Increasing fine flotation recovery for a complex copper ore

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ABSTRACT

The sulphide flotation circuit at First Quantum Minerals' Kansanshi mine in Zambia produced over 100,000 t of copper in 2019. For this circuit, mineralogical analysis has shown that the majority of the copper lost is hosted in fine liberated chalcopyrite, which is a paramagnetic mineral. The objective of this work was therefore to improve fine chalcopyrite recovery in the sulphide flotation circuit at Kansanshi, using a magnetic conditioning technology to agglomerate fine paramagnetic minerals. This theoretically increases the probability of attachment during collision and therefore improves recovery.

A four-month paired 't' test plant trial was carried out and comprised of consecutive ON-OFF periods with and without magnetic conditioning in the rougher flotation bank of the sulphide circuit. The experimental design involved assessment of recovery by size based on daily and weekly composite samples of feed and tails, sized using both wet-screening and cyclosizer. Both the daily plant data and the sized samples showed an increase in Cu recovery with magnetic conditioning ON. A 0.56% copper recovery improvement was measured with magnetic conditioning at a 99.4% confidence level.

Keywords: Flotation, fine mineral, chalcopyrite, magnetic aggregation

1. Introduction

1.1. Kansanshi Flotation Circuit

Kansanshi flotation circuit consists of Outotec mechanical flotation rougher and cleaner cells. Concentrate cleaning is conducted via Jameson cells. A total of seventeen ProFlote magnets are installed in the first two rougher cells.

1.2. Kansanshi Mineralogy

Copper mineralogy in the sulphide plant feed is variable, but predominately chalcopyrite, which constitutes about 90% of the total copper mineral. Secondary copper sulphide minerals constitute a further 7%, with a mix of copper oxides, carbonates and silicates the remaining 3%.

The target grind size at Kansanshi is a P80 of 150 µm in the flotation feed. Despite this relatively course grind however, 34% of the total feed mass is in the <38 µm fraction. In the final tail, about 75% of the copper is sulphide copper, and about 60% of the Cu in final tail is <38 µm sulphide Cu. This highlights that fine sulphide Cu recovery is critical to the economic performance at Kansanshi and its priority in plant projects.

1.3. Fine Sulphide Mineral Recovery

Sulphide flotation recovery is largely dictated by particle size, with losses primarily in the coarse and fine fractions. In many processing plants, flotation operators continually monitor the P80 grind size of particles that enter the flotation circuit to ensure adequate mineral liberation, to reduce coarse losses. For even coarse grinds like Kansanshi, there is always a proportion of <38 µm liberated sulphide mineral that reports to flotation and is difficult to recover (Trahar and Warren, 1976; Trahar, 1981).

Fine particles have poor flotation recoveries because of low collision efficiencies with air bubbles (Duan *et al*., 2009). That is, poor flotation recovery of fine sulphides is purely a physical characteristic of their size and not a chemical phenomenon. Nevertheless, this size limitation has provided an opportunity for metallurgists to explore ways to improve fine mineral recovery to enhance the economic viability of their operation.

Many methods have been explored and tested to tackle the poor recovery of fine mineral, but the major impediment to implementation of these methods is their lack of selectivity, or their large capital and operating costs and subsequent implementation complexities. Amongst the methods commonly evaluated by industry are; Torrisi *et al.* (2003) investigated split flotation, Song *et al.* (2000) floc-flotation, Holder (1994) shear flocculation and Ahmed *et al.* (1989) agitator speed. No single method has received widespread acceptance in commercial flotation operations, therefore, improving fine mineral flotation recovery continues to be a critical focus for plant metallurgists.

1.4. Magnetic Aggregation of Fine Paramagnetic Minerals

Some minerals recovered by froth flotation, like chalcopyrite, sphalerite (containing iron), bornite and cassiterite are paramagnetic (Svoboda, 1987). Also, common concentrate contaminants are not strongly paramagnetic: siliceous gangue is diamagnetic and pyrite has a negligible magnetic susceptibility (Svoboda, 1987). Therefore, the difference in magnetic susceptibility between minerals allows improved flotation selectivity increasing valuable metal recovery in the concentrate.

