



Dynamic froth stability of copper flotation tailings

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ARTICLE INFO

Keywords:

Particle size
Column flotation
Copper tailings
Dynamic froth stability

ABSTRACT

In this work, dynamic froth stability is used for the first time to investigate the flotation behaviour of copper tailings. Reprocessing of material from tailings dams is not only environmentally desirable, but also increasingly economically feasible as head grades can be high compared to new deposits. Flotation tailings, however, usually contain a large proportion of fine (10–50 μm) and ultra fine (< 10 μm) material and the effect of these particle sizes on froth stability is not yet fully understood.

For this study, samples were obtained from the overflow and underflow streams of the primary hydrocyclone at a concentrator that reprocesses copper flotation tailings. These samples were combined in different ratios to assess the dynamic froth stabilities at a wide range of particle size distributions and superficial gas velocities. The findings have shown that the effect of particle size on dynamic froth stability can be more complex than previously thought, with a local maximum in dynamic froth stability found at each air rate. Moreover, batch tests suggest that a local maximum in stability can be linked to improvements in flotation performance. Thus this work demonstrates that the dynamic froth stability can be used to find an optimum particle size distribution required to enhance flotation. This also has important implications for the reprocessing of copper tailings as it could inform the selection of the cut size for the hydrocyclones.

1. Introduction

One of the key challenges currently facing the mining industry is the decreasing head grades whilst the global demand for metals is ever increasing. It is therefore becoming more important for the industry to look to other potential sources to meet the demand. One such source is tailings dams. Historically, processing efficiency was much lower than it is today, resulting in tailings being higher grade (Falagán et al., 2017). For example, over the 20th century the copper grade of tailings has fallen from 0.75% to 0.14% (Gordon, 2002). In some cases historic tailings dams can therefore be higher grade than current deposits. Reprocessing this material is beneficial to industry for several reasons. Firstly, there are lower costs involved compared to a new mine as the ore has already been mined and milled. Secondly, tailings dams present a significant environmental problem, so reprocessing can help to reduce environmental contamination (Chen et al., 2014). However, there is no blanket approach to reprocessing tailings as there will be different requirements associated to each individual dam (Edraki et al., 2014). Another problem is that the majority of material held in tailings dams is fine grained, < 50 μm .

1.1. Fine particle flotation

There are several challenges in the flotation of fine particles, generally those less than 50 μm in size. Firstly, the probability of bubble particle attachment occurring is low (Miettinen et al., 2010). Secondly, they are more easily entrained due to the low particle diameter to Plateau border size ratio (Trahar, 1981) and thirdly, they can require higher quantities of reagents in order to increase the contact angle caused by a higher specific surface area (Chipfunhu et al., 2011).

Whilst there has been a significant body of work in fine particle flotation, it is not yet fully understood whether fine particles stabilise or destabilise the froth. Johansson and Pugh (1992) studied the effects of different contact angles and different particle sizes of quartz on the dynamic froth stability in a laboratory scale, stirred flotation column. For the finest particle size investigated, 26–44 μm , it was found that particles stabilised the froth when they were moderately hydrophobic (Contact Angle \approx 50–65°), however at lower contact angles they had little effect on the stability and at higher contact angles they destabilised the froth. Tao et al. (2000) showed that a small increment in the solids concentration of very fine coal particles (10 μm), also in a laboratory scale flotation column, lead to a large decrease in water recovery and this suggested that the fine particles had a destabilising

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effect on the froth.

Ahmed and Jameson (1985) suggested that a potential way to achieve the flotation of fine and coarse particles is to split the feed and use different operating conditions to treat each size. However, this requires a more complex flowsheet and so it is also important to understand if there are techniques for treating different sizes together. The interaction between fine particles and coarse particles of pure silica has been studied by Vieira and Peres (2007) and Rahman et al. (2012). The work by Vieira and Peres (2007) investigated the effects that changing the amount of fine material (38–74 μm) in the feed had on the flotation recovery of different particle sizes using a Denver cell. The results showed that there is an intermediate amount of fines required in the feed to optimise the solids recovery of all particle sizes investigated. They suggested that this can be attributed to an improvement in froth stability. Rahman et al. (2012) also studied the effects of changing feed size (with d80s ranging from 80 to 240 μm) on solids recovery in a laboratory scale flotation column. They found that an increase in the amount of fine material (i.e. a decrease in d80) resulted in increased recoveries. Contrary to Vieira and Peres (2007), Rahman et al. (2012) did not observe that an intermediate amount of fines in the feed produced the best results.

