Short water recirculation during the flotation of a UG2 Cu-Ni-PGM ore: Effects on tailings dewatering and quality of the recovered water

Malibongwe S. Manono, Michael S. Ngau, Kirsten C. Corin

Centre for Minerals Research, Department of Chemical Engineering, University of Cape Town, Private Bag X03, Rondebosch, 7701, South Africa, malibongwe.manono@uct.ac.za, ORCID 0000-0002-2928-9368, ngxmic00x@myuct.ac.za, ORCID 0000-0002-5839-4618, kirsten.corin@uct.ac.za, ORCID 0000-0001-9908-423X

Abstract

Water recirculation during flotation can substantially influence physicochemical characteristics of flotation tailings, their dewatering characteristics as well as the return water quality from tailings dewatering processes unit operations. Effective tailings management is essential to minimize the environmental footprint of mining operations. In this study, the effect of short water recirculation in mineral processing of a Cu-Ni-PGM ore on the coagulation of tailings and return-water quality was investigated. A bench scale short water recirculation simulation developed in this study considered the following: (1) monitoring the accumulation of inorganic electrolytes in the process water on the laboratory comminution and flotation facilities; (2) investigating the effects of point of addition of recirculated water (i.e. to the mill or the float cell.); and (3) investigating the effects that short water recirculation has on the coagulation of tailings. The techniques utilised in this study were as follows: (1) coagulation of tailings through UV/Vis spectrometry, and 3) monitoring selected ionic species present in the water recovered from the tailings using a Gallery Discrete Automated Photometric (Colorimetric) Analyzer (GDAPA). The results of this study have shown that short water recirculation leads to an increase in ionic concentrations due to ore dissolution in the mill and during froth flotation. The choice of point of addition plays a crucial role in water quality and dewatering characteristics of the tailings; recycling water to the mill may lead to lower of Ca^{2+}, Mg^{2+}, SO_4^{2-} concentrations in the water while recycling water to the float cell results in higher concentrations of the same ions.

Keywords: Coagulation, flotation reagents, inorganic electrolytes, water recirculation, tailings