Paramagnetic minerals are weakly magnetic, relative to ferromagnetic minerals, so very strong magnetic fields are required for paramagnetic particle magnetisation and subsequent aggregation to occur. Table 1 is reproduced from Svobada (1987) and gives the magnetic susceptibility of some minerals present in base metal flotation.

Table 1.
Magnetic susceptibility of minerals (Svobada, 1987).

Mineral	Reported magnetic susceptibility m^3kg^{-1} x 10^{-9}
Chalcopyrite	1596
Bornite	101
Marmatite	38-5900
Cassiterite	2136
Pyrite	1-5
Quartz	-5.7

Although magnetic aggregation of paramagnetic minerals has been reported widely in the 1990's, the reports focused on non-sulphides minerals like haematite, rutile and siderite. (Svoboda *et al*, 1983: Svoboda, 1981: Svoboda, 1981: Tsouris, *et al*, 1995; Lu, *et al*, 1988: Wang, *et al*, 1994). The research was laboratory based and applied to settling, rather than flotation. However, it provided a theoretical basis for its application to the aggregation of fine paramagnetic sulphide minerals to improve their flotation recovery.

Many plant studies, including those by; Engelhardt *et al*. (2005), Holloway *et al*. (2008), Rivett *et al*. (2007), Zoetbrood *et al*. (2010) and Lacouture *et al*. (2016), have demonstrated the practical application of fine paramagnetic aggregation in commercial flotation circuits. These detailed statistical plant tests use high strength rare earth magnets to magnetise and aggregate the fine paramagnetic sulphides to increase their flotation recovery. The range of paramagnetic sulphide minerals which have shown increased recovery spans most sulphide minerals floated, including chalcopyrite, bornite, galena, sphalerite, pentlandite and precious metal minerals.

The paper by Engelhardt *et al*. (2005) has a more detailed description of the theoretical basis of fine paramagnetic aggregation and its application to sulphide mineral flotation.

2. Experimental

In 2018, a four-month plant trial of magnetic conditioning was undertaken at FQML's Kansanshi operation, in the sulphide flotation plant. Seventeen high strength, high gradient, rare earth magnetic conditioning units were installed in the first two cells of the Cu rougher circuit. The aim; to selectively improve <38 µm chalcopyrite recovery. The installation was carried out in the Cu rougher circuit rather than the cleaner circuit because the cleaner circuit is in closed loop configuration, i.e. the cleaner tails recirculate back to the head of the rougher circuit instead of exiting to final tail. Therefore, if the installation was carried out in the cleaner circuit, any reduction of copper in cleaner tails does not necessarily mean a reduction in detectable losses to overall plant tails, which was the objective in this test.

A sequential 2 day ‘ON’ 2 day ‘OFF’ paired t-test was used to measure any changes in overall plant performance. While the paired t-test is ideally suited for parallel lines that process the same ore, Kansanshi only has one row of rougher cells. Nevertheless, Napier Munn (2010) considers a paired t-test the most powerful statistical method for this type of evaluation. An automated pneumatic system controls the position of the magnets inside their stainless steel cases, relative to the slurry. When the magnetic conditioning technology is in the ‘ON’ state, the high strength, high gradient, rare earth magnets are cycled in and out of the slurry at regular intervals to allow removal of ferromagnetic material in the slurry that will blanket the surface of the magnetic casings. During the ‘OFF’ state, the magnets are lifted out of the slurry and stay there for the entire two-day duration.

Over the length of the trial period, four types of data sets were analysed:

- A 24 hour average of the 2 hourly plant composite assay data of key variables.
- Variance between predicted and actual plant copper recovery.
- Daily size by size recovery data for +/- 38 microns and
- Weekly size-by-size recovery data for cyclosized fractions.

Each set of data was screened for abnormal events like plant shutdowns and shifts with low tonnage throughputs. This is an acceptable method of filtering raw data as an accurate analysis can be carried out using only normal, representative plant conditions.