Work by Leistner et al. (2017) investigated the effect that the size of gangue material, quartz, had on the recovery of ultrafine (< 10 μm) and fine (10–50 μm) particles of the target mineral, magnetite. These experiments were conducted in a mechanical laboratory scale flotation cell. The results indicated that using fine quartz increases magnetite recovery for both size fractions whilst using ultrafine quartz particles has the opposite effect. This indicates that the recovery of ultrafine valuable particles can be improved in the presence of coarser gangue particles.

Froth stability is not only dependent on particle size or hydrophobicity, as already discussed, but the superficial gas velocity also plays an important role. Recently, Norori-McCormac et al. (2017) used a novel laboratory scale mechanical flotation cell to investigate the effects of superficial gas velocity and particle size on froth stability, measured using air recovery. They found that at high air rates a relatively fine feed, d80 of 89.6 μm , resulted in higher froth stabilities, yet at lower air rates it was an intermediate feed size that yielded the higher froth stabilities. This suggests that the relationship is more complex than previously thought.

1.2. Dynamic froth stability

The Bickerman test was developed to investigate the foam stability of dynamic systems using a flotation column (Bickerman, 1948). In this test gas is bubbled through a porous membrane into liquid in the column, allowing a foam layer to form at the top. This foam will rise until it reaches a steady state where the volume of gas entering the system, as bubbles, is equal to the volume of gas escaping when the bubbles burst (Bickerman, 1948). Many studies have shown that the height of the column of foam is proportional to the rate of flow of gas in the system and Bickerman (1948) defines the rate of proportionality as the dynamic foam stability (Σ):

$$\Sigma = \frac{V_f}{Q} = \frac{H}{J_g}, \quad (1)$$

where V_f is the volume of the foam, Q is the volumetric flow rate of the gas, H is the foam height of the system at steady state and J_g is the superficial gas velocity. This rate of proportionality does not only apply to foams but also to froths and can also be described as the average lifetime of a bubble in the froth (Bickerman, 1973).

There have been several studies looking at the effects of particle size and superficial gas velocity on froth stability. Ip et al. (1999) investigated the relationship between froth stability and particle size, using a silica, water, air system. Although the results showed a general

decrease in stability with an increase in mean particle size, this was not a smooth change; between a size of 60 μm and 90 μm there was little variation in froth stability. Barbian et al. (2003) used a modified Denver cell with a Platinum Group Metal (PGM) ore and observed that the dynamic froth stability factor decreased with an increase in superficial gas velocities. However, the superficial gas velocities in their work ranged between 0.13 cm s^{-1} and 0.66 cm s^{-1} and were therefore low compared to industrial flotation cells. Aktas et al. (2008) used a similar cell, again with a PGM ore, and observed the same relationship between dynamic froth stability and superficial gas velocity, again investigating the effects at low superficial gas velocities, between 0.26 cm s^{-1} and 0.53 cm s^{-1} . In addition to varying the gas velocity (Aktas et al., 2008) also varied the particle size and found that as the particle size increased the dynamic froth stability decreased, however, only four different sizes were used and these were coarse (d90 of 118 μm to 306 μm) and so the study doesn't give information about a broad range of both fine and coarse particles. More recently, Liang et al. (2015) investigated the effects of coal particles of different sizes on the froth stability again using a modified stability column. Four different size fractions were used here, namely -74 μm , -125 + 74 μm , -250 + 125 μm and -500 + 250 μm . Whilst these sizes consider a wider overall distribution than other studies, each of the size ranges tested was quite broad. These experiments were also run at low gas velocities of 0.2 cm s^{-1} . McFadzean et al. (2016a) studied the effects of particle size on dynamic froth stability for three different ores: a synthetic silica and pyrite ore, a PGM ore, and an Itabirite ore. The results for all three ores showed a smooth decreasing power law relationship when increasing the average feed particle size. Whilst the particle size of the synthetic ore ranges from around 16 μm to 210 μm the other two ores had smaller size ranges, between 29 μm and 71 μm . These experiments were run at a superficial gas velocity of 0.98 cm s^{-1} .

