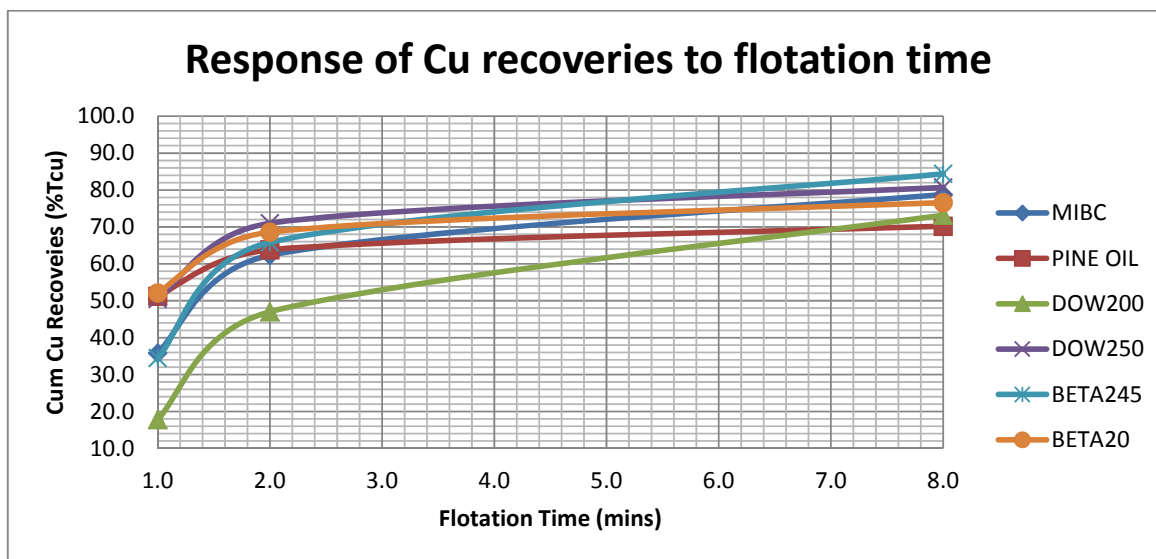
Fig. 4.45: Flotation kinetics of Kansanshi sulphide ore showing flotation recoveries as a function of flotation time at optimal condition of 80% passing 150μm and frother dosage of 80g/t

Figure 4.45 above shows that fastest flotation kinetics were achieved when using Betafroth 20, pine oil and Dowfroth 250 by recovering 52%TCu and 51%TCu and 50%TCu respectively in the first one minute of flotation. The frother with the slowest kinetics was Dowfroth 200 which only achieved 17%TCu recovery in the first minute of flotation.

After two minutes of flotation, Dowfroth 250 gave the fastest kinetics by achieving a cumulative copper recovery of 71%TCu, followed by Betafroth 20 (69%TCu) and MIBC (62%TCu). However, when flotation was extended for a further five minutes, the highest cumulative recovery of 84%TCu was achieved using Betafroth 245 followed by Dowfroth 250 (81%TCu), MIBC (79%TCu) and Betafroth 20 (77%TCu). Pine oil offered the lowest kinetics and achieved overall recovery of 70%TCu only.
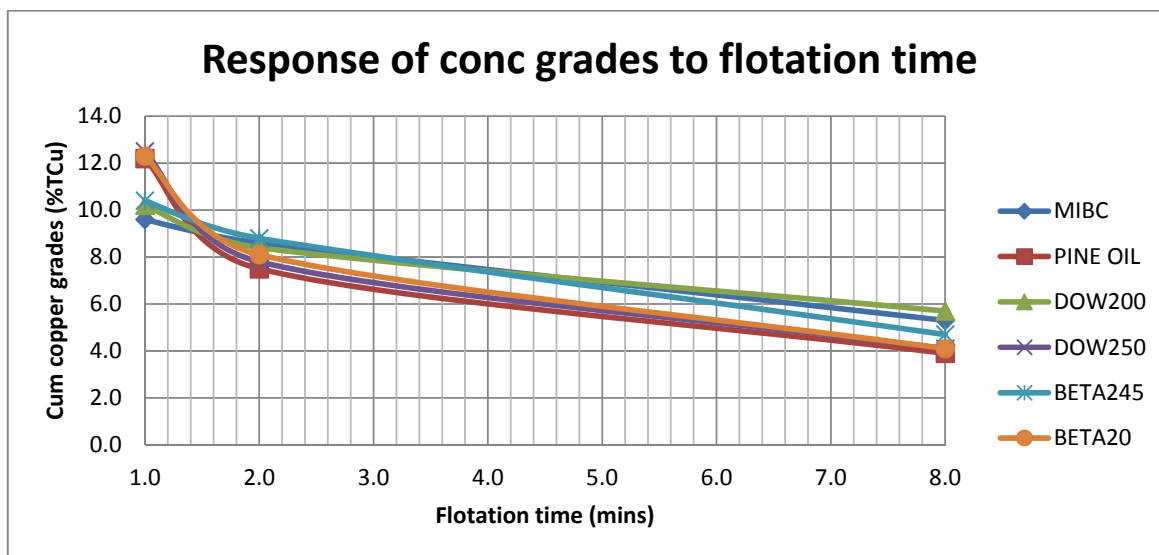
Fig. 4.46: Flotation kinetics of Kansanshi sulphide ore showing concentrate grades as a function of flotation time at optimal condition of 80% passing 150μm and frother dosage of 80g/t

On the concentrates, Figure 4.46 above shows that Dowfroth 200 gave the highest cumulative concentrate grade of nearly 6%TCu at the end of eight minutes of flotation, followed by MIBC and then Betafroth 245 with final concentrate grade of around 5%TCu. The rest (pine oil, Dowfroth 250 and Betafroth 20) all grave the lowest concentrate quality of 4%TCu each.
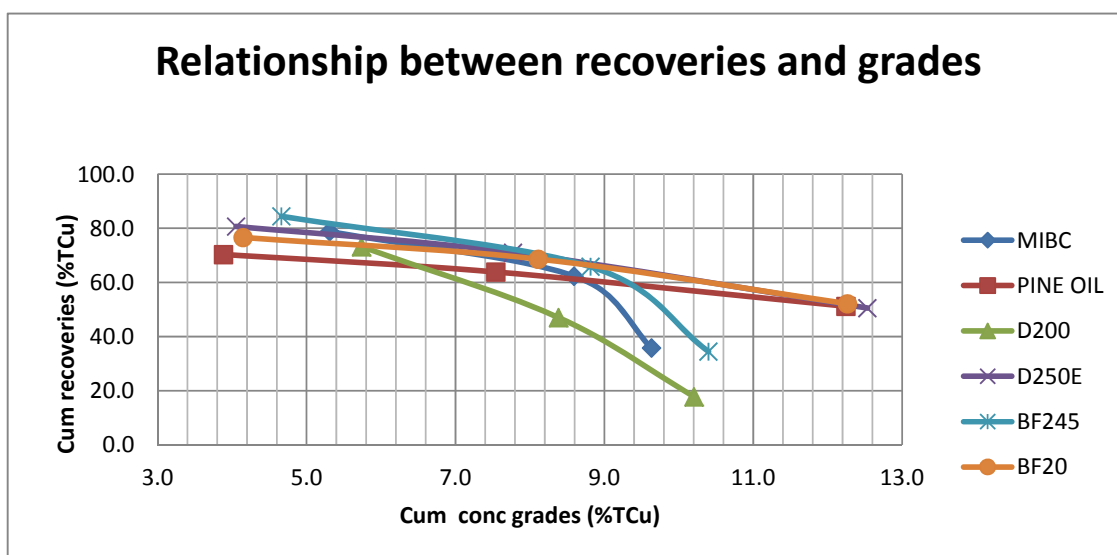
Fig. 4.47: The relationship between concentrate grades and flotation recoveries for Kansanshi sulphide ore

On Kansanshi sulphide ore, Figure 4.47 above confirms that higher molecular weight glycol-based frothers Betafroth 245 seemed to offer better grade-recovery curves, followed by Betafroth 20.

4.12   Discussion of flotation kinetics of Kansanshi sulphide ore

For Kansanshi ore, the fastest flotation kinetics were achieved using Betafroth 20 followed by pine oil and Dowfroth 250 in the first one minute of flotation. The frother with slowest kinetics in the first minute was Dowfroth 200.

After two minutes of flotation, Dowfroth 250 gave the highest flotation kinetics, followed by Betafroth 20 and Betafroth 245. However, after another five minutes of flotation, the highest (recoveries) kinetics were achieved using Betafroth 245 followed by Dowfroth 250, then MIBC and Betafroth 20. Pine oil gave out the lowest kinetics.

On the concentrate quality, though Dowfroth 200 gave the lowest concentrate grade at the first minute of float, it ended up with the highest concentrate quality at the end of full flotation, followed by MIBC. While pine oil gave the highest concentrate grades at start of flotation, it ended up with the lowest concentrate grade after the full eight minutes of flotation as shown in Figure 4.45. This can be attributed to the thinking that Kansanshi ore is highly disseminated and therefore the minerals only respond well at finer grind. But MIBC and Dowfroth 200 being of lower molecular weight glycol make-up offered higher selectivity, by picking up finer gangue initially but later rejecting it as flotation progressed [26].

The superior flotation performance of Betafroth 245 and MIBC on Kansanshi ore can be seen in Figure 4.45 above. Frothers Dowfroth 250, Betafroth 20 and pine oil came out third, fourth and fifth respectively, while Dowfroth 200 gave lowest grade-recovery curves.