3. Results and Discussion

3.1. Copper Results – Plant Data

The plant data analysis was carried out by a paired t-test and the Excel spreadsheet used is available on request.

Table 2.

Magnetic conditioning plant results in Kansanshi’s copper circuit.

	%Cu Rec
Magnetic Conditioning ON	91.4
Magnetic Conditioning OFF	90.4
Difference	1.0
Level of Confidence	97%

The results show an increase in total copper recovery of 1.0 % with magnetic conditioning to a very high 97 % statistical level of confidence. There was no change in final Cu concentrate grade to high statistical confidence which demonstrates a selective increase in copper recovery.

3.2. Copper Results – Variance from Predicted Recovery.

While actual recovery is used for daily production monitoring, metallurgists at Kansanshi have produced a linear regression model based on key variables, on similar processed ore, to predict current plant copper recovery. The predictive model, which predominately uses feed grade related variables, largely serves as an estimation as to what the overall copper recovery for each day should be. Metallurgists are able to compare the predicted and actual plant copper recovery and provide a root cause analysis to management, if large variations occur. These models are updated regularly to incorporate the impact of any significant plant and mineralogy changes.

The measured variance between predicted and actual copper recovery was also analysed with the magnetic conditioning technology in both the 'ON' and 'OFF' state. A paired t-test of the variance between these two recoveries was analysed in Excel.

Table 3.

Magnetic conditioning results of the variance between predicted and actual plant copper recovery.

	%Variance (Actual %Cu Rec-Predicted % Cu Rec)
Magnetic Conditioning ON	-0.23
Magnetic Conditioning OFF	-1.07
Difference	0.84
Level of Confidence	98%

The results in Table 4 demonstrate that the variance between actual and predicted copper recovery has improved when the magnetic conditioning technology was ON. The paired t-test of the variance showed that predicted plant copper recovery improved by 0.84% to 98% level of confidence. The result is very similar to the 1.0 % actual difference in recovery and confirms the reality of the measured difference.

The slightly lower delta recovery improvement obtained via the predictive method, implies that the feed grade for the ON period was slightly more favourable for recovery than the OFF periods (from a mineralogy point of view). This is potentially the key reason for the difference and hence the benefit of the predictive recovery model.

However, there are limitations in predicted copper recovery calculations. These calculations use past data to predict future recoveries and ore change fluctuations over the short term are not always well captured by these models. Similarly, for each variable, whether it is a % Cu assay, or plant operating variable, there exists an associated error that may incorporate random and systematic error. A two-product formula to calculate plant copper recovery incorporates just three assay variables, far less than a predicted model, that may include, different metal assays, grind size or throughput and concentrate metal grades. Therefore, it is not surprising to see a slight difference in predicted plant copper recovery variance, and total copper recovery difference. However, the data is consistent; with the conclusion that the improvement in plant copper recovery with the magnetic conditioning technology is a real result and similar magnitude independent of the method that was used.

3.3. *Copper Results – Daily Sizing Data*

Magnetic conditioning is a method to improve the selective recovery of < 38 µm minerals. Therefore, with magnetic conditioning, the one percent increase in total plant copper recovery would be expected to be in the < 38 µm fraction. The size analysis pairs each daily ON size Cu recovery with the sequential daily OFF size Cu recovery and then averaged over the duration of the test for each size fraction. This was analysed using a paired t-test.