Barbian et al. (2005) developed a froth stability column to be used at industrial scale, allowing froth stability to be correlated to flotation performance. The results, from a copper sulphide ore, showed that the highest dynamic froth stability resulted in the highest copper grade but lowest recovery. McFadzean et al. (2016b) also showed a link between dynamic froth stability and flotation performance in their work. Their study investigated the effects of different frother blends on the froth stability of a PGM ore with an agitated laboratory scale column. The results showed that a higher froth stability resulted in higher recovery, but that there was little correlation with grade. The results from these two studies are contradictory suggesting that the relationship between froth stability and flotation performance is more complicated.

Whilst there have been various studies investigating the dynamic froth stability and the link to particle size, different gas velocities and flotation performance, there has been no attempt to link all three aspects. This work fills this gap by determining the dynamic froth stability of copper flotation tailings, considering different particle size distributions and at a range of superficial gas velocities. In addition, batch flotation tests were performed for selected conditions to obtain a preliminary assessment of flotation performance. The range of particle sizes investigated here are wider than have previously been studied and the superficial gas velocities are higher, and closer to those encountered in industrial flotation cells.

2. Methodology and equipment

2.1. Case study: tailings reprocessing plant

A processing plant in Chile has been reprocessing copper flotation tailings from two historic and one fresh tailings dams since 1992. The grade ranges from 0.12% Cu for the fresh tailings to 0.27% Cu for the historic tailings. The feed from these tailings dams to the plant contains a high proportion of fines, approximately 50%, by mass, of the material passing 10 μm . Once the tailings feed has been transported to the plant it passes through the primary hydrocyclone for the different particle

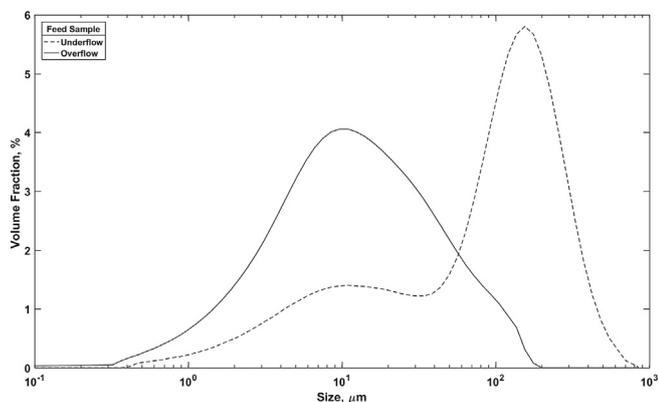


Fig. 1. Cumulative size distributions of the hydrocyclone overflow and underflow streams from the copper tailings reprocessing plant.

sizes to be treated separately. The underflow stream, with a d90 of 270 μm, is sent to the flotation circuit.

2.2. Materials

Samples of copper tailings were collected from the overflow and underflow streams of the primary hydrocyclone at the processing plant discussed in Section 2.1. The d90s of these samples were 63.7 μm and 279 μm respectively and the particle size distributions of each can be found in Fig. 1. The samples were obtained as slurry, which was subsequently dried and the two sizes combined in different proportions, by mass, to produce seven particle size distributions, which can be seen in Table 1. All experiments were conducted using the same batch of solids collected from the processing plant to minimize any effects due to mineralogy. The experiments were carried out using Sodium Isopropyl Xanthate, as a collector, at a concentration of 50 g t⁻¹ and Dow-Froth400 at a concentration of 20 g t⁻¹ as frother. The slurry was modified to pH9 using lime. This reagent environment was studied in previous work by Molina et al. (2016).

2.3. Froth stability experiments

A laboratory scale, unstirred flotation column (Fig. 2) was used for the dynamic froth stability experiments in a modified Bikerman test. This set up is similar to the systems used in a variety of other studies (Ip et al., 1999; Cilek and Karaca, 2015; Li et al., 2017). The column was 157 cm tall with graduations on the front wall and a square cross-sectional area of 139.2 cm². Air was injected into a chamber at the base of the column where it then passed through a porous disk (porosity No. 1) of sintered glass, 8 cm in diameter in order to produce bubbles. Six liters of slurry were used with a solids content of 10% for all experiments (Molina et al., 2016). Between each experiment the column and frit were cleaned thoroughly by rinsing each wall with water and then ethanol twice and then finishing with a final rinse with water to ensure

Table 1

The proportions of overflow and underflow material in the seven different particle size distributions investigated and their corresponding d10, d50 and d90s

Overflow	Underflow	d10, μm	d50, μm	d90 μm
1	0	2.6	13	64
0.75	0.25	3.4	36	117
0.50	0.50	4.2	59	171
0.375	0.625	4.6	70	198
0.25	0.75	5.0	82	225
0.125	0.875	5.3	89	241
0	1	5.8	105	279