Introduction

Operators of mineral processing circuits are becoming increasingly aware of their effects on the environment, particularly on tailings management and water resource management. Effective tailings management and water management are therefore essential to minimise the environmental footprint of mining operations. Closed water circuits and water recirculation during froth flotation are seen as steps in the right direction towards effective water management in mineral processing (Le et al. 2020). The recycling of process water in mineral processing can substantially influence the dewatering characteristics of tailings as the water that requires recirculation is drawn from tailings thickeners, concentrate thickeners, filtrates and tailings dams (Slatter et al., 2009). There are two main distinct modes of operations or strategies on water recirculation, namely, short water recirculation and long water recirculation (Slatter et al. 2009; Le et al. 2020). Short water recirculation is water recycled from dewatering unit operations onsite whereas long water recirculation refers to water recirculated from tailings dams. Short cycle water recirculation and the recovery of water from tailings slurries has the potential to result in improved dewatering performance due to reduced water content in the tailings. The reduced water content in the tailings would in turn enhance the consolidation and compaction properties of the tailings, thereby facilitating the formation of a denser and more stable tailings deposit that can be repurposed or stacked in a dry manner and thus reducing the risk associated with tailings dams. Furthermore, short cycle water recirculation can promote the formation of a coarser tailings particle size distribution owing to the use of dewatering aids, these contribute to enhanced dewatering efficiency. The quality of water recovered from tailings dewatering unit operations also plays a vital role in environmental sustainability and onsite water resource management. Short cycle water recirculation has the potential to improve the quality of the recovered water by reducing the concentration of various contaminants (Le et al. 2020). Studies have demonstrated that short cycle water recirculation residence times result in lower concentrations of dissolved ions and other pollutants in the recovered water (Le et al. 2020). Additionally, the reduced water content in the tailings leads to a higher concentration of solids, this aids in the removal of suspended particulate matter during water treatment processes. These findings highlight the potential of short cycle water recirculation to produce cleaner and less contaminated water which can be re-used for flotation. While short cycle water recirculation during flotation offers several advantages such as reduced dependence on municipal fresh water, lower operating costs emanating out of a reduction in fresh reagent dosage due to residual reagents being present in recycled water etc. (Manono et al. 2019), it also presents certain challenges and considerations such as the accumulation of inorganic electrolytes which may be detrimental to the process as well as increasing maintenance costs where process water pipelines may be prone to fouling and scaling. One key challenge however is the potential effects on flotation performance, particularly the concentrate grades owing to the presence of hypersaline conditions which stabilise the froth, thereby increasing the entrainment and recovery of gangue minerals (Manono et al. 2018). Thus, there may very well be a trade-off between improved dewatering and reduced flotation recovery rates, however, research studies are yet to elucidate such concerns. The shorter residence time in short cycle water recirculation may also mean less clarity of the water compared to long water cycles, thus more total dissolved solids (TDS), total suspended solids (TSS) and increased concentrations non-degraded residual frothing compounds which can affect the stability of the froth, leading to decreased valuable minerals grades (Manono and Corin 2022). It therefore stands to research that it is critical that researchers must find a balance between optimal dewatering and acceptable flotation performance to maximise the overall economic efficiency of the process when considering high dewatering efficiencies and implementation of close water circuits for improved environmental sustainability. Future research should therefore focus on optimising water recirculation strategies and should further evaluate the economic and environmental feasibility of short cycle water recirculation in specific mining contexts. Implementing such research findings can contribute to more sustainable and responsible mining practices while minimising the environmental impact of mining operations. Thus, this paper considered the short cycle recirculation of process water during the flotation of a UG2 ore with a keen interest on the dewatering characteristics of tailing post flotation as well as the quality of water recovered after the dewatering of tailings. Results on the implications of this practice at a bench scale on flotation performance and froth stability are presented elsewhere (Manono et al. 2023).

Methods

Short Water Recirculation during the Flotation of a UG2 Ore

Short water recirculation in this study was performed using a 3 L Barker batch flotation. For each flotation test, a pre-prepared 1.3 kg sample of a UG2 ore ground to 60% passing 75% was used. To achieve the desired grind size, the ore sample was added to an Eriez stainless still rod mill and a volume of water, synthetically prepared process water – fresh water (3 SPW) or the required recycled water, was added to make up a slurry of 60% water by volume in the presence of sodium isobutyl xanthate (SIBX) as the collector at a dosage of 150 g/t. The milled slurry was transferred into a 3 L Barker flotation, an additional volume of either fresh or recycled water was added to the cell to make a slurry of 66% vol. water and the rest being solids. The cell was also dosed with sodium carboxymethl cellulose (CMC), Deparmin 267 as a depressant at a dosage of 100 g/t. Dow 200, a polyglycol ether was also added to the cell as a frother at a dosage of 40 g/t. The standard UCT batch flotation procedure was used to recover concentrates and tailings post-flotation. The collected tailings and concentrates were filtered. The filtrate from the tailings was then recovered to either the mill or the float cell in order to evaluate the effect of point of addition when recycling water within a mineral processing circuit. An outline of the design of experiments is illustrated in Fig. 1. All measurements were conducted in triplicate to allow for statistical analysis of the results. Subsequent error analysis was found to be within 5 % for the amount solids of solids recovered and within 10 % for the amount of water recovered.