However, flotation kinetics tests conducted at UNZA were compared with tests conducted at Kansanshi mine site (Figure 4.48), they showed superior kinetics of Dowfroth 250 from the start of flotation just to be over-taken towards the end of flotation by Betafroth 245. The Figure 4.48 also shows the slow starting kinetics of Dowfroth 200.
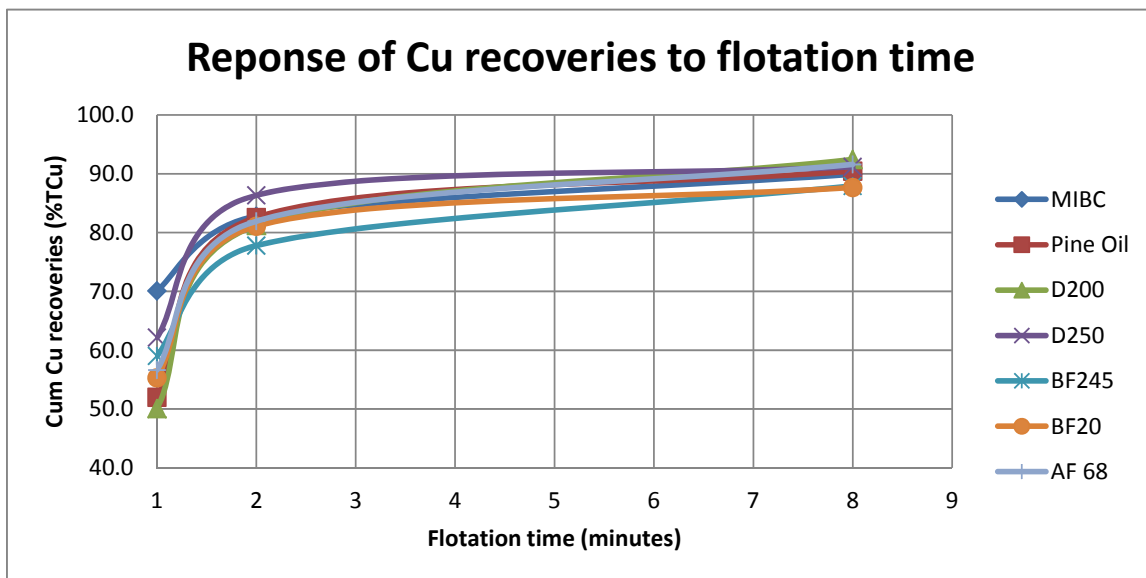
Fig. 4.48: Flotation kinetics of Kansanshi ore during water recovery testwork (cumulative recoveries)
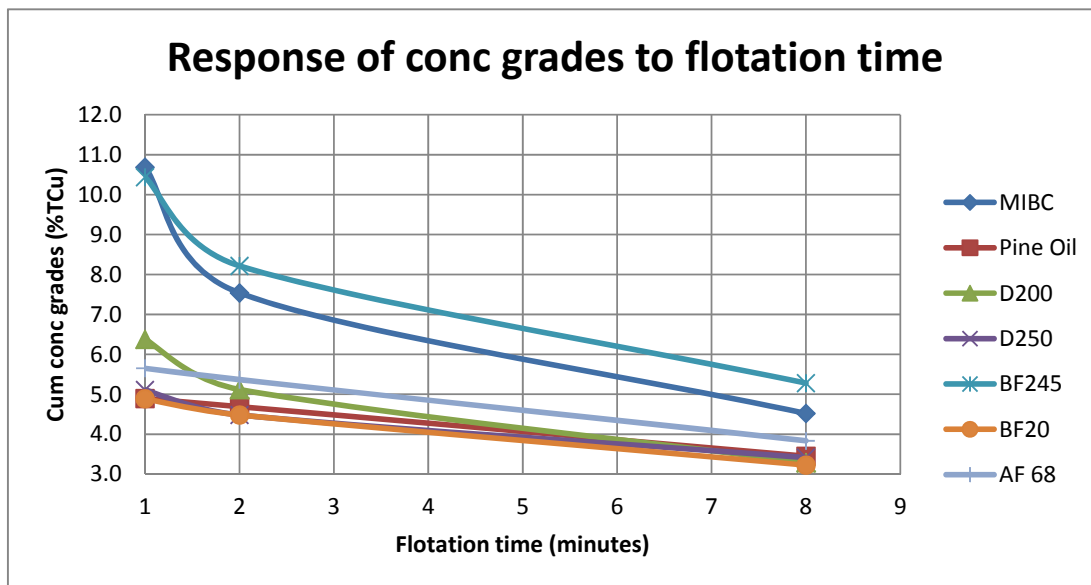
Fig. 4.49: Flotation kinetics of Kansanshi ore during water recovery testwork (cumulative concentrate grades)

Figure 4.49 above shows that Betafroth 245 gave superior concentrate grades throughout the entire flotation period, followed by MIBC. On the other end Betafroth 20 and Dowfroth 250 gave out the lowest concentrate grades.
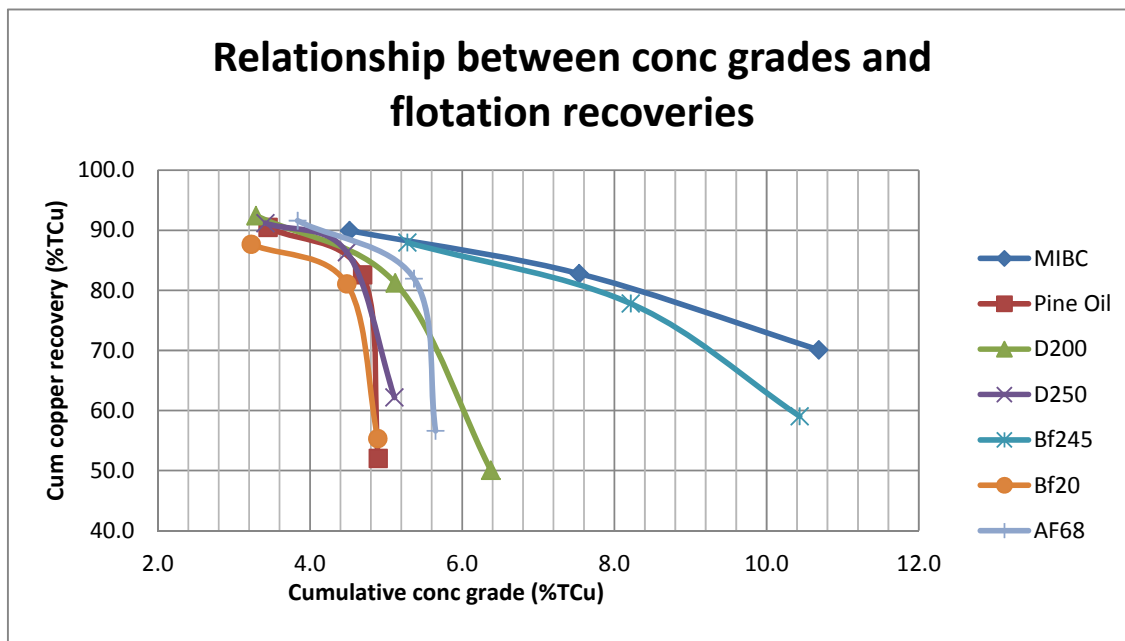
Fig. 4.50: Flotation kinetics grade-recovery (average) curves for Kansanshi ore

When flotation recoveries (Figure 4.48) and concentrate grades (Figure 4.49) were plotted in a grade-recovery relationship to produce Figure 4.50, it can clearly be seen that MIBC and

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Betafroth 245 gave superior grade-recovery curves, confirming results obtained earlier (Figure 4.47).

4.13   Discussion of flotation kinetics of Lumwana and Kansanshi ores

In general it seemed that although Lumwana ore was floated at a coarser grind (65% passing 150µm), lower molecular weight glycol-based and alcohol frothers (Dowfroth 200, MIBC and Betafroth 20) perform better in terms of concentrate grades and recoveries, yet the same frothers except MIBC did not perform as well on Kansanshi sulphide ore, which was floated at a finer grind (80% passing 150µm). This could be attributed to the fact that Lumwana ore contains appreciable amounts of semi-floatable fine gangue, while Kansanshi ore was only able to respond well (especially on recoveries) at finer grind and higher frother dosages, particularly when higher molecular weight glycol-based frothers (Betafroth 245 and Dowfroth250) were used. At finer grind and higher frother dosage, as earlier discussed [9], both glycol-based and alcohol frothers tend to perform well. Thus Betafroth 245 and MIBC gave superior results on Kansanshi ore.

On one hand, lower molecular weight and alcohol-based frothers (Dowfroth and MIBC) were more selective on Lumwana ore, while glycol-based frothers like Betafroth 245 and MIBC were more selective on Kansanshi ore. On the other hand higher molecular weight glycol frother, Dowfroth 250 and higher molecular alcohol-based frother Betafroth 20 were less selective on both ores. This goes further to explain that Lumwana ore contains some appreciable levels of semi-floatable gangue as shown [63], that dilutes concentrates produced by the two higher molecular weight frothers (Dowfroth 250 and Betafroth 20), due to the stabilisation effect of these finer gangue particles on froths formed by these frothers as seen from water recovery tests. Figures 4.56 and 4.57 show that on both ores Dowfroth 250 and Betafroth 20 recovered the largest quantities of water amongst all frothers tested. This finding goes on to agree with the secondary finding [49] that showed that fine gangue is more likely to give higher gangue entrainment into the concentrate, particularly when a higher molecular weight and stable frother like Dowfroth 250 is used at higher dosages.

The superiority of a linear aliphatic alcohol frother (MIBC), a lower molecular weight glycol frother (Dowfroth 200) and a mid to higher molecular weight glycol-based frother (Betafroth 245) over other frothers in terms of achieving higher grades and recoveries during flotation of Lumwana Kansanshi ores is shown in Figures 4.26 and 4.47. In these Figures the three frothers are shown to give higher grade-recovery curves because they contain lower molecular alcohols and lower molecular weight glycols and middle to higher molecular weight glycols respectively, that end up improving the physical properties of particle and bubbles attachment. The results should indicate that frothers containing lower to middle molecular weight glycols or alcohols allow better drainage of marginal particles in the froth phase and goes further and somehow affects the attachment of collector to marginal particles, hence the improvements in both concentrate grades and recoveries[27].

4.14   Determination of flotation characteristics of test frothers

In order to establish and compare the frothing characteristics of the frothers under investigations, it was essential to evaluate the frothers in terms of the effect each frother has on surface tension, bubble size, froth stability, and gangue entrainment. As stated earlier, measurement of surface tension helps in understanding the role a frother in particular or a surfactant in general plays in reducing surface tension of liquid in order to promote flotation. Also as explained earlier, bubble size measurement helps in understanding the role a frother plays in creation of smaller bubbles, controlling the rate at which a bubble can rise through the pulp phase, and promoting froth

stability. Measurements of froth stability and gangue entrainment levels help in understanding the role a frother plays in froth formation, distribution and stability.

Therefore, surface tension, bubble size analysis and froth stability tests were conducted at University of Cape Town, Centre for Mineral Research (CMR) laboratories.

4.14.1 Surface and interfacial tension analyses

The surface tension experiments were conducted on a two-phase (water/air) system using the ring method by varying frother concentration in distilled water. The concentration of the frother in water was varied from zero ppm (pure distilled water), 6.25ppm, 12.5ppm, 25ppm, 50ppm and 100ppm. From the results obtained (see Appendix VI) the graph below was drawn;
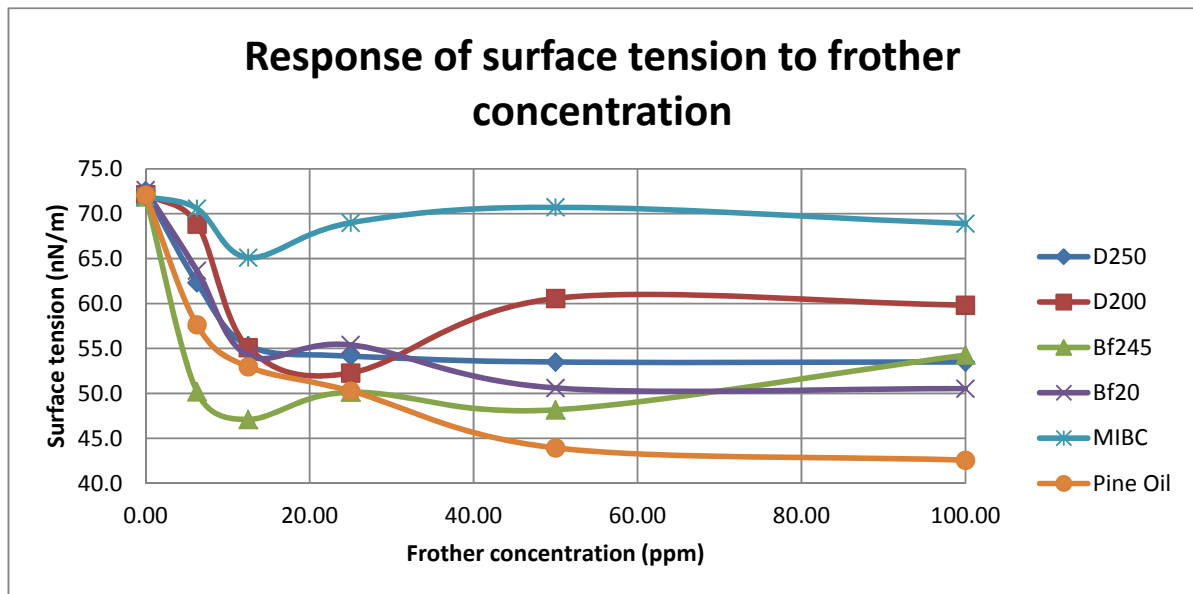
Fig.4.51: Two-phase (water/air) surface tension results at different frother concentrations

Figure 4.51above shows surface tension as a function of concentration of the six frothers tested (i.e. Dowfroth 250, Dowfroth 200, Betafroth 245, Betafroth 20, MIBC and pine oil). Initially the surface tensions of all frothers decreased drastically from 74nN/m (surface tension of pure distilled water), to less than 55nN/m for all except MIBC which only decreases to 65nN/m at the concentration of 12,5ppm. As frother concentration increased from 12,5ppm to 25ppm the surface tensions rose again after which it leveled till the final concentration of 100ppm. This behavior indicates that the critical micelle concentration (c.m.c.) for surfactants could have been reached around 25ppm.

