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Modeling and simulation of a gold concentrator plant implementing a dissolution loop method

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Abstract: Mineral processing applications increasingly use recycled water to preserve freshwater natural resources and comply with environmental regulations. However, accumulating anions, cations, and reagents in the process water may affect plant flotation performance and production continuity. Therefore, many cost actions may be needed to mitigate the recycled water effects. Typically, the process water properties and their effects on flotation performance are unknown for a greenfield project. Often, the result is an over-scaling up of the process plant with an additional financial cost. The experimental methodology in the paper focuses on creating water for testing that is closer to the actual process water during the comminution and flotation process for any greenfield project. The scope of the study consists of creating possible process water, conducting flotation experiments, and simulation. In order to validate the dissolution loop method, refractory gold flotation plant conditions were selected in our Finland laboratory. The simulation results of dissolution loop flotation kinetics were compared with the actual plant mass balance. According to the comparative results, the process water created by the dissolution loop method has the same physical and chemical properties as the actual process water at the site except for SO_4^{-} concentration. Moreover, comparing the simulation results of the experimental data and plant mass balance studies shows that the gold grade and recovery results in the simulation were lower than the actual plant mass balance.

Keywords: simulation, dissolution loop, water matrix, gold, flotation, modeling, mass balancing, plant survey

1. Introduction

With the development of technology, gold is becoming even more desirable, especially in electronics, the superconductor industry, aviation, medicine, space technology, and many other areas. The increasing need for gold also brings an enormous demand for gold processing technologies. Therefore, due to the high demand for gold, the gold beneficiation industry is forced to expand further (Liang et al., 2021).

Gravity separation, cyanidation, mercury mixing, and flotation are widely known as beneficiation processes for gold extraction (Liu et al., 2016). Gold ore flotation is one of the well-known beneficiation methods for gold ore deposits that separate minerals using different physical and chemical surface properties (Dunne, 2005). Gold ore flotation processes are continuous, complex industrial processes with multiple inputs and outputs.

Consequently, a flotation plant survey and site audit are critical to thoroughly assess a concentrator plant's metallurgical performance and identify its bottlenecks. The survey's primary purpose is to collect data from the process, generate a mass balance, and analyze the performance of the process from the established mass balance. The data required for the mass balance includes throughputs, solids contents, and chemical compositions of the process streams. Part of the data can be collected from the automation system or the daily production reports, but most of the data needs to be based on a sampling campaign (Metso Outotec, 2021).

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Water usage and quality are becoming more crucial in mineral processing plants, especially in the flotation industry (Chen et al., 2009; Sinche-Gonzalez et al., 2016; Castro, 2018). For this reason, plant operations focus on decreasing water consumption and recirculating process water. However, it is widely known that recycled process waters may affect flotation kinetics due to the occurrence of thiosulfates in sulfide flotation. In sulfide flotation, thiosalts are formed due to the oxidation of pyrite, pyrrhotite, and chalcopyrite (Rao, 2011). Özturk et al. stated that thiosulfates are a significant effecting parameter for sulfide flotation (Özturk et al., 2018). Siche-Gonzalez and Fornasiero suggested that the explanations for thiosulfates action range from competing with collectors, increasing the surface oxidation or to precipitation of metal sulfate compounds, which all kinds of depressants in mineral flotation; on the other hand, increased mineral flotation has been attributed to a surface cleaning effect by sulfate ions (Sinche-Gonzalez & Fornasiero, 2021). The fundamental studies on pure minerals showed that tetrathionates in solution oxidized the sulfide mineral surfaces, as evidenced by the increased presence of thiosulfate species, iron hydroxy oxide, and oxide species on the sulfide minerals (Mode et al., 2021).

On the other hand, flotation plants are typically designed using freshwater at the bench scale and pilot scale test work. Usually, the effect of process water is not tested due to the nonexistence of actual process water. The process water's properties may cause a different flotation residence time than the tap water and result in a sizing problem in flotation processes in a greenfield project (Liu et al.,2013). Consequently, a dissolution loop method can solve the sizing problems, especially in greenfield cases where the process water's chemical and physical properties are unknown (Le & Dahl, 2020).