Preparation of Synthetic Plant Water

The Centre for Minerals Research (CMR) at the University of Cape Town (UCT) developed a synthetic plant water (1 SPW) recipe to mimic typical water quality determined at several PGM concentrators across the Bushveld Igneous Complex (BIC) (Wiese et al. 2005). At the time, this water comprised of a total dissolved solids content (TDS) of 1023 mg/L and an ionic strength (IS) of 0.0242 mol.dm^{-3}. However, steady increases in dissolved ion concentrations in process, recycled and tailings water has rendered water of TDS of 1023 mg/L atypical of most PGM concentrators today. Therefore, synthetic plant water of higher TDS content was proposed to better represent typical water concentrations in PGM concentrators. Individual salts of analytical grade, supplied by Merck, were dissolved in de-ionised water to prepare synthetic plant water, namely 3 SPW. The recipe was adapted from 1 SPW by multiplying the concentration of respective ions by three to represent the increase in ion concentration on-site over time. The salts were dissolved in de-ionised water and stirred with an impeller in two 3 L buckets. 3 SPW was considered to represent the current on-site feed process water quality and was used as the baseline water quality. Standards ionic concentrations contained in 3 SPW are shown in Tab. 1.

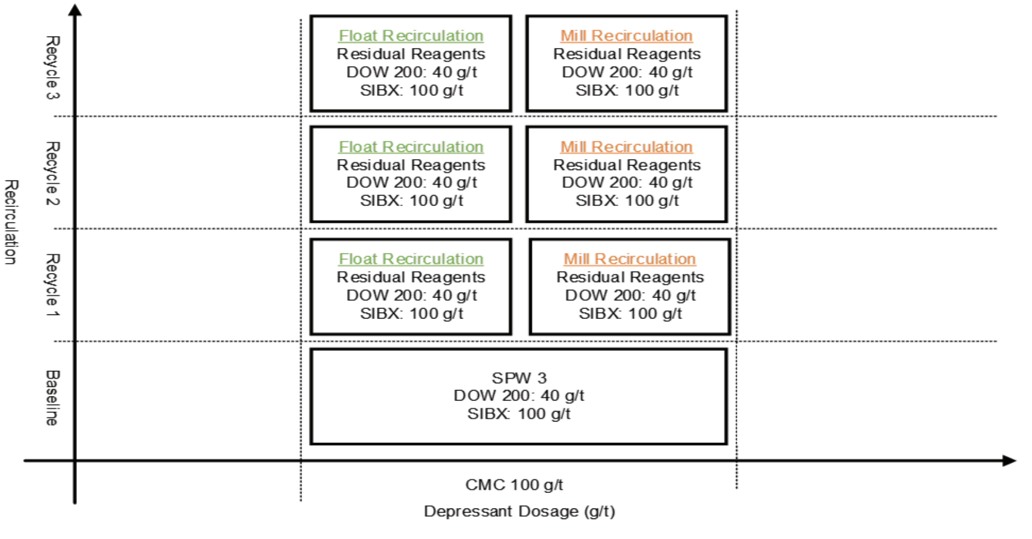

***Figure 1** One Factor at a Time Design for the Experimental Conditions Tested on the UG2 Ore*

Table 1 *The Concentration of Ions Presents in Synthetic Plant Water in mg/L (adapted from Manono* et al. *2018)*

	Ca^{2+} mg/L	Mg^{2+} mg/L	Na^{+} mg/L	Cl^{1-} mg/L	SO_4^{2-} mg/L	NO_3^{-} mg/L	CO_3^{2-} mg/L	TDS mg/L
3 SPW	240	212	459	861	719	527	51	3069