4.14.2 Discussion of surface tension analyses results

As stated earlier, surface tension as a function of concentration of the frothers tested decreased as the number of frother molecules move from the bulk solution to the interface, and reached its final value when the interface was fully occupied. As observed from the graphs in Figure 4.51 all the frothers, including MIBC to a lesser extent, show a sudden drop in the surface tension at lower concentration up to about 20ppm, indicating that the frothers tested were more surface active at lower concentrations. The decrease in the surface tension is an indication that there is an increase in frother adsorption [7] at the air/water interface. These solutions of surfactants exhibit

unusual physical properties, in that at dilute concentrations, the surfactant acts as a normal solute. But at fairly defined concentrations, however, abrupt changes in the physical properties, such as surface tension of the solution take place. These changes can suggest that some considerable association is taking place for surfactants[19].

Beyond the concentration of 20ppm however, the surface tension started to level off suggesting that the interface was saturated and the critical micelle concentration (c.m.c) had been reached. The critical micelle concentration denotes the concentration at which any addition of surfactant or frother after the c.m.c, instead of absorbing on the air/water interface, it is utilized in the formation of colloidal aggregates, known as micelles, within the bulk of the solution[7].

Surface tension measurements could also help explain the hydrophobic effect the frothers have on lowering the critical micelle concentration of the solutions. Figure 4.51 also shows that the frothers that achieved the lowest critical micelle concentrations were Dowfroth 200, Betafroth 245, MIBC and to lesser extent Betafroth 20, in that order. The three frothers showed a sudden dip in c.m.c between 6,25ppm and 25ppm concentrations, while the rest of the frothers showed a gradual decline in the relevant concentration range. The theory illustrated with Figure 2.3[7] had showed that the surfactant with a lowest c.m.c. leads to higher hydrophobicity effect[19] on the flotation process. Interestingly, the three frothers (Betafroth 245, MIBC, and Dowfroth 200) seemed to have also given superior flotation performance (grade-recovery curves) during flotation of the two ores. It can therefore be deduced that hydrophobicity effect created by the same frothers went further to create synergistic action with the collector during flotation, probably due to a reduction in repulsion which exists between the ionic polar groups[7]. The synergy between the frothers and collector had a positive effect on performance of the surfactants and consequently resulted in appreciable improvement in flotation response of the ores when the three frothers were used.

4.14.3 Bubble size analyses

The concentration of each of the six frothers was varied at 5ppm, 12.5ppm, 25ppm, 50ppm and 100ppm and then tested on the UCT bubble size analyser. All the experiments were conducted using simulated plant (synthetic) water. From the results obtained (see Appendix VII), the graphs below were drawn;
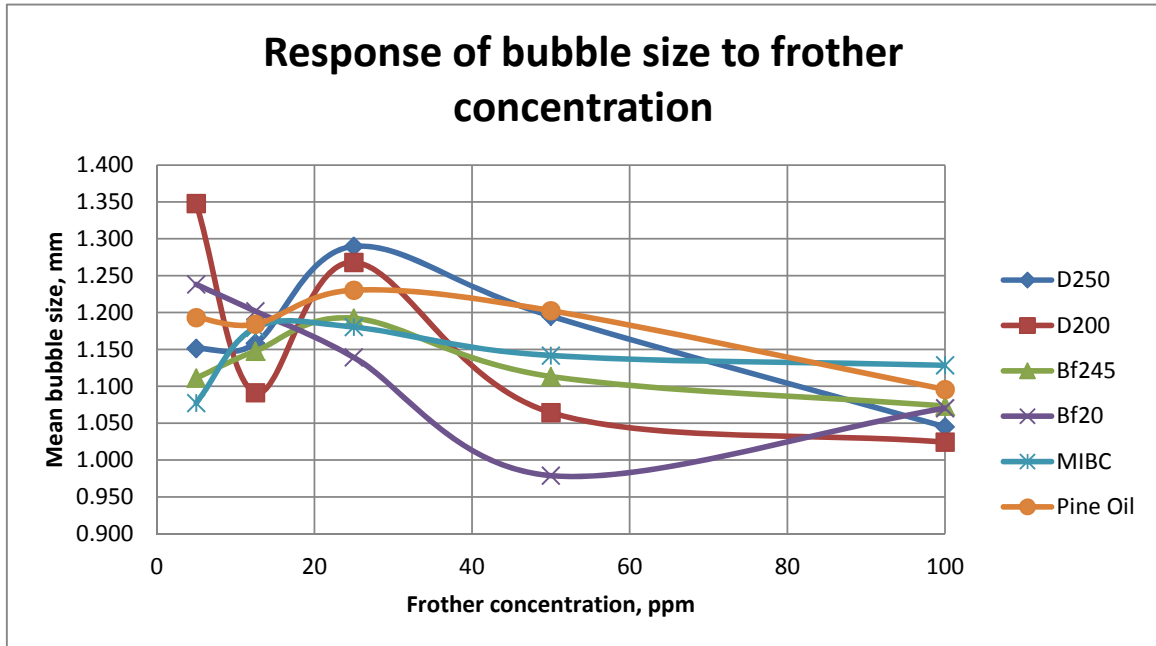
Fig. 4.52: Mean bubble size results at different frother concentrations

Figure 4.52 above shows bubble size distribution obtained as a function of concentration of the six frothers tested (i.e. Dowfroth 250, Dowfroth 200, Betafroth 245, Betafroth 20, MIBC and pine oil). Betafroth 20 seemed to have produced smallest bubbles of around 1.00mm diameter at 40ppm before leveling-off after the 50ppm concentration. The smaller bubble size of Betafroth 20 was followed by Dowfroth 200 and then Betafroth 245. At 40ppm concentration, Dowfroth 250, pine oil and MIBC produced larger bubbles sizes of 1.25mm, 1.20mm and 1.15mm respectively.

Generally, the graphs show that bubble size decreases as the concentration of frothers in the water increases. And all the frothers, with exception of Betafroth 20 (which gave a gradual drop), showed a sudden drop in the bubble size from 5ppm to 12.5ppm concentration and then another peak at 25ppm, after which there seems to be a steady decrease to 60ppm. This behaviour can indicate that the critical coalescence concentration was around 25ppm.

4.14.4 Discussion of bubble size analyses results

Results of the bubble size analyser show there are various bubble sizes obtained as a function of concentration of the six frothers tested. Figure 4.52 shows that bubble size decreases as the concentration of frother in the water increases. However, all the frothers showed a sudden drop in the bubble size from 5ppm to 12.5ppm concentration and another peak around 25ppm, after which there seem to be a gradual decline through 60ppm till 100ppm concentrations.

A frother plays two major roles, in the pulp phase it reduces bubble size by preventing coalescence, while in froth phase it increases froth stability. While it is a known fact that frother prevents bubble coalescence in the pulp phase, there exists a critical concentration of frother called critical coalescence concentration, beyond which any extra frother added, apart from giving smaller bubbles will also give improved froth stability[33]. In the experiments, this critical coalescence concentration (CCC) seemed to have been reached by nearly all frothers tested

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around 25ppm (Figure 4.52). In practice however, the aim is to dose sufficient frother to ensure that the CCC is surpassed. This condition gives the smallest possible bubbles in the cell required for maximizing the bubble specific surface area available to particles attachment[33].

On one hand, prevention of coalescence and creation of stable froth helps in improving the concentrate grades, on the other hand, controlling the rate at which air bubbles rise in the pulp to the surface determines the mineral recovery or recovery of valuables from the pulp. Yet, the rate at which bubbles are transported through the cell is largely influenced by operational variables of air flow-rates and froth depth[53].

Hence Figure 4.52 shows that after the critical coalescence concentration was passed Dowfroth 200, Betafroth 245 and MIBC came out with smallest bubble sizes of around 1,0mm. This may seem to support the performance of the three frothers, particularly on Lumwana ore, whereby smaller bubbles that were formed created a large surface area and hence increased kinetics (recoveries). Smaller bubbles were good for rejection of finer gangue from the concentrate, thus improving selectivity, when the three frothers were used.

On one hand, the bubble size distribution of Betafroth 20 from Figure 4.52 may seem to suggest that this frother gave smaller bubbles immediately after the CCC was surpassed, but the bubbles suddenly grew in size after reaching a concentration of 60ppm. This could help explain the behaviour of the frother (Betafroth 20) during the flotation of both Lumwana and Kansanshi ores, whereby the frother started with very high kinetics (when the bubbles were smaller), but only to drop in kinetics as flotation progressed (due to increase in bubble sizes). Consequently, the frother became less selective.

Figure 4.52 further shows that Dowfroth 250 gave the larger bubble size distribution at lower frother concentrations (dosages), but at higher frother concentrations (100ppm) the frother produced smaller bubbles second only to bubble sizes produced with Dowfroth 200. This seems to agree with it general flotation performance, in that its performance was enhanced at higher dosages.