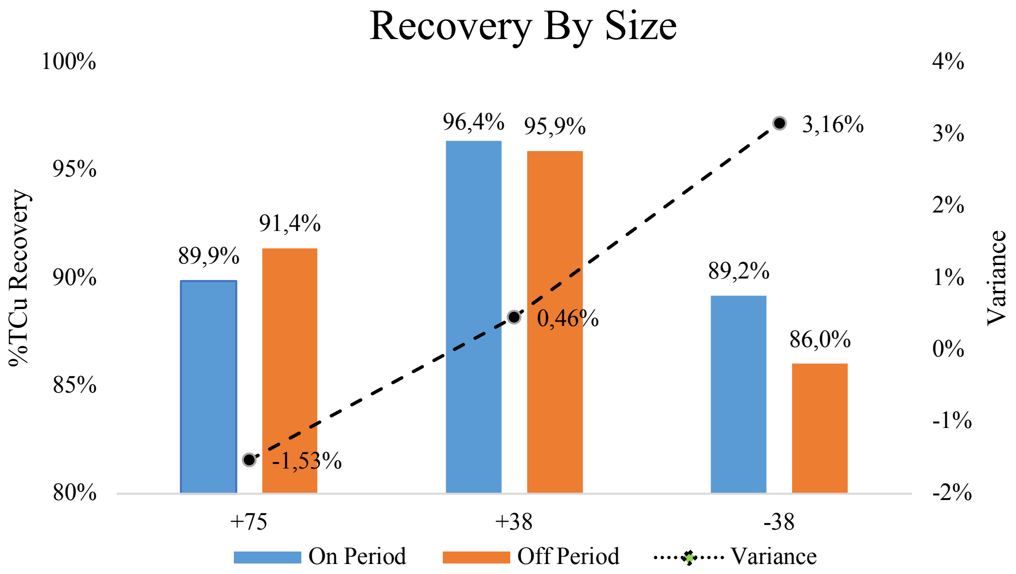

Fig. 1. Paired size by size copper recovery data at three different size fractions.

For flotation plants like Kansanshi where a significant proportion of chalcopyrite predominates in the fine fraction, Figure 1 clearly shows that <38 microns copper recovery is the major limiting factor for Kansanshi's overall copper recovery. However, when the magnetic conditioning equipment was ON, a 3.16 % increase in copper recovery in the < 38 µm fraction was observed to an exceptionally high 99.9 % statistical level of confidence. The difference in copper recovery for the other size fractions was not to statistical confidence, and just represents the normal plant variability. The results confirm that the agglomeration mechanism of the magnetic conditioning technology specifically targets the fine < 38 µm fraction. That is, there is no statistical difference in coarse copper recovery, which has been confirmed at other plant tests (Rivett *et al.* 2005).

The fine copper recovery improvement relates well to overall plant performance that was seen during the four-month test. Although Kansanshi's grind size targets a course P80 of approximately 150 µm, about 40 % of the copper in flotation feed is less than 38 µm. Hence, one would expect a 1.3 % increase in plant performance from a 3.16 % increase in less than 38 µm copper recovery. This is very similar to the 1.0 % increase in overall copper recovery that was measured with the plant data. The variation probably caused by the natural variability and the extra processing steps in sized analysis.

If all the size fractions are considered, the overall coppery recovery improvement is 0.56% with a high 99.4% statistical level of confidence. This is the recovery improvement value chosen for a more conservative economic justification.

3.4. Copper Results – Weekly Cyclosize Data

Weekly cyclosized data was also carried out and was used to confirm the daily sizing and plants results as well as to further understand which size fraction in the < 38 µm fraction showed a statistical improvement in copper recovery with magnetic conditioning ON. Weekly size data is a composite of all ON and all OFF samples for each week. Daily cyclosizing was not performed because of resource constraints such a major program would impose at Kansanshi's laboratory.