Determining the Coagulation of Tailings

Spectroscopy was utilised to investigate the settling rate of solids in the tailings, utilising the methodology developed from Thierie (2018) who used a Short Wavelength Near Infrared light beam to investigate hindered settling of solids in wastewater. This method was adopted to ensure real time visible light spectrometer to monitor the change in absorbance over time to indicate the settling rate of the solid phase. The maximum absorbance for 3 SPW water was achieved at 850 ± 1.63 nm wavelength, and this was chosen to be the operating wavelength for the coagulation tests. The settling time was determined immediately after each experimental run to prevent the residual reagents present from reactions that could infuence the settling time. The impeller in the float cell was kept on while a sample was drained to ensure consistent pulp concentrations in the sample. A tailing sample was tapped from the tailings outflow pipe. The sample was weighed. A P5000 Gilson air displacement pipette with a sliced tip was set to 3 ± 0.01 mL and used to extract and place the sample in a transparent plastic cuvette with 3.50 mL capacity and a light path of 10 mm. The UV/Vis spectrometer was set to 850 nm blanked with a 3 SPW sample. The sample was thoroughly shaken and placed in the spectrometer with a timer switched on simultaneously. The absorbance of the sample was recorded for 2 h Eq. (1) adapted was used to calculate transparency (T(t)%) of the sample as a function of time where A_b is the dark current obtained by cutting the power supply, A_o is the absorbance of the blank 3 SPW sample and Am(t) is the absorbance of the sample at the measured time.

$$T(t)\% = \frac{A_b - A_{m(t)}}{A_b - A_o}\% \qquad \text{Eq. (1)}$$

$$T(t)\% = \frac{T_\infty^2 * k * t}{1 + T_\infty * k * t}\% \qquad \text{Eq. (2)}$$

Eq. (2) is a second order kinetic model of the transparency ($T(t)$%) where time is denoted as (t), with a maximum transparency (T_∞) and a transparency rate (k) as constants. The T_∞ and k were model fit to a second order kinetic model from using a chi squared test used to establish whether a relationship exists between the experimental variables under the null hypothesis that no relationship exists. A chi squared value (x^2) was calculated using Eq. (3) where the experimental value is (O_i) is subtracted from the predicted value is (E_i). A GRG non-linear solver minimises the x^2 value be changing the R_∞ and k values. A P value is developed for (n (number of readings)$^{-1}$) from a chi table for an alpha value of 0.05, hence a 95% confidence interval. Models with x^2 within the confidence interval were accepted and considered to be an adequate representation of the experimental values.

$$x^2 = \sum_{i=0}^{n} \frac{(O_i - E_i)^2}{E_i} \qquad \text{Eq. (3)}$$

Specific Anion and Cation Analysis from the Tailings Water using GDAPA

This study also focused on monitoring the ionic species present in the water to be recycled using a Gallery Discrete Automated Photometric (Colorimetric) Analyzer (GDAPA). The ions chosen are ions that have elevated concentrations in typical PGM concentrators. GDAPAs have been used by water quality analysts and regulators to develop an understanding of complex water matrices; primarily to monitor increased inputs of Total Dissolved Solids (TDS) and specific ions present in water resulting from mining activities, wastewater effluent discharge and nutrient cycling in hypersaline environments (Stanton et al. 2017). An account on how GDAPAs operate is summarised in Stetson et al. (2019).