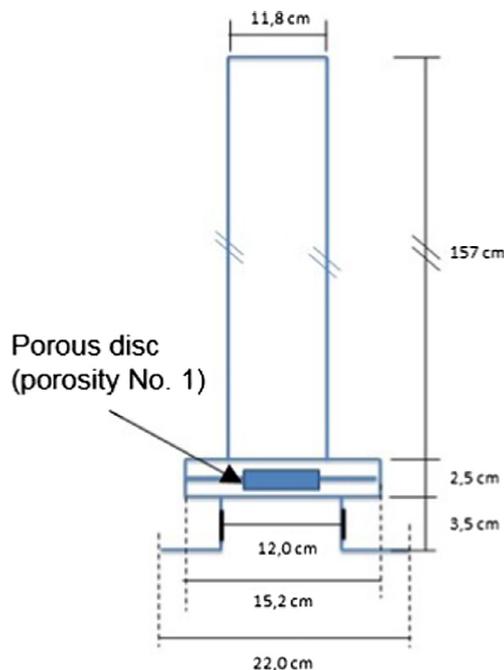


Fig. 2. Schematic of the laboratory scale flotation column. Adapted from Molina et al. (2016).

no ethanol remained on the walls.

The froth heights for each of the seven particle size distributions were investigated in the column, each at three different superficial gas velocities that ranged between 0.96 cm s⁻¹ and 1.92 cm s⁻¹. It is important to note that since a wide range of conditions were evaluated, not all cases could be run at the same three values of superficial gas velocity. For fine particles at high air rates the froth was very stable and would quickly reach the full height of the column and overflow. At the other extreme, coarse particles at low air rates did not produce a stable froth at all. Measurements of the froth height, to the nearest 0.5 cm, were recorded regularly over a 30 min period and each experiment was duplicated.

2.4. Flotation performance experiments

Preliminary flotation performance tests for selected particle size distributions were conducted in a 3L Denver cell with a cross-sectional area of 169 cm² at a superficial gas velocity of 1.44 cm s⁻¹. This air rate was chosen to match the air rate for which dynamic froth stability experiments were run for all seven of the particle size distributions. These tests were performed with the same reagent environment and solids concentration as in the column flotation tests. The Denver cell was operated with an agitation speed of 1200 rpm, a conditioning time of 5 min and a flotation time of 10 min. The performance of three particle size distributions were investigated in this set of experiments, those with d90s of 117 μm, 225 μm and 279 μm.

2.5. Sample analysis

The particle size distributions of the varying feeds were determined using a Malvern Mastersizer 2000 particle analyser. The concentrate samples from the flotation performance experiments were analysed chemically using atomic adsorption spectrometry to determine copper content.

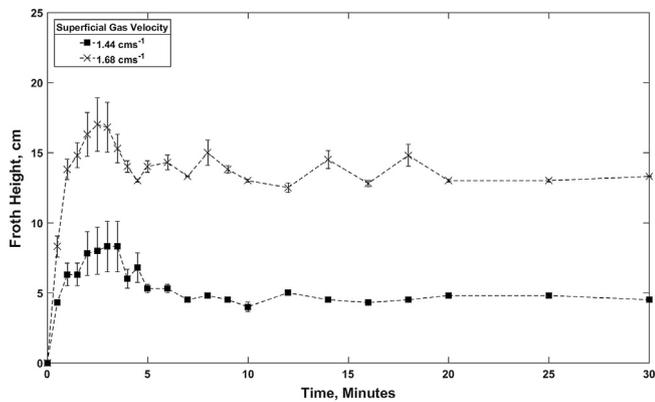


Fig. 3. Froth height growth for experiments with d_{90} of $279 \mu\text{m}$ over 30 min of operation at two different superficial gas velocities. Intervals represent one standard deviation.

3. Results & discussion

3.1. Particle size and dynamic froth stability

Fig. 3 shows froth height for the experiments at two different air rates for the coarsest particle size distribution, with a d_{90} of $279 \mu\text{m}$. Each curve represents average data across duplicated experiments, with intervals representing one standard deviation. This illustrates that the froth height initially increased and after a period of 5 min slightly decreased again, reaching steady state. Previous work has referred to the maximum froth height, H_{max} , when calculating Σ , Eq. (1), however as can be seen from these experiments the maximum height the froth achieves is not the froth height at steady state. In this work, when calculating the dynamic froth stability we have used the equilibrium height, H_{eq} , which is the steady state froth height reached after approximately 30 min of operation.