4.14.5 Froth stability test analyses

Froth stability measurements were conducted using the Bikerman column flotation cell (Figure 3.5). The measurements were conducted on the two-phase (water/air) system at frother concentrations of 50ppm, 100ppm, 150ppm, 200ppm, 250ppm and 300ppm. The froth height achieved with each dosage and time it took for the froth to collapse (reaction time) was recorded. Thereafter, from the data obtained (see Appendix V) the graphs below were drawn.
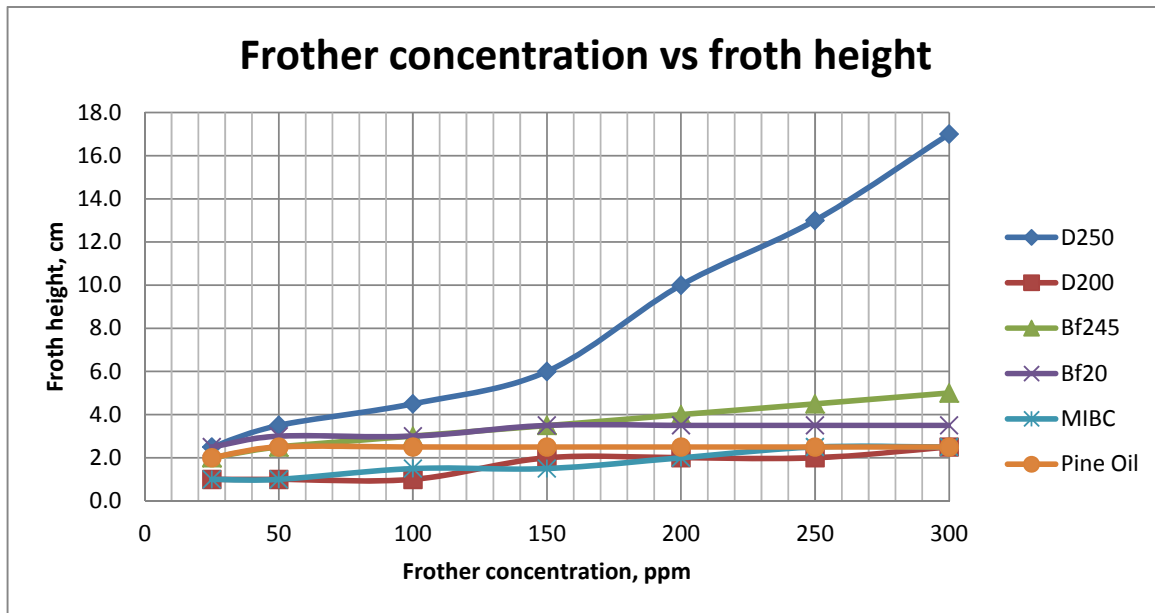
Fig. 4.53: Response of froth height to frother concentration

Figure 4.53 above shows that of all the frothers tested, Dowfroth 250 gave the highest froth heights at all concentrations tried. The highest froth height given was 17cm, achieved when the frother was used at a concentration of 300ppm. Betafroth 245 was a distant second achieving a maximum froth height of 5cm when used at 300ppm concentration. Betafroth 245 was followed by Betafroth 20 achieving a maximum froth height of 4cm at 150ppm. The rest of the frothers (D200, MIBC and pine oil) achieved maximum froth heights of 2.5cm each at the concentrations of 300ppm.
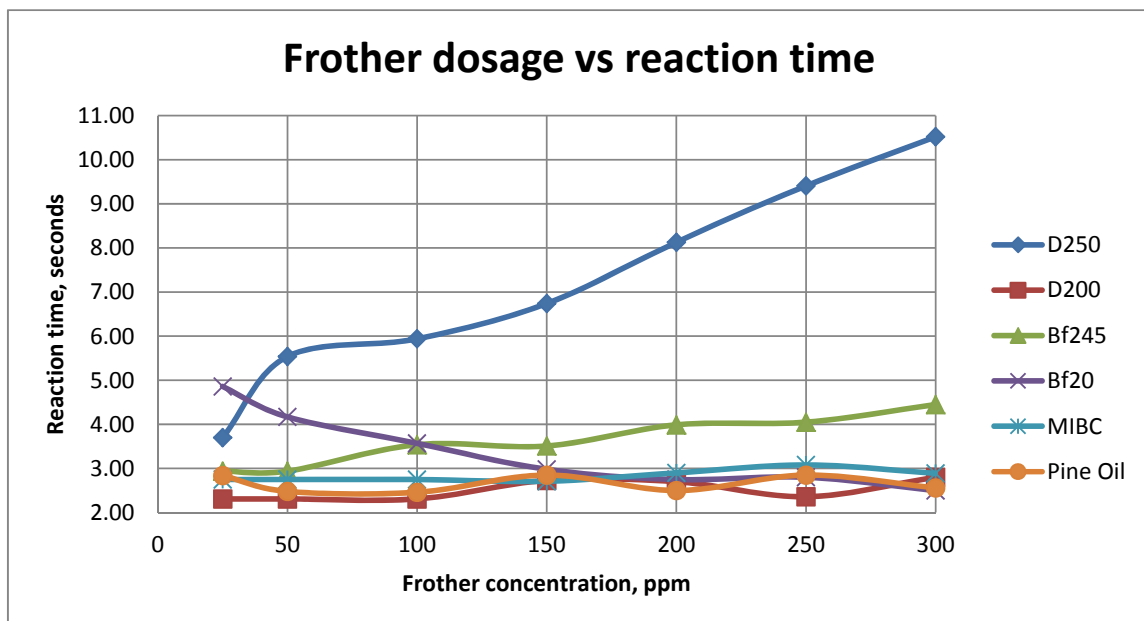
Fig. 4.54: Relationship between frother concentration and collapse rate (reaction time)

Figure 4.54 above shows that when frothers concentration was recorded against time it took for the froth to collapse (reaction time), Dowfroth 250 gave the highest reaction time, achieving a maximum of 10.5 seconds for the froth to completely collapse from dosage of concentration 300ppm. The Dowfroth 250 was followed by Betafroth 245, which gave the maximum reaction time of almost 4.5 seconds at the same concentration. The rest of the frothers (Dowfroth 200, Betafroth 20, MIBC and pine oil) achieved a reaction time of 3 seconds each.
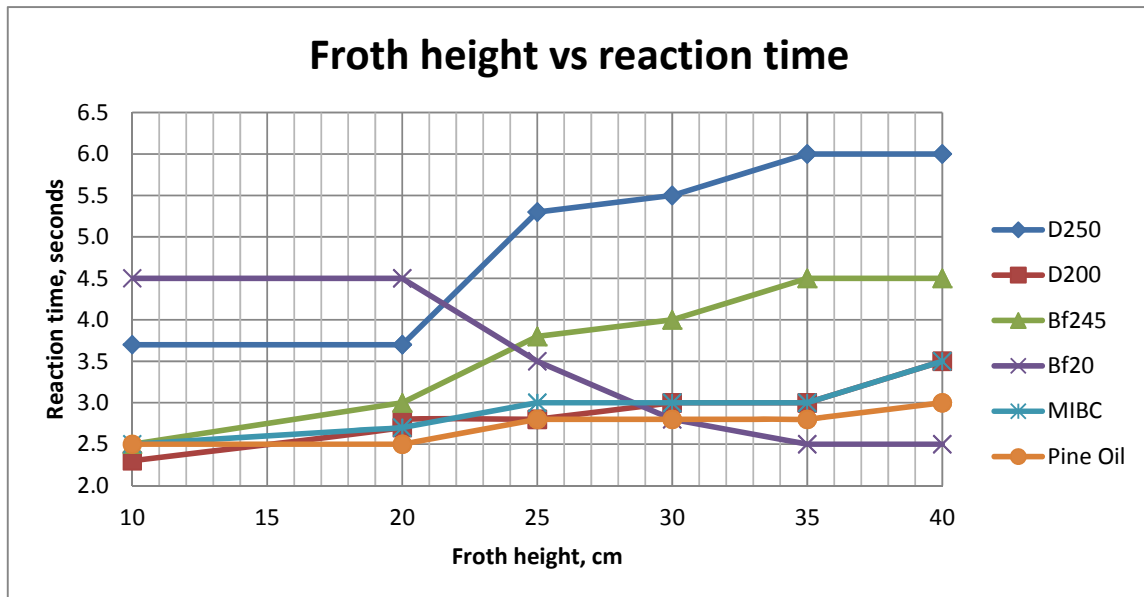
Fig.4.55: Relationship between froth height and collapse rate (reaction time)

Similarly, when froth height was plotted against the reaction time (collapse rate) (Figure 4.55), it can be seen that Dowfroth 250, followed by Betafroth 245 achieved the highest or reaction times of 6 seconds and 4.5 seconds respectively from a froth height of 40cm. Betafroth 20 gave the lowest reaction time of 2.5 seconds.

4.14.6 Discussion of froth stability tests

From the results of froth stability tests it can be deduced that high molecular weight glycol frother Dowfroth 250 formed a highly stable froth compared with all other five frothers tested. But this high stability was formed at the expense of high water recovery and therefore higher entrained gangue. However, the froth formed by Betafroth 245 was a much "drier", because as seen in Figures 4.53, 4.54 and 4.55, frother Betafroth 245 recovered less water compared to Dowfroth 250, consequently the frother gave higher concentrate grade-copper recovery curves, particularly on Kansanshi ore (Figure 4.47).

When computer regression (trend) lines were fitted to the graphs shown in Figure 4.55, in order to obtain a linear relationship between froth height and reaction time [34] (see Appendix V), following collapse rate constants, k, were obtained; MIBC ($0.082s^{-1}$), Pine Oil ($0.049s^{-1}$), Dowfroth 200 ($0.094s^{-1}$), Dowfroth 250 ($0.095s^{-1}$), Betafroth 245 ($0.200s^{-1}$) and Betafroth 20 ($-0.242s^{-1}$). It can be seen from collapse rate constants that Betafroth 245 and Dowfroth 250 gave the largest rate constants, meaning the two frothers had the fastest collapse rates [34].

Recovery of valuables and good concentrate grades are strongly dependent on the stability of the froth phase within the flotation system. Hence, a stable froth zone allows for the efficient

transportation of material for downstream processing. The use of higher frother dosages may also be a way to stabilise the froth phase. As stated above, during bubble size analysis, any extra frother added after reaching critical coalescence concentration had no effect on the pulp phase kinetics, but gave smaller bubbles for improved froth stability [33].

4.14.7 Water recovery and entrainment tests

In order to further compare the effect each frother could have on gangue entrainment, water recovery flotation tests were conducted on Lumwana and Kansanshi ores at the respective mine sites. A kinetic flotation testwork was carried out using the six test frothers plus the two plant standard frothers. The flotation work involved testing each frother at flotation conditions of 60g/t frother dosage and of 65% passing 150µm grind for Lumwana ore, and 80g/t and 80% passing 150µm for Kansanshi ore respectively. The tests were conducted in duplicate and average results obtained (Appendix IV) were used to draw the graphs shown below.
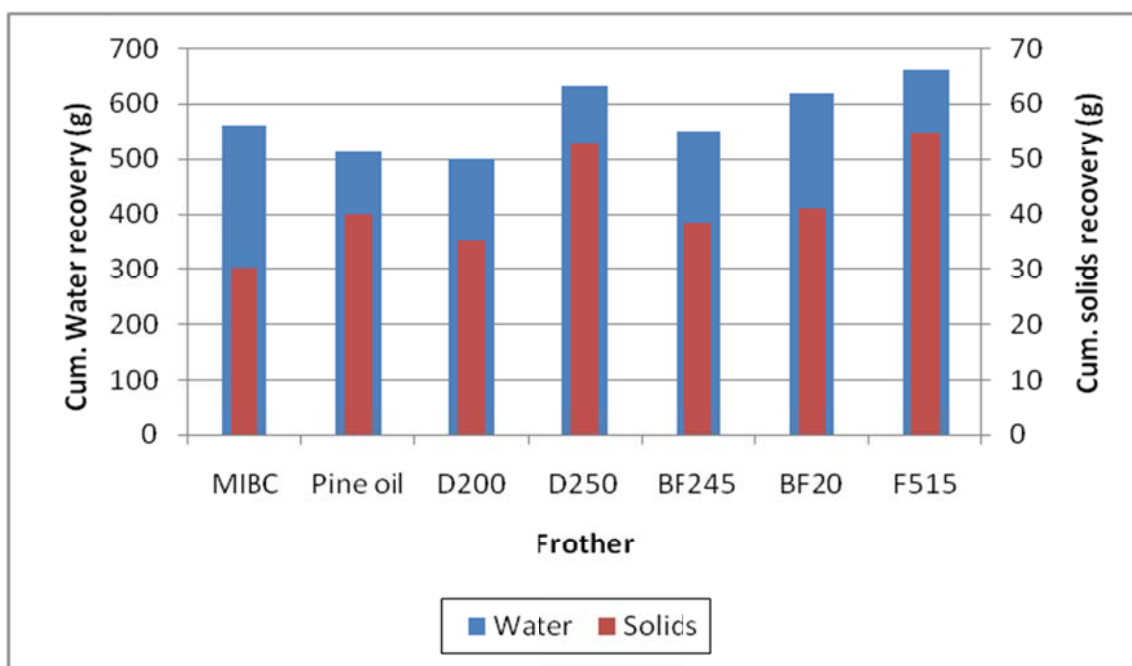
Fig.4.56: Water recovery and entrainment levels for Lumwana ore