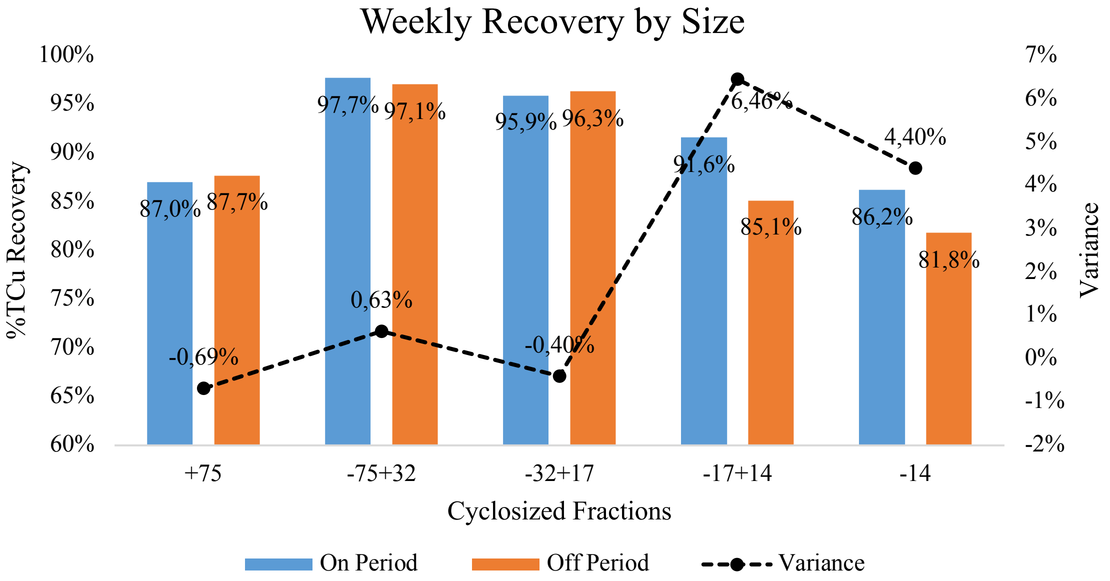

Fig. 2. Weekly size by size copper recovery data for cyclosized fractions.

Analysing the data shows that the copper recovery improvements with the magnetic technology ON is in the <38 µm fraction and is largely due to the -17/+14 µm and the -14 µm size fraction. Specifically, a 6.46 % copper recovery increase in the -17/+14- µm size fraction was observed to 93.5 % statistical confidence with the magnetic conditioning technology ON. Similarly, a 4.40 % copper recovery increase in the -14 µm size fraction was observed to 83.2 % statistical confidence with the magnetic conditioning technology ON. No statistical differences were seen in size fractions greater than 17 µm. While the differences in fractional copper recovery are very large, the confidence levels are not as high as the plant data. The reason is twofold, fewer pairs - weekly pairs, not daily pairs and the increase variability due to the increase in processing steps. Nevertheless, they are entirely consistent with the daily sizing analysis and the daily plant analysis but add the insight that the main difference is in the < 17 µm Cu fractions, not the entire < 38 µm fraction. This is consistent with other published results with magnetic conditioning (Rivett *et al.* 2005)

A weighted average of these size by size recoveries with respect to the Cu size distribution in feed measures about a 2.0 % increase in < 32 µm copper recovery. This in turn relates to about a 0.80 % increase in overall plant copper recovery assuming 40 % of copper in the feed is <38 µm. This 0.8 % increase is slightly less than the measured 1.3% increase in the daily sizing data. From a technical perspective, it would have been beneficial to perform more frequent weekly cyclosized composite samples over the test duration, to increase the confidence levels in the cyclosized fractions, however, as the plant data and daily sizing data were already conclusive, there was no need to expend the much greater resources for simply confirmatory data.

4. Conclusion

Four months of magnetic conditioning test work in Kansanshi's copper sulphide ore circuit has been concluded and shown to improve the efficiency of the selective separation of copper flotation by increasing overall copper recovery by 0.56 % to a high 99.4 % statistical level of confidence. This result was confirmed with magnetic conditioning giving an improvement of 0.84 % in the variance to modelled recovery to a high 98 % statistical level of confidence.

Daily and weekly sizing data was used to understand which size fractions were being impacted by the magnetic conditioning. The results are entirely consistent with the magnetic aggregation mechanism as the sizing analysis showed increases in copper recovery in size fractions less than 38 µm to high statistical confidence.

At the completion of the test, the magnetic conditioning technology has been left operating continuously. The key decision to retain the units were due to the confidence in the results, ease of realising the benefit and subsequent financial benefit. The reason for the latter was that it did not require a change in operating philosophy and results were achieved immediately upon switching the magnets continuously ON.

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