The ITERAMS project has developed the first version of a dissolution protocol to create recycled water that contains closely the same impurities as actual process water. Le et al. (2020) conducted research using two different ores. The results indicate that the protocol quite nicely defines the main direction of the water matrix will evolve when the plant is operated. The dissolution loop is a simple method compared to the complex interactions between the plant's ore, water, and operating conditions (ITERAMS, 2020).

In this study, Dragon Mining Oy has provided the Jokisivu gold ore to validate the dissolution loop method for the Werte (Business Finland-sponsored) research and development project.

Fig. 1. Satellite image of the Vammala gold concentrator plant (Google Earth, 2022)

The Vammala Concentrator Plant is in southern Finland, 160 kilometers northwest of the Finnish capital Helsinki and comprises the Vammala Plant, the operational Jokisivu Gold Mine. The Vammala Plant is a 300,000 tonne per annum crushing, milling, and flotation facility recommissioned in June 2007. Since recommissioning, the plant has produced 409,502 ounces of gold as concentrate to 31 December 2021. Ore processed through the Vammala Plant is sourced from the Jokisivu Gold Mine, 40 kilometers southwest. Most gold concentrate generated at the Vammala Concentrator is processed at the

Company's owned Svartliden plant in northern Sweden. A small amount of gravity gold is also delivered to the Argor-Heraeus refinery in Switzerland (Dragon Mining, 2021). The concentrator plant consists of two grinding stages with a closed circuit configuration. The ground material is fed to six Outokumpu 16 m^3 rougher flotation cells. The rougher concentrates are combined and thickened at the concentrator plant before transportation. The simplified flowsheet of the plant can be seen in Fig. 2.

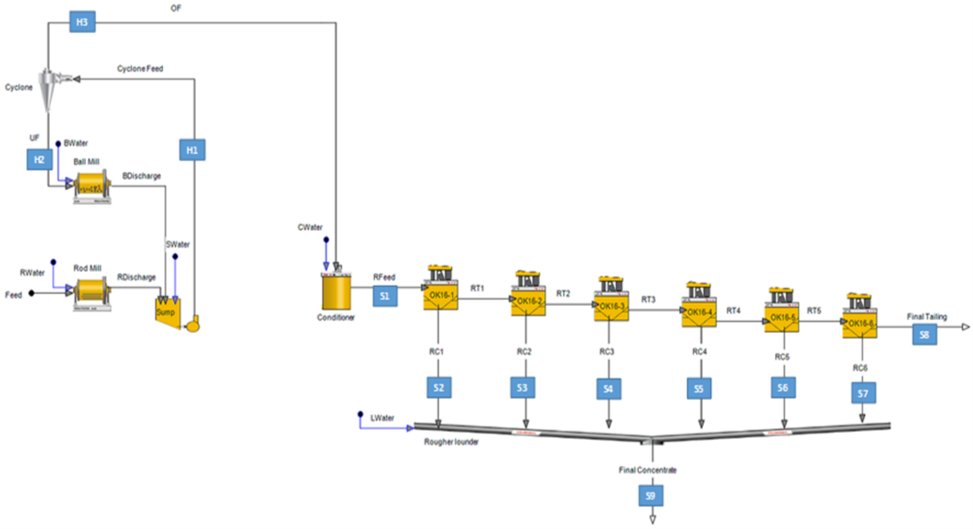

Fig. 2. The simplified flowsheet of the Dragon Mining concentrator plant

2. Materials and methods

2.1. Materials

A 100 kg of representative feed ore was taken from Dragon Mining Oy Vammala gold concentrator crushed ore bin. The sample was transported to Metso Outotec Research Center for experimental studies.

The sample was crushed -1.14 mm and divided into 1.5 kg batches for dissolution and flotation tests. The dissolution and flotation experiments were conducted at d_{80} particle size 100 microns (Fig. 3) to follow the same operation conditions at Dragon Mining Oy.

After total dissolution, the chemical analysis of metals in solids was conducted using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES, Thermo Scientific iCAP 6000). The combustion method determined the total carbon and sulfur concentrations (Eltra CS-2000). The gold content was determined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS, Thermo Scientific). The chemical and mineralogical composition of the material is shown in Tables 1 and 2, respectively.