The dynamic froth stability factor, Eq. (1), was calculated for each experiment using the equilibrium heights, which can be found in

Table 2

Average equilibrium heights, H_{eq} , and dynamic froth stability factors, Σ , for all particle size distributions and superficial gas velocities, J_g , investigated.

Condition No.	d_{90} , μm	J_g , cm s^{-1}	H_{eq} , cm	Σ , s
1	64	0.96	11.7	12.2
2	64	1.20	19.6	16.3
3	64	1.44	30.2	20.9
4	117	0.96	3.8	3.9
5	117	1.20	7.8	6.5
6	117	1.44	23.4	16.3
7	171	1.20	4.1	3.44
8	171	1.44	15.7	10.9
9	171	1.68	30.2	18.0
10	198	1.20	7.0	5.8
11	198	1.44	14.8	10.3
12	198	1.68	42.0	25.0
13	225	1.20	3.9	3.2
14	225	1.44	17.6	12.2
15	225	1.68	47.9	28.5
16	241	1.20	2.9	2.4
17	241	1.44	7.5	5.2
18	241	1.68	21.6	12.8
19	279	1.44	4.7	3.2
20	279	1.68	13.2	7.9
21	279	1.92	25.8	13.4

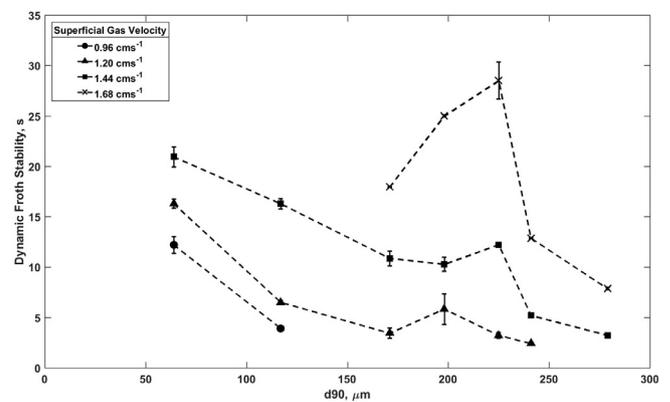


Fig. 4. Dynamic froth stability for different particle size distributions at a range of superficial gas velocities. Error bars represent one standard deviation.

Table 2. Fig. 4 shows the dynamic froth stability factor, for different particle size distributions at constant air rates. For all particle size distributions, decreasing the superficial gas velocity will lead to a decrease in dynamic froth stability factor. This is contrary to what was found by Aktas et al. (2008). It is important to note that the superficial gas velocities used in this work are higher than those used in previous work and similar to industrial values.

From the results in Fig. 4 there is an overall decrease in dynamic froth stability with increasing particle size. However, the decrease is not smooth and two stability regimes can be seen. The first is at finer particle size distributions, below $171 \mu\text{m}$, where the dynamic froth stability factor decreases as d_{90} increases. At the coarser particle size distributions, above $171 \mu\text{m}$, there is a local maximum in froth stability at a given superficial gas velocity. This maximum is much more pronounced at higher superficial gas velocities.

Previous work by Aktas et al. (2008), Liang et al. (2015) and McFadzean et al. (2016a) only reported a decrease in dynamic froth stability with an increase in particle size. However, there are several differences in experimental method (as discussed in detail in Section 1.2), such as the range of particle sizes considered and the superficial gas velocities used, meaning that a similar maximum may exist in those systems but was not encompassed by the data. At the lower of the two air rates investigated here the data is smoother. These air rates are similar to the one used in experiments by McFadzean et al. (2016a), 0.98 cm s^{-1} , suggesting that it is not just the particle size that plays an important role in froth stability but there is also a superficial gas velocity effect. These results also show that the relationship is more complex than previously thought. This is similar to the findings from Norori-McCormac et al. (2017) when investigated the effects particle size and superficial gas velocity have on the air recovery. Whilst Ip et al. (1999) discuss that their results illustrate the same decrease in froth stability with an increase in size, the relationship was not smooth. In fact, the data shows a plateau at a similar particle size to where there local maximum is seen in our data.

It is clear that, when operating towards the right hand side of the graph, there is an optimal particle size distribution that will improve the dynamic froth stability. This suggests that if the tailings reprocessing plant were to slightly lower the cut size of the primary hydrocyclone they could improve the froth stability in the flotation cells. As previously discussed a higher dynamic froth stability has been shown to correlate to an improvement in grade (Barbian et al., 2005) or recovery (McFadzean et al., 2016b).