Figure 4.56 above shows that for Lumwana ore, lower molecular weight glycol frother Dowfroth 200 recovered the least amount of water and consequently less gangue entrainment. Dowfroth 200 was followed by alcohol frother pine oil and then glycol-based formulated frother Betafroth 245. On the other hand, Lumwana plant standard frother Oreprep F515 and higher molecular weight glycol frother Dowfroth 250 recovered the largest amounts of water and therefore, largest amounts of entrained gangue, followed by Betafroth 20.
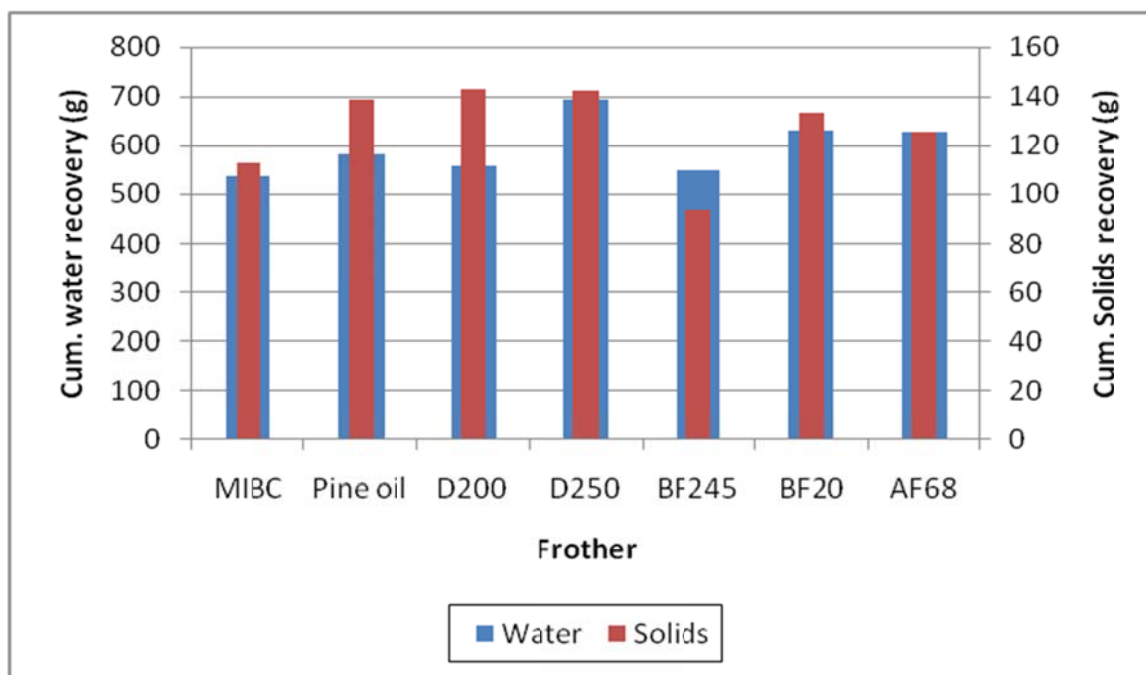
Fig.4.57: Water recovery and entrainment levels for Kansanshi sulphide ore

From the graphs in Figure 4.57, it can be seen that on Kansanshi sulphide ore, glycol-based formulated frother Betafroth 245 recovered the least amount of water, followed by MIBC and Dowfroth 200. On the contrary, higher molecular weight glycol frother Dowfroth 250 recovered the largest amount of water, followed by alcohol-based frother Betafroth 20 and then the Kansanshi plant standard frother Aerofroth 68.

4.14.8 Discussion of water recovery and gangue entrainments tests results

From the water recovery tests one can conclude that on Lumwana ore pine oil, followed by lower molecular weight glycol frother Dowfroth 200, recovered the least amount of water, while higher molecular weight glycol frother Dowfroth 250 followed by Betafroth 20, recovered the largest amounts of water (Figure 4.56). On Kansanshi sulphide ore, however, glycol-based frother Betafroth 245 followed by aliphatic alcohol MIBC recovered the least amount of water, while Dowfroth 250 followed by Betafroth 20 still recovered the largest amounts of water (Figure 4.57).

Research work elsewhere [45,49] had shown that 20 percent recovery of water in the froth gives 20 percent recovery of fines in the froth, and the same work found that the recovery of valuable minerals is directly related to the stability of the froth phase, since entrained gangue follows water recovery. Therefore, when graphs in Figures 4.24to 4.46 are examined against those in Figures 4.56 and 4.57, and since higher molecular weight glycol frother Dowfroth 250 recovered largest amounts of water, it can be seen that the frother Dowfroth 250 also gave an inferior grade-recovery curve compared to those given by MIBC and Betafroth 245, due to the fact that the froth formed by Dowfroth 250 was also responsible for recovery of significant amounts of finer gangue particles. While a frother that gives a stable froth is desirable for good valuable mineral recovery, it is possible for the same frother to recover large amounts of water too. This is true for Dowfroth 250 in that apart from giving higher copper recoveries, it also recovered large amounts of water, compared to MIBC, Dowfroth 200 and Betafroth 245. The good flotation response

with, MIBC, Dowfroth 200 and Betafroth 245 can be explained in the make-up of the respective frothers. As stated earlier MIBC and Dowfroth 200 are lower molecular weight alcohol and glycol frothers, while Betafroth 245 though is classified as higher molecular weight frother (C_5 and C_6) contains some lower and middle molecular weight glycols (C_3 and C_4) , as shown in the secondary findings [61,62,69].

CHAPTER FIVE

5.0   CONCLUSIONS AND RECOMMENDATIONS

5.1   Lumwana ore optimisation testwork

The laboratory optimisation testwork on Lumwana ore established the following;
- The economic (standard) flotation conditions for the ore were determined as being at a grind of 65% passing 150μm and a frother dosage of 60g/t.
- The highest copper recoveries were achieved using frothers Dowfroth 250, MIBC, Betafroth 245 and Dowfroth 200, at all flotation conditions tested.
- Higher flotation recoveries were achieved using lower molecular weight frothers (MIBC and Dowfroth 200) only when the frothers were used at higher frother dosages and finer grind.
- Alcohol frother, pine oil gave the lowest flotation recoveries and grades across, at all flotation conditions tested.
- The highest concentrate grades were achieved using lower molecular weight frothers (MIBC and Dowfroth 200), particularly at lower frother dosages and finer grind.
- The lowest concentrate grades were given by higher molecular weight glycol frother Dowfroth 250 across all flotation conditions tested.
- At a grind of 65% passing 150μm and a frother dosage of 60g/t, Betafroth 245 offered the superior grade-recovery curve.

5.2   Lumwana ore flotation kinetics testwork

Flotation kinetics conducted on Lumwana ore at established optimum conditions and showed the following average results;

Frother type	Grade(%TCu)	Recovery (%TCu)
MIBC	8.9	74.9
PINE OIL	6.5	70.3
DOWFROTH 200	7.3	72.1
DOWFROTH 250	6.2	75.0
BETAFROTH 245	6.7	74.1
BETAFROTH 20	5.8	73.7

- The best flotation recoveries were achieved using a higher molecular weight glycol Dowfroth 250 closely followed by an aliphatic alcohol frother MIBC and formulated frothers Betafroth 245 and Betafroth 20.
- Alcohol frother, pine oil gave the lowest flotation recoveries.
- The best concentrate grades were achieved using MIBC, followed by a lower molecular weight frother Dowfroth 200 and Betafroth 245.
- Betafroth 20 gave the lowest concentrate grades.
- The lower molecular weight frothers (MIBC and Dowfroth 200) offered superior grade-recovery curves.
- The fastest overall flotation kinetics were given by lower molecular weight glycol frother Dowfroth 200 followed by glycol-based formulated frother Betafroth 245.
- The lowest gangue entrainments levels were achieved using a lower molecular weight glycol frother Dowfroth 200, followed by pine oil, Betafroth 245 and MIBC.

5.3   Kansanshi sulphide ore optimisation testwork

The laboratory optimisation testwork on Kansanshi ore established the following;
- The economic conditions for flotation of Kansanshi ore were determined as being at a grind of80% passing 150μm and frother dosage of 80g/t.
- The highest copper recoveries were achieved using frothers Dowfroth 250, MIBC and Betafroth 245 across all flotation conditions tested.
- Higher recoveries for alcohol frothers were normally achieved at higher frother dosage and finer grind.
- The highest concentrate grades were achieved using lower molecular weight frothers (i.e. Dowfroth 200 and MIBC) at all conditions tested.
- Alcohol frother pine oil gave the lowest flotation recoveries and grades across all flotation conditions tested.
- At a grind of 80% passing 150μm and a frother dosage of 80g/t, Betafroth 245 offered the superior grade-recovery curve.

5.4   Kansanshi ore flotation kinetics testwork

Flotation kinetics was conducted on Kansanshi ore at established economic conditions and showed the following average results;

Frother type	Grade(%TCu)	Recovery (%TCu)
MIBC	4.9	84.4
PINE OIL	3.7	80.4
DOWFROTH 200	4.5	82.9
DOWFROTH 250	3.8	85.9
BETAFROTH 245	5.0	86.2
BETAFROTH 20	3.7	82.1

- The best flotation recoveries were achieved using a higher molecular weight glycol-based formulated frother Betafroth 245 closely followed by higher molecular weight glycol frother Dowfroth 250 and aliphatic alcohol frother MIBC.
- Alcohol frother pine oil gave the lowest recoveries.
- The best concentrate grades were achieved using glycol-based formulated frother Betafroth 245,closely followed by MIBC and Dowfroth 200.
- Pine oil and Betafroth 20 gave the lowest concentrate grades.
- Formulated frother Betafroth 245 and alcohol MIBC offered superior best concentrate grade-recovery curves followed Dowfroth250.
- The fastest overall flotation kinetics were achieved using lower molecular weight glycol frother Dowfroth 200 followed by glycol-based formulated frother Betafroth 245.
- The lowest gangue entrainment levels in the concentrate were achieved using glycol-based formulated frother Betafroth 245 followed by MIBC and Dowfroth 200.

5.5   Surface tension analyses

Frothers Dowfroth 200, Betafroth 245, MIBC and Betafroth 20 achieved the lowest critical micelle concentrations. A lower critical micelle concentration being an indication that there is increased adsorption of surfactant (frother) at the interface and therefore, the frothers had a higher hydrophobicity effect on the flotation performance of the ore by creating synergy with the collector, resulting in superior flotation results.

5.6   Bubble size analyses

Beyond the critical coalescence concentration, Betafroth 20, Dowfroth 200, Betafroth 245 and MIBC came out with smallest bubble sizes. Smaller bubbles enhanced flotation kinetics (recoveries) and selectivity (concentrate grades) for the mentioned frothers thus giving superior flotation performance on the two ores tested

5.7   Froth stability testwork analyses

Higher molecular weight glycol frother Dowfroth 250 gave a highly stable froth and fastest collapse rates (reaction time) followed by glycol-based formulated Betafroth 245.