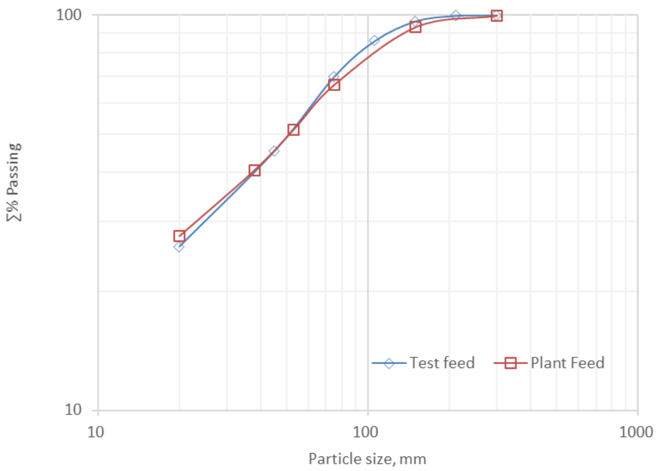

Fig. 3. Particle size distribution of representative ore sample and plant feed

Table 1. Chemical composition of the studied sample

Element/oxide		Method	Content
Au	ppm	ICP MS	2.40
Na_2O	%	ICP OES	2.80
MgO_2	%	ICP OES	2.59
Al_2O_3	%	ICP OES	14.39
P_2O_5	%	ICP OES	0.16
K_2O	%	ICP OES	2.11
CaO	%	ICP OES	4.89
TiO_2	%	ICP OES	0.80
Fe	%	ICP OES	5.78
Cu	%	ICP OES	<0.05
Zn	%	ICP OES	<0.05
As	%	ICP OES	0.08
Ba	%	ICP OES	0.03
Pb	%	ICP OES	<0.05
C	%	Eltra	<0.5
S	%	Eltra	0.6
SiO_2	%	UV-vis	61
Magnetite	%	Satmagan	0.7

Table 2. Mineralogical composition of the studied sample

Mineral	Formula	Content, %
Plagioclase (anorthite, albite)	$(Na, Ca)(Si,Al)_4O_8$, $NaAlSi_3O_8$	38.73
Quartz	SiO_2	22.23
Amphiboles	$Ca_2(Mg_{4.5\text{-}2.5}Fe_{0.5\text{-}2.5})\ Si_8O_{22}OH_2$ $Ca_2Mg_4Al_{0.75}Fe^{3+}{}_{0.25}(Si_7AlO_{22})\ (OH)_2$	16.53
Biotite+ chlorite	$KMg_{2.5}Fe^{2+}{}_{0.5}AlSi_3O_{10}(OH)_{1.75}F_{0.25}$ $(Fe^{2+}, Mg,Al,Fe^{3+})_6(Si,Al)_4O_{10}(OH,O)_8$	11.18
K-feldspar	$KAlSi_3O_8$	7.61
Magnetite	$Fe^{3+}{}_2Fe^{2+}O_4$	0.70
Pyrrhotite	$Fe_{(1\text{-}x)}\ S$	1.48
Arsenopyrite	$Fe^{3+}AsS$	0.17
Apatite	$Ca_5(PO_4)_3F$	0.37
Ti-minerals, garnet, and other		~1.0
Total		100.00

2.2. Method

2.2.1. Grinding procedure

The grinding tests were performed with a laboratory-type ball mill 21 kg mild steel ball charge at 65 % w/w solid ratio. Twenty-four minutes were a needed primary grinding time for the target fines d_{80} of 100 microns. The 1.5 kg batch size was combined with tap water and fed to the grinding ball mill. The ground material was flushed using tap water prior to the dissolution methodology.

2.2.2. Flotation procedure

The flotation experiments were conducted using a laboratory-type Outotec GTK LabCell™ flotation machine. The machine has an adjustable external water feed pump for constant pulp levels. An automatic froth scraper system recovers froth. GTK lab cell equipped with a water feed system can be seen in Fig. 4.

Dragon mining flotation experiments with different water qualities, such as tap, process, and dissolution water, were carried out using a 35% solid ratio of 1.5 kg feeds in 4 liters of flotation cells.