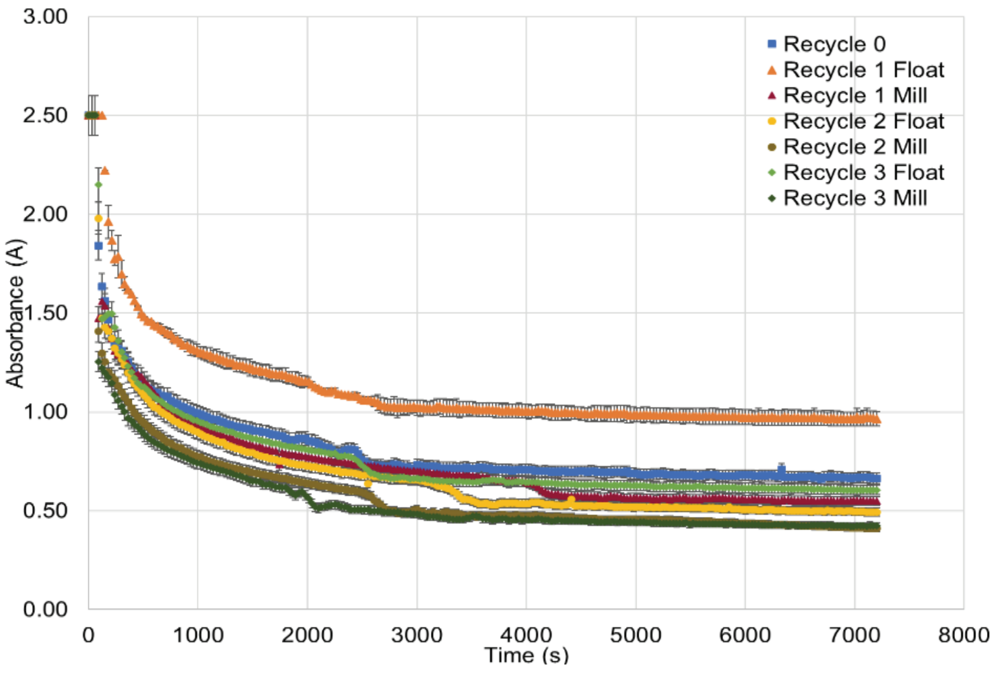

Figure 2 *The Absorbance (A) Of 3 mL Tailings Water Sample as a Function of Time (s) for All Tested Conditions*

Results

Coagulation-Flocculation of Flotation Tailings: Implications for Tailings Dewatering

Fig. 2 demonstrates the absorbance (*A*) of 3 mL tailings water samples measured in a spectrometer as a function of time in seconds for all the tests conducted. All samples displayed a maximum absorbance at the start of the tests (i.e. at time 0 s). Most of the settling of solid particles occurred in the first 3000 s (≈ 1 h), with a rapid decrease in absorbance in the first 500 s, followed by a steady decrease in absorbance between 500 and 3000 s. The minimum absorbance value achieved at the maximum test time, 7200 s, differed in each sample, with the lowest absorbance in Recycle 2 and 3 in Mill recirculation, followed by Recycle 2 to the Float Cell, Recycle 1 to the Mill, Recycle 3 to the Float Cell, Recycle 0 and Recycle 1 to the Float Cell, in that order.

Fig. 3 shows second order kinetic models fitted to the transparency, *T* (%) of the tailing samples as a function of time across all the tests conducted in this study. The first 500 s are marked by a rapid increase in transparency, the transparency was 50% in most samples excluding Recycle 1 when recycling to the float cell that had a transparency of 40%. Overall recycled water, except for Recycle 1 in float cell recirculation, achieved maximum transparency at a higher transparency rate in recycled water as compared to Recycle 0. Also, recycling water through the mill achieved higher maximum transparency *T* (%) at a higher transparency rate compared to recycling through the float cell.

Concentration of Selected Anions and Cations of the Water Recovered from the Tailings: Implications of Short Water Recirculation on Water Quality

Tab. 2 illustrates the concentration of magnesium (Mg^{2+}), calcium (Ca^{2+}), sulfate (SO_4^{2-}), and chloride (Cl^-) ions in the tailings water recovered after filtering tailings slurries from the flotation process. The gallery discrete colorimetric analyser provides concentrations of ions in the tailings water in mg/L from the water samples recovered