5.8   Water recovery gangue entrainment testwork

Water recovery tests showed that, on both ores, MIBC, Dowfroth 200 and Betafroth 245 recovered the least amounts of water. In order to get best grade-recovery curves frothers MIBC, Dowfroth 200 and Betafroth 245 are best suitable for treatment of Lumwana and Kansanshi ores respectively.

5.9   Recommendations

5.9.1   Recommendations for action

- Since it is practically difficult to come up with firm conclusions in the case of laboratory evaluation of frothers, it is being recommended to test MIBC or Dowfroth 200 and Betafroth 245 or Dowfroth 250 on Lumwana and Kansanshi circuit respectively. Together with price of these products, the plant trials will enable the respective plants to confirm the frother consumption patterns and thereafter economically evaluate the products.

- Depending on the pricing of MIBC and Dowfroth 200 a new lower molecular weight product (a combination between Betafroth 245, Betafroth 20, MIBC and Dowfroth 200) should be formulated for Lumwana circuit, since formulated products are generally cheaper than single or tradition products.

5.9.1   Recommendations for further study

- Further work is recommended to establish the role pH would play in the hydrophobic effect of a frother between a mineral particle and bubble at one end, and the interfacial surface carrying opposite charge on the other, in order to confirm the results of the surface tension and bubble size analysis.

- This work did not include froth formation and distribution measurements. It is therefore, being recommended that bubble formation and distribution tests, using high speed camera, be carried out in order to fully appreciate the role frothers play in froth formation, distribution and stability.

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APPENDICES

Appendix I – Screen analyses results

<u>Lumwana ore screen analysis results, using British Standard, BSS 410</u>

- Aperture	-	-	- 15mins	-	- 30mins	- 45mins	- 60mins
300			78,3		89,0	96,8	98,8
212			64,7		79,2	92,7	96,6
180			**59,8**		**75,1**	**90,5**	**95,3**
125			43,1		56,5	79,1	87,4
90			31,6		40,4	67,9	79,3
63			**22,7**		**30,9**	**59,3**	**71,8**
-63			0,0		0,0	0,0	0,0
Total							

<u>Kansanshi ore screen analysis results, using British Standard, BSS 410</u>

- Aperture	- 5mins	- 10mins	- 15mins	- 20mins	- 30mins	- 45mins	- 60mins
300	61,5	68,9	72,2	79,7	80,5	84,4	87,9
212	58,1	67,2	71,3	79,3	80,2	84,2	87,8
180	**57,1**	**66,2**	**70,9**	**78,9**	**80,1**	**84,2**	**87,8**
125	57,0	61,4	67,7	76,5	79,0	83,6	87,5
90	45,5	61,0	62,0	76,5	75,8	82,1	86,6
63	**37,4**	**45,4**	**52,0**	**61,8**	**67,5**	**76,5**	**82,9**
-63	**0,0**	0,0	0,0	0,0	0,0	0,0	0,0
Total							

Appendix II - Laboratory metallurgical testwork – flotation optimisation

Two-variable experimental design for optimisation of Lumwana Ore

Test No.	Fixed factor Collector (g/t)	Variable factor (grind) Grind time (mins)	Particle size (µm)	MIBC (g/t)	Pine Oil (g/t)	D200 (g/t)	D250 (g/t)	Bf245 (g/t)	Bf 20 (g/t)	Recovery (%TCu)	Grade (%TCu)
1	100	15		40						73,3	12,9
2	100	15			40					70,6	12,8
3	100	15	p55 = 150µm			40				62,8	14,5
4	100	15					40			78,1	12,0
5	100	15						40		71,6	13,5
6	100	15							40	78,2	11,7
7	100	15		60						78,5	12,8
8	100	15			60					73,5	11,4
9	100	15	p55 = 150µm			60				79,0	13,5
10	100	15					60			72,2	7,8
11	100	15						60		80,3	11,8
12	100	15							60	72,7	13,5
13	100	15		80						83,3	14,8
14	100	15			80					67,7	8,4
15	100	15	p55 = 150µm			80				80,0	10,7
16	100	15					80			82,2	8,1
17	100	15						80		79,3	9,3
18	100	15							80	81,7	9,9
19	100	30		40						81,9	10,7
20	100	30			40					79,3	10,7
21	100	30	p65 = 150µm			40				78,8	11,4
22	100	30					40			81,0	9,3
23	100	30						40		81,6	10,9
24	100	30							40	79,4	11,1
25	100	30		60						81,4	8,2
26	100	30			60					77,7	8,0
27	100	30	p65 = 150µm			60				81,5	10,3
28	100	30					60			83,3	7,7
29	100	30						60		86,6	7,9
30	100	30							60	81,1	9,4
31	100	30		80						83,1	9,4
32	100	30			80					76,2	8,6
33	100	30	p65 = 150µm			80				84,8	7,0
34	100	30					80			85,1	6,9
35	100	30						80		83,6	7,2
36	100	30							80	85,2	7,2
37	100	45		40						79,6	11,8
38	100	45			40					76,2	12,2
39	100	45	p85 = 150µm			40				74,3	13,7
40	100	45					40			80,3	9,3
41	100	45						40		79,8	13,3
42	100	45							40	77,7	11,9
43	100	45		60						79,8	14,7
44	100	45			60					76,4	11,8
45	100	45	p85 = 150µm			60				82,6	7,4
46	100	45					60			83,7	7,4
47	100	45						60		80,2	9,4
48	100	45							60	82,1	7,9
49	100	45		80						78,8	13,6
50	100	45			80					77,7	10,0
51	100	45	p85 = 150µm			80				82,4	9,8
52	100	45					80			79,5	9,0
53	100	45						80		82,3	10,0
54	100	45							80	83,9	8,3
55	100	60		40						81,0	7,5
56	100	60			40					82,6	8,2
57	100	60	p90 = 150µm			40				81,4	7,7
58	100	60					40			82,2	9,2
59	100	60						40		81,1	8,3
60	100	60							40	83,3	6,7
61	100	60		60						79,2	9,6
62	100	60			60					75,4	9,2
63	100	60	p90 = 150µm			60				74,7	9,3
64	100	60					60			79,7	7,2
65	100	60						60		74,9	6,7
66	100	60							60	75,3	7,1
67	100	60		80						75,9	9,8
68	100	60			80					77,6	8,3
69	100	60	p90 = 150µm			80				84,4	7,8
70	100	60					80			80,7	8,1
71	100	60						80		83,6	8,9
72	100	60							80	81,5	7,9

Two-variable experimental design for optimisation of Kansanshi ore testwork

Test No.	Collector (g/t)	Grind time (mins)	Particle size (µm)	MIBC (g/t)	Pine Oil (g/t)	D200 (g/t)	D250 (g/t)	Bf245 (g/t)	Bf 20 (g/t)	Recovery (%TCu)	Conc grade (%TCu)
1	100	5		40						69,1	5,4
2	100	5			40					56,5	5,1
3	100	5	p55 = 150µm			40				58,8	5,8
4	100	5					40			60,9	6,7
5	100	5						40		71,7	6,3
6	100	5							40	64,0	6,0
7	100	5		60						63,1	5,9
8	100	5			60					58,7	5,7
9	100	5	p55 = 150µm			60				71,8	6,6
10	100	5					60			63,1	6,0
11	100	5						60		78,6	5,7
12	100	5							60	67,2	6,0
13	100	5		80						67,1	7,0
14	100	5			80					68,7	5,3
15	100	5	p55 = 150µm			80				75,0	5,7
16	100	5					80			62,0	8,3
17	100	5						80		58,1	6,9
18	100	5							80	65,2	7,2
19	100	10		40						78,6	4,9
20	100	10			40					68,5	4,8
21	100	10	p65 = 150µm			40				65,6	5,6
22	100	10					40			76,3	5,6
23	100	10						40		75,3	5,2
24	100	10							40	57,4	4,6
25	100	10		60						90,3	5,2
26	100	10			60					82,5	5,1
27	100	10	p65 = 150µm			60				82,8	5,2
28	100	10					60			67,3	4,2
29	100	10						60		79,1	5,2
30	100	10							60	88,3	6,8
31	100	10		80						88,5	6,0
32	100	10			80					73,1	5,2
33	100	10	p65 = 150µm			80				83,9	6,0
34	100	10					80			82,8	5,6
35	100	10						80		79,7	5,6
36	100	10							80	72,8	5,3
37	100	30		40						69,6	6,4
38	100	30			40					93,2	5,0
39	100	30	p80 = 150µm			40				73,0	5,0
40	100	30					40			95,7	5,3
41	100	30						40		82,0	5,4
42	100	30							40	92,6	4,6
43	100	30		60						95,8	5,0
44	100	30			60					89,6	5,3
45	100	30	p80 = 150µm			60				71,5	6,7
46	100	30					60			89,2	5,0
47	100	30						60		90,3	5,5
48	100	30							60	87,0	6,4
49	100	30		80						83,4	7,3
50	100	30			80					73,7	6,5
51	100	30	p80 = 150µm			80				87,8	8,6
52	100	30					80			96,1	5,7
53	100	30						80		95,7	7,4
54	100	30							80	93,1	6,4
55	100	30		60						85,6	6,1
56	100	30			60					75,3	4,0
57	100	30	p80 = 150µm			60				78,5	6,8
58	100	30					60			86,0	4,6
59	100	30						60		85,4	5,2
60	100	30							60	77,6	4,4

Appendix III - Laboratory metallurgical testwork–flotation kinetics

Lumwana ore flotation results

FROTHER	TEST 1		TEST 2		TEST 3		TEST 4		AVERAGE	
	Grade (%TCu)	Rec (%TCu)	Grade (%TCu)	Rec (%TCu)	Grade (%TCu)	Rec (%TCu)	Grade (%TCu)	Rec (%TCu)	Grade (%TCu)	Rec (%TCu)
MIBC	4,6	73,2	8,4	86,7	8,7	68,3	13,9	71,5	**8,9**	**74,9**
PINE OIL	6,6	75,0	5,1	80,0	7,4	64,7	7,0	61,5	**6,5**	**70,3**
D200	7,2	81,2	8,7	86,7	7,4	60,2	5,8	60,3	**7,3**	**72,1**
D250	5,0	77,9	7,7	90,0	5,6	66,8	6,3	65,4	**6,2**	**75,0**
BF245	6,1	80,0	6,3	88,9	6,6	66,5	7,9	61,0	**6,7**	**74,1**
BF20	4,4	83,5	7,9	86,1	4,3	59,0	6,6	66,2	**5,8**	**73,7**

Kansanshi ore flotation results

FROTHER	TEST 1		TEST 2		TEST 3		TEST 4		AVERAGE	
	Grade (%TCu)	Rec (%TCu)	Grade (%TCu)	Rec (%TCu)	Grade (%TCu)	Rec (%TCu)	Grade (%TCu)	Rec (%TCu)	Grade (%TCu)	Rec (%TCu)
MIBC	6,1	85,6	4,5	72,0	5,1	87,9	4,0	91,9	**4,9**	**84,4**
PINE OIL	4,0	75,3	3,8	65,4	3,6	90,5	3,3	90,5	**3,7**	**80,4**
D200	6,8	78,5	4,7	68,0	3,5	91,8	3,1	93,1	**4,5**	**82,9**
D250	4,6	86,0	3,5	75,3	3,6	90,8	3,3	91,6	**3,8**	**85,9**
BF245	5,2	85,4	4,1	83,5	5,8	89,7	4,8	86,2	**5,0**	**86,2**
BF20	4,4	77,6	3,9	75,5	3,1	84,2	3,4	91,2	**3,7**	**82,1**

