Flotation frother mixtures: Decoupling the sub-processes of froth stability, froth recovery and entrainment

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ABSTRACT

The flotation process consists of two distinct phases: the pulp and froth phase. One of the main roles of the froth phase is to create a suitable environment for the separation of floatable, valuable minerals from non-selectively recovered, entrained gangue minerals. As a result the froth phase plays a significant role in the metallurgical performance of industrial flotation cells. Froth stability is important for the recovery of valuable minerals. However, a stable froth may contribute to increased entrainment and, consequently, a lower grade.

This study compares the effect of frother mixtures with that of their single component frothers on the froth stability, froth recovery and entrainment of a platinum-bearing UG2 ore using polyglycol and alcohol frothers. The study showed that frother mixtures resulted in a greater froth stability than either of their component frothers. The increased froth stability was reflected in increased froth recoveries and greater overall recoveries. However, the important aspect in the use of frother blends was that they altered the froth structure and resulted in a lower degree of entrainment. This, together with the increased recovery, resulted in higher grades of valuable mineral recovered to the concentrate when using the frother mixtures.

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1. Introduction

Froth flotation has been used in the mineral processing industry since the early 20th century and is the largest tonnage separation process worldwide. As the name "froth flotation" suggests the froth phase plays a significant role in the process. The froth phase assists in transporting valuable minerals from the bulk slurry to the concentrate and in separating valuables from entrained gangue minerals. The froth phase is metastable (Exerowa and Kruglyakov, 1997), but to ensure its role during the froth flotation process it must persist long enough to reach the concentrate launder. Particles of optimum size and hydrophobicity provide much of the stability in the froth phase (Ata, 2012; Horozov, 2008; Hunter et al., 2008). However, to aid in froth stability and to prevent coalescence of bubbles in the pulp, surfactants called frothers are commonly added. Frothers of different chemical structures are used during flotation. Those that will be focussed on in this paper belong to two categories: the polypropylene glycols (PPG's) and aliphatic alcohols. Recently there has been a shift from the traditional use of single frother components to dual frother blends (Tan et al., 2005). It is

acknowledged that there has been little research done on the reasons behind the shift towards the use of frother blends (Laskowski et al., 2003; Tan et al., 2005). Some studies have shown frother blends to improve foamability, reduce the critical coalescence concentration and improve recovery and grade (Ngoroma et al., 2013; Tan et al., 2005; Elmahdy and Finch, 2013). The literature on surfactant mixtures attributes synergistic effects to increased packing and stabilisation of the adsorbed layer at the air–water interface. This is enabled by a reduction in repulsion between the polar or ionic head groups of a surfactant molecule when a second molecule is interspersed between them (Chang et al., 1992; Manoli and Avranas, 2013). One would not normally expect strong synergism to be shown in non-ionic surfactants, since the beneficial intermolecular interactions mentioned above are absent (Huibers and Shah, 1997). However, it has been shown that mixtures of similar structures may also produce synergistic surfactant effects. Shinoda et al. (1971) showed that when a polyoxyethylene polymer with a large molecular weight distribution is purified to a single chain length, it is a less effective surfactant than the polydisperse molecular weight distribution. In another study by Huibers and Shah (1997) they found that the greatest water solubilisation in oil was obtained when mixing surfactants which were highly oil soluble with surfactants that were highly water soluble. These were poor surfactants alone since they partitioned into the

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oil or water phase, but this was overcome when they were blended and they partitioned to the interface, enabling the stabilisation of a larger interfacial area.

A flotation cell can be separated into two zones – the froth zone and the pulp zone. These can be modelled separately, with an associated froth zone recovery and pulp zone rate constant (Vera et al., 1999). Froth recovery is the fraction of particles entering the froth phase that reports to the concentrate (Finch and Dobby, 1990). The overall recovery of valuable particles is dependent on the froth recovery which is, in turn, dependent on the froth stability, among other factors. All froth recovery measurements are subject to strengths and limitations. The method of varying froth depth was chosen in this study. This method measures the rate constant at varying froth depths. The linear relationship obtained between froth depth and flotation rate constant is extrapolated to zero froth depth to predict the pulp zone rate constant. The limitations of this technique are that it overestimates the froth zone recovery since it does not take into account the losses at the pulp-froth interface. In addition, the assumption that the pulp zone rate constant is the same at all froth depths is not true since at deeper froths there will be more drop-back of valuable particles, creating a higher pulp feed grade than at lower froth depths (Runge et al., 2010). Other froth recovery measurements such as a direct measure of the bubble load into the froth or a mass balancing technique have the limitations of requiring special equipment or not producing enough sample for assay of the sparsely occurring platinum group minerals. The variable froth depth method, as employed in frequent other studies (Feteris et al., 1987; Laplante et al., 1983; Vera et al., 1999, 2002; Schwarz, 2004), was chosen for this study as being the simplest method and adequate for a comparative study.