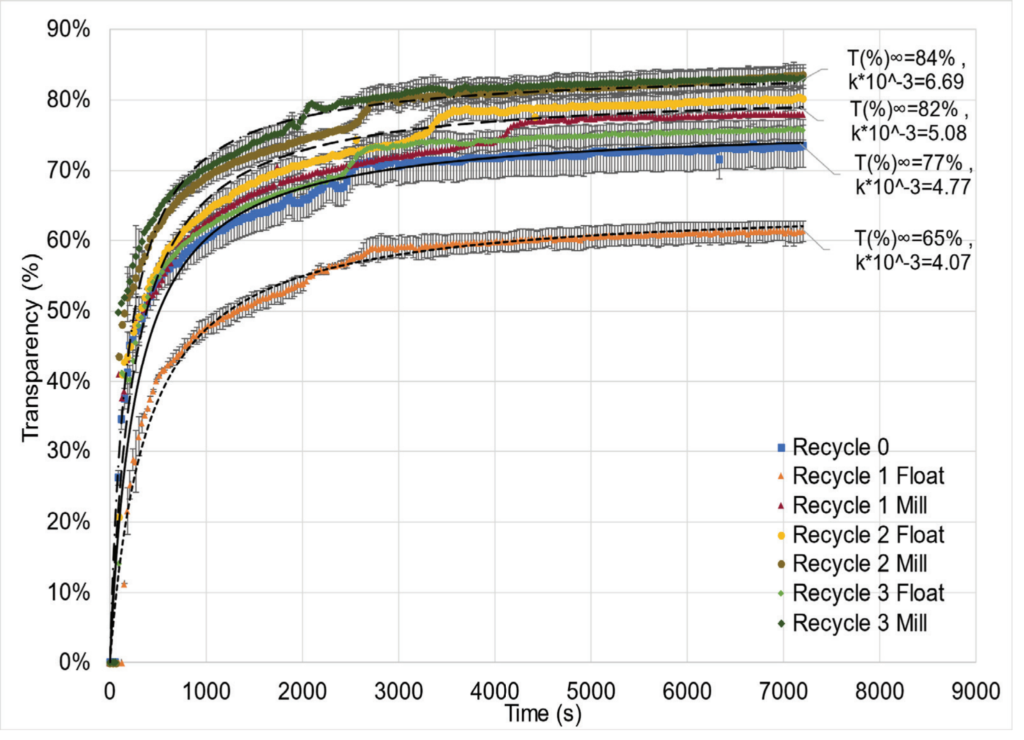

Figure 3 *Second Order Kinetic Models Fitted to the Tailings Sample Transparency T (%) as a Function of Time (s)*

after the dewatering of flotation tailings. The concentrations of cations in the tailings water from flotation under baseline conditions were at 240 mg/L and 207 mg/L for Ca^{2+} and Mg^{2+} respectively, which were close to the calculated concentration of these ions in feed water (3 SPW) shown in Tab. 1, thus this method could be deemed appropriate in estimating approximate cation concentration in the tailings water.

Conclusions

This study successfully showed that water recycling leads to an increase in ionic concentrations due to ore dissolution in the mill and during froth flotation. The dissolved ions are primarily from the common gangue minerals found in the ore used in this study such as Ca^{2+}, Mg^{2+}, SO_4^{2-} and Cl^-. The choice of point of addition plays a crucial role in water

Table 2 *Concentration in mg/L of Dissolved Ca^{2+}, Mg^{2+} SO_4^{2-} and Cl^- Present in Tailings Water Recovered Post Flotation*

	3 SPW	Recycle 0	Recycle 1		Recycle 2		Recycle 3	
			Mill	Float	Mill	Float	Mill	Float
Ca^{2+}	240	240 ± 3	237 ± 6	248 ± 1	234 ± 6	254 ± 2	241 ± 6	258 ± 6
Mg^{2+}	212	207 ± 3	207 ± 12	242 ± 7	193 ± 1	198 ± 3	164 ± 12	191 ± 12
SO_4^{2-}	719	792 ± 10	708 ± 14	804 ± 57	740 ± 9	805 ± 17	783 ± 14	813 ± 14
Cl^-	861	1247 ± 127	1057 ± 15	999 ± 120	1032 ± 12	1027 ± 128	1054 ± 15	1021 ± 15

quality and dewatering characteristics of the tailings; recycling water to the mill may lead to lower of Ca^{2+}, Mg^{2+}, SO_4^{2-} concentrations in the water while recycling water to the float cell results in higher concentrations of the same ions. Furthermore, the settling rate in tailings thickeners may initially be controlled by the flow of large particle sizes but is aided by the presence of ions that improve the flocculation in the pulp hence thickener operations would benefit from water recycling.

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