Average - Mass balance for Lumwana ore flotation testwork

Reagent	Product	Wt (g)	Cum.Wt (g)	Wt (%)	Cum.Wt (%)	Grade (%TCu)	Cum.Grade (%TCu)	Recovery (%TCu)	Cum.Rec (%TCu)
MIBC	Conc1	5,2	5,2	1,1	1,1	13,91	13,9	43,3	43,3
	Conc2	5,4	10,6	1,1	2,2	7,45	10,6	26,3	69,6
	Conc3	9,1	19,8	1,9	4,0	1,68	6,5	10,3	79,9
	Tails	470,2	490,0	96,0	100,0	0,06	0,3	20,1	100,0
	Total	490,0		100,0		0,34		100,0	
PINE OIL	Conc1	7,5	7,5	1,5	1,5	12,25	12,3	44,8	44,8
	Conc2	6,0	13,5	1,2	2,8	5,32	9,1	16,7	61,4
	Conc3	12,7	26,3	2,6	5,4	2,50	5,9	16,1	77,5
	Tails	462,4	488,7	94,6	100,0	0,10	0,4	22,5	100,0
	Total	488,7		100,0		0,41		100,0	
DOWFROTH200	Conc1	6,8	6,8	1,4	1,4	17,22	17,2	47,5	47,5
	Conc2	5,7	12,5	1,2	2,5	9,78	13,8	22,8	70,4
	Conc3	13,6	26,2	2,8	5,3	2,50	7,9	13,6	83,9
	Tails	466,3	492,4	94,7	100,0	0,09	0,5	16,1	100,0
	Total	492,4		100,0		0,50		100,0	
DOWFROTH250	Conc1	7,7	7,7	1,6	1,6	15,11	15,1	55,2	55,2
	Conc2	7,5	15,2	1,5	3,1	5,11	10,2	18,3	73,5
	Conc3	13,0	28,2	2,7	5,8	1,74	6,3	10,5	83,9
	Tails	461,9	490,1	94,2	100,0	0,07	0,4	16,1	100,0
	Total	490,1		100,0		0,43		100,0	
BETAFROTH245	Conc1	7,8	7,8	1,6	1,6	12,11	12,1	47,9	47,9
	Conc2	6,9	14,7	1,4	3,0	7,04	9,8	23,9	71,8
	Conc3	12,8	27,5	2,6	5,5	2,00	6,2	12,7	84,4
	Tails	469,4	496,9	94,5	100,0	0,07	0,4	15,6	100,0
	Total	496,9		100,0		0,41		100,0	
BETAFROTH20	Conc1	6,5	6,5	1,3	1,3	13,63	13,6	52,2	52,2
	Conc2	5,2	11,7	1,1	2,4	6,75	10,6	20,3	72,4
	Conc3	12,4	24,1	2,5	4,9	1,76	6,2	12,4	84,8
	Tails	463,0	487,1	95,1	100,0	0,06	0,3	15,2	100,0
	Total	487,1		100,0		0,35		100,0	

Average - Mass balance for Kansanshi ore flotation testwork

Reagent	Product	Wt (g)	Cum.Wt (g)	Wt (%)	Cum.Wt (%)	Grade (%TCu)	Cum.Grade (%TCu)	Recovery (%TCu)	Cum.Rec (%TCu)
MIBC	Conc1	8,1	8,1	1,7	1,7	9,6	9,6	35,8	35,8
	Conc2	8,3	16,4	1,7	3,4	7,3	8,6	26,5	62,3
	Conc3	17,1	33,5	3,5	6,9	2,2	5,3	16,5	78,8
	Tails	453,5	487,0	93,1	100,0	0,1	0,5	21,2	100,0
	Total	487,0		100,0		0,5		100,0	
PINE OIL	Conc1	10,4	10,4	2,1	2,1	12,2	12,2	51,2	51,2
	Conc2	10,6	21,0	2,2	4,3	3,0	7,5	12,7	63,8
	Conc3	23,9	44,9	4,9	9,2	0,7	3,9	6,5	70,3
	Tails	444,3	489,1	90,8	100,0	0,2	0,5	29,7	100,0
	Total	489,1		100,0		0,5		100,0	
DOWFROTH200	Conc1	4,4	4,4	0,9	0,9	10,2	10,2	17,8	17,8
	Conc2	9,8	14,2	2,0	2,9	7,6	8,4	29,2	47,0
	Conc3	18,4	32,6	3,8	6,8	3,7	5,7	26,2	73,2
	Tails	449,6	482,1	93,2	100,0	0,2	0,5	26,8	100,0
	Total	482,1		100,0		0,5		100,0	
DOWFROTH250	Conc1	9,0	9,0	1,8	1,8	12,5	12,5	50,5	50,5
	Conc2	11,2	20,2	2,3	4,1	4,0	7,8	20,5	71,0
	Conc3	23,7	44,0	4,9	9,0	0,9	4,1	9,7	80,7
	Tails	444,6	488,5	91,0	100,0	0,1	0,4	19,3	100,0
	Total	488,5		100,0		0,4		100,0	
BETAFROTH245	Conc1	7,1	7,1	1,5	1,5	10,4	10,4	34,5	34,5
	Conc2	8,7	15,8	1,8	3,3	7,6	8,8	31,3	65,8
	Conc3	22,9	38,7	4,8	8,1	1,8	4,7	18,6	84,4
	Tails	439,5	478,2	91,9	100,0	0,1	0,4	15,6	100,0
	Total	478,2		100,0		0,4		100,0	
BETAFROTH20	Conc1	10,1	10,1	2,1	2,1	12,3	12,3	52,1	52,1
	Conc2	10,0	20,2	2,1	4,1	3,9	8,1	16,5	68,6
	Conc3	23,8	44,0	4,9	9,0	0,8	4,1	8,0	76,6
	Tails	445,1	489,1	91,2	100,0	0,1	0,5	23,4	100,0
	Total	488,3		100,2		0,5		100,0	

Appendix IV - Laboratory metallurgical testwork – water recovery

Average- Mass balance for Lumwana ore water recovery restwork

Frother	Description	Wt (%)	CumWt (%)	Grade (%)	CumGrade (%)	Recovery (%TCu)	CumRec (%TCu)
MIBC	Conc1	1,22	1,22	20,22	20,22	50,13	50,13
	Conc2	0,86	2,08	8,41	15,26	15,02	65,15
	Conc3	1,00	3,08	2,19	11,31	4,78	69,93
	Tails	96,92	100,00	0,30	0,49	30,07	100,00
	Total	100,00				100,00	
PINE OIL	Conc1	1,57	1,57	12,32	12,32	40,70	40,70
	Conc2	1,25	2,82	5,59	9,20	14,87	55,58
	Conc3	1,26	4,08	2,76	7,21	7,51	63,09
	Tails	95,92	100,00	0,36	0,47	36,91	100,00
	Total	100,00				100,00	
D200	Conc1	0,68	0,68	18,95	18,95	33,30	33,30
	Conc2	0,78	1,46	8,90	13,59	17,89	51,18
	Conc3	2,08	3,54	1,70	6,60	9,06	60,24
	Tails	96,46	100,00	0,32	0,39	39,76	100,00
	Total	100,00				100,00	
D250	Conc1	2,00	2,00	13,08	13,08	54,19	54,19
	Conc2	1,27	3,27	2,61	9,02	6,79	60,98
	Conc3	2,09	5,36	1,18	5,96	5,14	66,12
	Tails	94,64	100,00	0,35	0,49	33,88	100,00
	Total	100,00				100,00	
BF245	Conc1	1,16	1,16	16,99	16,99	44,56	44,56
	Conc2	0,93	2,09	4,67	11,48	9,91	54,46
	Conc3	1,81	3,89	2,31	7,23	9,32	63,78
	Tails	96,11	100,00	0,34	0,45	36,22	100,00
	Total	100,00				100,00	
BF20	Conc1	1,67	1,67	10,35	10,35	47,03	47,03
	Conc2	0,97	2,63	2,99	7,64	7,93	54,96
	Conc3	1,61	4,24	1,69	5,43	7,64	62,60
	Tails	95,76	100,00	0,28	0,36	37,40	100,00
	Total	100,00				100,00	
F515	Conc1	1,80	1,80	10,35	10,35	46,39	46,39
	Conc2	1,64	3,45	2,97	6,79	12,39	58,78
	Conc3	2,10	5,55	1,50	4,76	7,82	66,60
	Tails	94,45	100,00	0,28	0,40	33,40	100,00
	Total	100,00				100,00	

Average - Mass balance for Kansanshi sulphide ore water recovery restwork

Frother	Description	Wt (%)	CumWt (%)	Grade (%)	CumGrade (%)	Recovery (%TCu)	CumRec (%TCu)
MIBC	Conc1	3,73	3,73	10,69	10,69	70,08	70,08
	Conc2	2,58	6,32	2,90	7,54	12,68	82,76
	Conc3	5,11	11,43	0,81	4,52	7,16	89,92
	Tails	88,57	100,00	0,13	0,57	10,08	100,00
	Total	100,00				100,00	
PINE OIL	Conc1	5,77	5,77	4,90	4,90	52,02	52,02
	Conc2	3,76	9,53	4,39	4,69	30,56	82,58
	Conc3	4,69	14,22	0,92	3,45	7,89	90,48
	Tails	85,78	100,00	0,12	0,54	9,52	100,00
	Total	100,00				100,00	
D200	Conc1	4,01	4,01	6,38	6,38	50,07	50,07
	Conc2	4,09	8,10	3,89	5,12	31,16	81,23
	Conc3	6,26	14,35	0,90	3,29	11,22	92,44
	Tails	85,65	100,00	0,09	0,51	7,56	100,00
	Total	100,00				100,00	
D250	Conc1	37,55	37,55	5,11	5,11	62,16	62,16
	Conc2	19,17	56,71	3,44	4,48	24,19	86,36
	Conc3	21,28	78,00	0,65	3,42	4,84	91,19
	Tails	85,73	163,73	0,11	0,53	8,81	100,00
	Total	163,73				100,00	
BF245	Conc1	3,23	3,23	10,44	10,44	59,03	59,03
	Conc2	2,12	5,34	4,90	8,21	18,77	77,80
	Conc3	4,06	9,40	1,41	5,28	10,15	87,95
	Tails	90,60	100,00	0,15	0,56	12,05	100,00
	Total	100,00				100,00	
BF20	Conc1	5,56	5,56	4,89	4,89	55,32	55,32
	Conc2	3,33	8,90	3,80	4,48	25,77	81,09
	Conc3	4,47	13,36	0,73	3,23	6,58	87,67
	Tails	86,64	100,00	0,14	0,49	12,33	100,00
	Total	100,00				100,00	
AF68	Conc1	5,22	5,22	5,65	5,65	56,62	56,62
	Conc2	2,76	7,99	4,86	5,37	25,33	81,95
	Conc3	4,52	12,51	1,13	3,84	9,65	91,59
	Tails	87,49	100,00	0,10	0,52	8,41	100,00
	Total	100,00				100,00	