UG2 ore is a multicomponent platinum group mineral (PGM) ore from the Bushveld complex in South Africa and contributes an estimated 40% of global platinum group element (PGE) resources (Mudd, 2012). UG2 ore is comprised largely of chromite (60–90% by volume) (Schouwstra and Kinloch, 2000), which is not naturally floatable, but significant quantities report to the concentrate by non-selective entrainment. This is a serious problem to the downstream smelting process, which generally has a 2.5% chromite (as Cr_2O_3) constraint to the smelter (Hay and Roy, 2010). It is acknowledged that the froth structure, in particular the water content, has an effect on the amount of entrained material reporting to the concentrate (Savassi et al., 1997; Melo, 2005). Frothers modify the physical and chemical properties of the froth and can, therefore, affect not just the amount of water reporting to the concentrate, but the amount of entrained material per unit water (entrainability). In the case of ores such as UG2 or hematite that exhibit reduced grades or recoveries because of non-selective entrainment, altering the froth's entrainability can be extremely beneficial.

This work decoupled the effects of frothers and frother blends on different sub-processes related to froth structure: froth recovery, froth stability and entrainment, with the aim of locating and interpreting where the beneficial effects of frother blends lies.

2. Experimental work

2.1. Reagents

The frothers used in the study are listed in Tables 1 and 2. They included three alcohol frothers, pentanol, hexanol and methyl isobutyl carbinol (MIBC), and three polypropylene glycols (PPG) of increasing molecular weight, PPG192, PPG425 and PPG725. The frothers were supplied by Sigma Aldrich. They have a generic structure of $H(OC_3H_6)_nOH$ where n ranges from 1 to more than 10. The purities of the frothers used were determined by Senmin (Pty) Ltd using gas chromatography and are shown in Tables 1 and 2. The alcohol frothers and PPG192 were of purity of at least 99.2%. PPG425 comprised of a distribution of propylene glycols (PG) with an average molecular weight of 421 g/mol. The molecular composition of the higher molecular weight frother, PPG725 could not be confirmed by the methods available but, according to Sigma Aldrich and by inference from the PPG425 data, it is normally distributed with an average molecular weight of 725 g/mol. The critical coalescence concentration (CCC) or the CCC95 – the frother concentration that gives a 95% reduction in bubble size – is given in Table 3. The collector used in all tests was sodium isobutyl xanthate (SIBX) supplied in powder form by Senmin (Pty) Ltd.

2.2. Ore

The ore that was used in the study was a sample of UG2 ore obtained from a Lonmin operation within the Bushveld Igneous Complex in Rustenburg (South Africa). The ore contained 3.15 g/t platinum group elements and 24.9% Cr_2O_3, among other constituents. The bulk ore sample had a particle size distribution of 13.8% passing 75 μm and was milled to the required particle size distribution of 60% passing 75 μm using a 3 kg SALA stainless steel rod mill at 60% pulp density.

All tests, unless stated otherwise, were performed using synthetic plant water, which was a modification of distilled water by means of addition of ionic salts. This was to ensure that the water attained a specific ionic strength typically found at PGM flotation plants. Synthetic water was prepared in 40 ℓ batches, the composition of which is shown in Table 4.

2.3. Froth stability test

The froth stability tests were performed using a froth stability column shown in Fig. 1. The column was made of Perspex for safety reasons. An impellor was necessary to maintain the solids in suspension and this was considered a safety risk in a glass column, which could shatter if the impellor impacted the glass. This raised the question of wall effects since the Perspex is hydrophobic and the froth may stick to the sides. Incidentally, there would still be

Table 1
Molar composition of alcohol frothers as determined by gas chromatography.

Frother	Molar composition (%)
1-Pentanol	100
1-Hexanol	99.2
MIBC	99.9

Table 2
Molar composition of PPG192 and PPG425 as determined by gas chromatography.

Component Molecular weight (g/mol)	PPG192	PPG425
Di-PG, 134	0.3	–
Tri-PG, 192	99.7	0.4
Tetra-PG, 250	–	5.6
Penta-PG, 308	–	10.8
Hexa-PG, 366	–	18.8
Hepta-PG, 424	–	28.7
Octa-PG, 482	–	20.9
Nona-PG, 540	–	10.7
Deca-PG, 598	–	4.0
Average molecular weight (g/mol)	191.8	421

*PG = Propylene glycol.