3.2. Particle size and flotation performance

In order to understand the effect of particle size distribution, not only on dynamic froth stability but also on flotation performance, preliminary experiments were conducted using batch flotation tests.

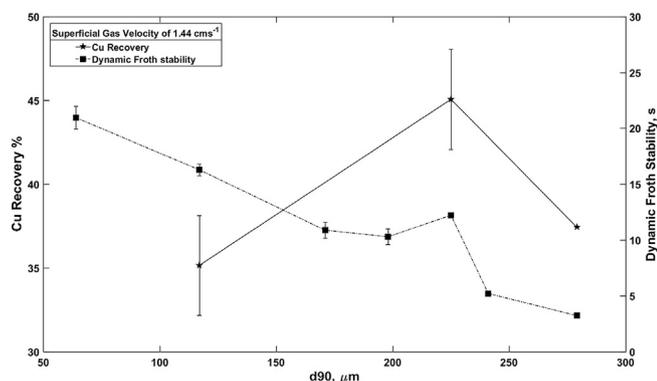


Fig. 5. Copper recovery from batch flotation tests and dynamic froth stability at a superficial gas velocity of 1.44 cm s^{-1} . Error bars represent one standard deviation.

These were performed on three particle size distributions with a superficial gas velocity of 1.44 cm s^{-1} , condition numbers 6, 14 and 19 (from Table 2). The three particle size distributions chosen were i) the closest to the feed to the primary hydrocyclone, ii) the local maximum in dynamic froth stability, and iii) the size currently being sent to the flotation circuit.

Fig. 5 shows the results of copper recovery as a function of particle size (d_{90}) for these tests compared to the dynamic froth stability at the same air rate from Fig. 4. It is observed that at the particle size distribution where there is the local peak in dynamic froth stability, d_{90} of $225 \mu\text{m}$, there is also a peak in copper recovery. It is also interesting to note that out of the three particle sizes the one with highest dynamic froth stability, d_{90} of $117 \mu\text{m}$, actually corresponds to the lowest copper recovery. This indicates that there is not always a direct correlation between dynamic froth stability and copper recovery contrary to the results from McFadzean et al. (2016b). For the tests in this work, the highest copper grade was achieved at the lowest dynamic froth stability, with a d_{90} of $279 \mu\text{m}$, which is the opposite of what was reported in Barbian et al. (2005). The results here show that dynamic froth stability alone cannot be used to determine an optimal particle size for performance, but it is also important to consider which of the two regimes is being investigated.

4. Conclusions

This work has investigated the effects of varying the particle size distribution on the dynamic froth stability of samples from a copper flotation tailings dam at different superficial gas velocities. Compared to previous work, this study has investigated a wider range of particle size distributions, and at superficial gas velocities that are more comparable to those used in industrial flotation cells. In all experiments, for the same feed particle size distribution, there was an increase in dynamic froth stability with an increase in superficial gas velocity.

When considering the relationship between particle size distribution and dynamic froth stability, we postulate the existence of two regimes. The first is at lower feed d_{90} s, where there is a decrease in froth stability for an increase in particle size. The second is at higher feed d_{90} s, where dynamic froth stability goes through a maximum as the d_{90} of the feed increases. A preliminary investigation of the relationship between dynamic froth stability and flotation performance was carried out using batch flotation tests for selected particle size distributions at one air rate. The results showed that the local peak in dynamic froth stability corresponded to a clear improvement in copper recovery for the system. This suggests that, when operating at coarser particle size distributions, the presence of fines in the system can, to some extent, improve the dynamic froth stability and flotation performance. However, if there is too high a proportion of fines the increase in dynamic froth stability does not necessarily correspond to improved

performance. In the case of the reprocessing plant this work suggests that operations may be improved by lowering the cut size of the primary hydrocyclone. Future work will include testing the same ore in laboratory experiments that are more representative of plant scale flotation.

This work has shown that the relationship between froth stability, particle size and air rate is more complex than previously thought. Particularly, in order to use dynamic froth stability to determine the optimum particle size distribution for flotation, a wide range of particle sizes should be considered.

Acknowledgments

This work was supported by the Engineering and Physical Sciences Research Council (award number 1661853); the Society for Chemical Industry and the Faculty of Engineering at Pontificia Universidad Catolica de Chile.

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