Appendix V – Froth stability test data

<u>**Froth stability tests**</u>

Dowfroth 250		
Frother dosage (g/t)	Froth height (mm)	Collapse time (s)
50,0	35,0	5,5
50,0	35,0	5,2
50,0	35,0	5,6
Average	**35,0**	**5,4**
100,0	45,0	5,9
100,0	45,0	5,7
100,0	45,0	6,3
Average	**45,0**	**5,9**
150,0	60,0	6,8
150,0	65,0	6,7
150,0	65,0	6,8
Average	**63,3**	**6,8**
200,0	100,0	8,4
200,0	105,0	8,7
200,0	105,0	7,8
Average	**103,3**	**8,3**
250,0	130,0	9,7
250,0	140,0	9,8
250,0	140,0	8,8
Average	**136,7**	**9,4**
300,0	170,0	10,5
300,0	170,0	10,6
300,0	170,0	10,5
Average	**170,0**	**10,5**

Dowfroth 200		
Frother dosage (g/t)	Froth height (mm)	Collapse time (s)
50,0	0,0	0,0
50,0	0,0	0,0
50,0	0,0	0,0
Average	**0,0**	**0,0**
100,0	10,0	2,6
100,0	10,0	2,2
100,0	10,0	2,2
Average	**10,0**	**2,3**
150,0	20,0	2,8
150,0	20,0	2,4
150,0	20,0	3,0
Average	**20,0**	**2,7**
200,0	20,0	2,8
200,0	20,0	2,8
200,0	20,0	2,5
Average	**20,0**	**2,7**
250,0	20,0	2,5
250,0	20,0	2,4
250,0	20,0	2,3
Average	**20,0**	**2,4**
300,0	20,0	2,9
300,0	20,0	2,8
300,0	20,0	2,7
Average	**20,0**	**2,8**

MIBC		
Frother dosage (g/t)	Froth height (mm)	Collapse time (s)
50,0	0,0	0,0
50,0	0,0	0,0
50,0	0,0	0,0
Average	**0,0**	**0,0**
100,0	15,0	2,8
100,0	15,0	2,5
100,0	15,0	3,0
Average	**15,0**	**2,8**
150,0	15,0	2,8
150,0	15,0	2,7
150,0	15,0	2,7
Average	**15,0**	**2,7**
200,0	20,0	2,9
200,0	20,0	3,0
200,0	20,0	2,8
Average	**20,0**	**2,9**
250,0	25,0	3,3
250,0	25,0	3,0
250,0	25,0	2,9
Average	**25,0**	**3,1**
300,0	25,0	2,8
300,0	25,0	2,6
300,0	25,0	3,2
Average	**25,0**	**2,9**

Betafroth 245		
Frother dosage (g/t)	Froth height (mm)	Collapse time (s)
50,0	20,0	3,1
50,0	20,0	2,8
50,0	20,0	2,9
Average	**20,0**	**2,9**
100,0	25,0	3,3
100,0	25,0	3,7
100,0	25,0	3,6
Average	**25,0**	**3,5**
150,0	30,0	3,3
150,0	30,0	3,7
150,0	30,0	3,6
Average	**30,0**	**3,5**
200,0	30,0	4,1
200,0	30,0	3,7
200,0	30,0	4,2
Average	**30,0**	**4,0**
250,0	30,0	4,0
250,0	30,0	3,9
250,0	30,0	3,8
Average	**30,0**	**3,9**
300,0	30,0	3,9
300,0	30,0	3,4
300,0	30,0	3,7
Average	**30,0**	**3,6**

Betafroth 20		
Frother dosage (g/t)	Froth height (mm)	Collapse time (s)
50,0	25,0	4,5
50,0	25,0	5,2
50,0	25,0	4,9
Average	**25,0**	**4,9**
100,0	30,0	3,3
100,0	30,0	4,6
100,0	30,0	4,6
Average	**30,0**	**4,2**
150,0	35,0	3,0
150,0	35,0	3,0
150,0	35,0	2,9
Average	**35,0**	**3,0**
200,0	35,0	2,9
200,0	35,0	2,7
200,0	35,0	2,7
Average	**35,0**	**2,8**
250,0	35,0	2,7
250,0	35,0	2,9
250,0	35,0	2,8
Average	**35,0**	**2,8**
300,0	30,0	2,4
300,0	35,0	2,9
300,0	35,0	2,6
Average	**33,3**	**2,6**

Pine Oil		
Frother dosage (g/t)	Froth height (mm)	Collapse time (s)
50,0	25,0	2,2
50,0	25,0	2,5
50,0	25,0	2,8
Average	**25,0**	**2,5**
100,0	25,0	2,7
100,0	25,0	2,4
100,0	25,0	2,3
Average	**25,0**	**2,5**
150,0	20,0	2,7
150,0	20,0	3,1
150,0	20,0	2,8
Average	**20,0**	**2,9**
200,0	25,0	2,3
200,0	25,0	2,6
200,0	25,0	2,6
Average	**25,0**	**2,5**
250,0	25,0	2,8
250,0	25,0	2,7
250,0	25,0	3,1
Average	**25,0**	**2,9**
300,0	25,0	2,0
300,0	25,0	2,2
300,0	25,0	2,5
Average	**25,0**	**2,2**

Reaction time of D250 — $y = 0,095x + 2,473$

Reaction time of D200 — $y = 0,094x + 2,378$

Reaction time of Bfroth 245 — $y = 0,200x + 2,621$

Reaction time of Bfroth 20 — $y = -0,242x + 4,738$

Reaction time of MIBC

y = 0,082x + 2,494

Reaction time, sec

3,6 3,4 3,2 3,0 2,8 2,6 2,4

0   5   10   15

Froth height (cm)

MIBC
Linear (MIBC)

Reaction time of Pine Oil

y = 0,049x + 2,46

Reaction time, sec

3,2 3,0 2,8 2,6 2,4

0   5   10   15

Froth height (cm)

Pine Oil
Linear (Pine Oil)

Appendix VI –Surface tension measurement data

Frother	Concentration	Mean reading (nN/m)	Number of readings
Dowfroth250	water	72.55	10
	6.25ppm	62.32	10
	12.5ppm	55.54	10
	25ppm	51.55	10
	50ppm	53.76	10
	100ppm	53.49	10
Dowfroth200	water	72.14	10
	6.25ppm	69.24	10
	12.5ppm	55.10	10
	25ppm	52.27	10
	50ppm	60.57	10
	100ppm	59.82	10
Betafroth245	water	71.89	10
	6.25ppm	50.18	10
	12.5ppm	47.10	10
	25ppm	50.15	10
	50ppm	48.17	10
	100ppm	54.27	10
Betafroth 20	water	72.64	10
	6.25ppm	63.68	10
	12.5ppm	54.21	10
	25ppm	55.40	10
	50ppm	50.60	10
	100ppm	50.63	10
MIBC	water	71.92	10
	6.25ppm	70.57	10
	12.5ppm	65.12	10
	25ppm	68.99	10
	50ppm	70.73	10
	100ppm	68.90	10
Pine Oil	water	71.99	10
	6.25ppm	57.64	10
	12.5ppm	52.97	10
	25ppm	41.08	10
	50ppm	43.93	10
	100ppm	42.57	10

Appendix VII–Bubble size analyses measurement data

FrotherConcentration		Bubble size (mm)	Number of bubbles
Dowfroth 250	5ppm	1.0357/1.1636/0.9975/1.1513	3605/3523/3627/3629
	Mean	1.1513	3629
Dowfroth 250	12.25ppm	1.1562/1.0719/1.2547/1.1578	3689/3749/3747/3796
	Mean	1.1582	3745
Dowfroth 250	25ppm	1.2799/1.3270/1.2137/1.3381	3479/3591/3658/3625
	Mean	1.2897	3688
Dowfroth 250	50ppm	1.0098/1.2153/1.3601/1.1951	2960/2936/2827/2908
	Mean	1.1951	2908
Dowfroth 250	100ppm	1.0650/1.1283/1.1992/1.2424	2574/2929/2814/3123
	Mean	1.1587	2860
Dowfroth 200	5ppm	1.4606/1.4027/1.2468/1.2816	2855/2597/2759/2735
	Mean	1.3479	2737
Dowfroth 200	12.25ppm	1.1148/0.9483/1.0408/1.1102	3575/3553/3556/3599
	Mean	1.0535	3571
Dowfroth 200	25ppm	1.2454/1.3117/1.2514/1.2639	3437/3491/3340/33509
	Mean	1.2681	3444
Dowfroth 200	50ppm	1.0188/1.0177/1.1504/1.0705	2755/2804/3016/2725
	Mean	1.0644	2825
Dowfroth 200	100ppm	1.0373/1.0000/1.0111/1.0487	2407/2455/2430/2484
	Mean	1.0243	2444
Betafroth 245	5ppm	1.1384/1.0724/1.1527/1.0810	3217/3194/3246/3252
	Mean	1.1111	3227
Betafroth 245	12.25ppm	1.0122/1.1944/1.1990/1.1852	3642/3621/3605/3505
	Mean	1.1477	3593
Betafroth 245	25ppm	1.1848/1.2462/1.1816/1.1565	3173/3054/3036/32987
	Mean	1.1923	3063
Betafroth 245	50ppm	1.1129/1.1683/1.0754/1.0963	2898/2874/2783/2692
	Mean	1.1132	2812
Betafroth 245	100ppm	0.9944/1.1125/1.1497/1.0358	2686/2987/3015/2863
	Mean	1.0731	2888
Betafroth 20	5ppm	1.4606/1.4027/1.2468/1.2816	2885/2597/2759/2735
	Mean	1.3479	2737
Betafroth 20	12.25ppm	1.1221/1.1918/1.2736/1.2288	3393/3444/3465/3559
	Mean	1.2018	3465
Betafroth 20	25ppm	1.1622/1.2237/0.9601/1.2110	2905/2915/2794/2954
	Mean	1.1393	2892

Betafroth 20	50ppm	0.8691/1.0720/0.9953	2636/2689/2799
	Mean	0.9788	2708
Betafroth 20	100ppm	1.0017/1.0039/1.1342/1.1413	2525/2564/2561/2639
	Mean	1.0703	2572
MIBC	5ppm	1.2298/1.0390/0.9691/1.0712	3318/3244/3260/3250
	Mean	1.0773	3268
MIBC	12.25ppm	1.2127/1.1924/1.1918/1.1203	3618/36577/3577/3671
	Mean	1.1793	3611
MIBC	25ppm	1.2888/1.1478/1.1335/1.1516	2855/3023/2937/3078
	Mean	1.1804	2973
MIBC	50ppm	1.1202/1.0940/1.1477/1.2045	2559/2624/2690/2654
	Mean	1.1416	2632
MIBC	100ppm	0.9612/1.1537/1.3601/1.1799	2824/2831/2750/3026
	Mean	1.1284	2858
Pine Oil	5ppm	1.4204/1.0837/1.1034/1.0752	3572/3627/3616/3638
	Mean	1.1932	3613
Pine Oil	12.25ppm	1.2000/1.2006/1.1993/1.1368	3391/3415/3545/3622
	Mean	1.1842	3493
Pine Oil	25ppm	1.2405/1.2169/1.1885/1.2752	3291/3452/3390/3327
	Mean	1.2303	3390
Pine Oil	50ppm	1.1963/1.1583/1.1993/1.2565	2905/3081/3077/3033
	Mean	1.2026	3024
Pine Oil	100ppm	0.9782/1.0561/0.19047/1.0687	2470/2400/2480/2548
	Mean	1.0019	2475