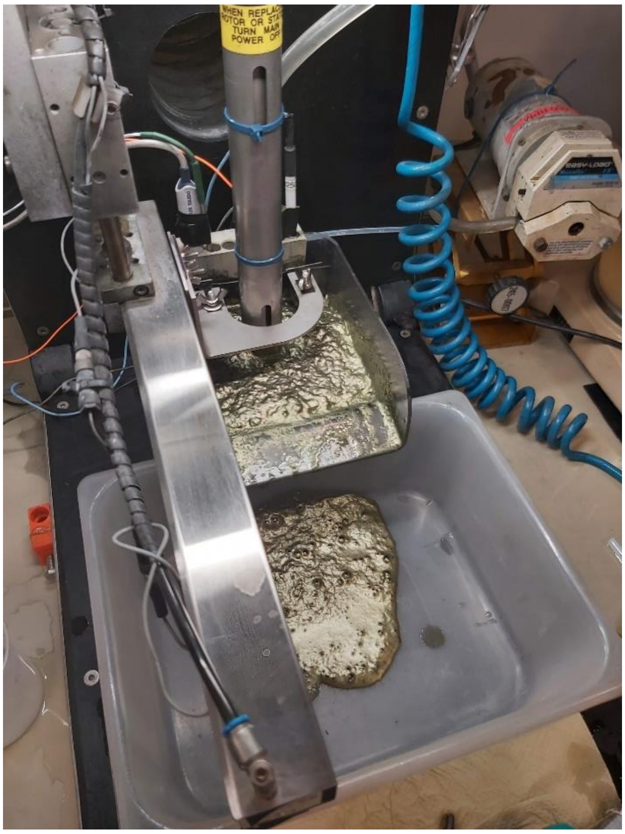

Fig. 4. Outotec GTK Flotation LabCell™

During the flotation experiments, water was added to maintain a constant pulp level in the flotation cell. The airflow was set to 3 L/min throughout the flotation test, and the air was fed in with a 15-20 second delay to build froth. Once the froth reaches the discharge lip, the flotation time and froth scraper are started.

An impeller rotational speed was selected to achieve a suitable pulp suspension in the flotation cell. Impeller rotational speeds of 1500 rpm were used in a 4 L cell.

Conditioning time was selected for reagents according to plant conditioner retention time. Reagents were added in the same way for each test. All reagent types and their commercial names are given in Table 3.

Rougher flotation concentrates were collected at 1, 4, 8, 12, 18, and 24 minutes to create a kinetic rate for the simulation. The general flowsheet of the experiments can be seen in Fig. 5.

Table 3. Reagents used in the flotation tests

Reagents	Name	Function	Supplier
SIBX	Sodium iso-Butyl Xanthate	Collector	N/A
KAX	Sodium iso-Amyl Xanthate	Collector	N/A
Danafloat 571	Sodium di-isobutyl phosphorothioate	Collector	Cheminova
Danafloat 468	Sodium di-sec-butyl dithiophosphates	Collector	Cheminova
Dowfroth 250	Polypropylene glycol methyl ether	Frother	Dow

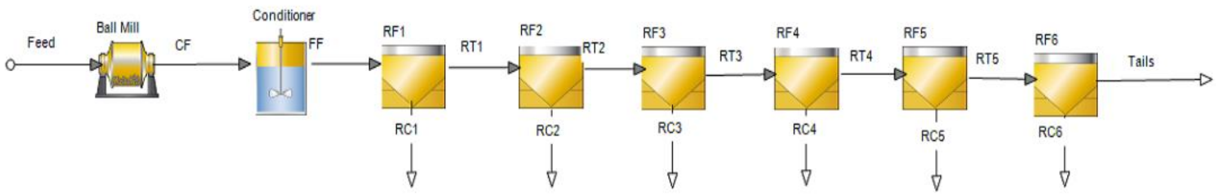

Fig. 5. General flowsheet of the rougher flotation test

Abbreviations: PW - the experiment was carried out by using Dragon Mining process water, TW - experiment with Pori tap water, DW - the experiment was carried out with dissolution water.

2.2.3. Dissolution loop method

The dissolution loop method consists of two sub-processes: the dissolution loops and the flotation tests. Two flotation tests are performed, one with the starting water (the tap water) and one with the final water obtained from the dissolution loops tests.

In the case of Dragon Mining ore, one dissolution loop test comprises six rounds. The grinding is performed at 65% using tap water. One 100 ml water sample is collected for analysis at the end of each round, marked with a triangle and square shapes in Fig. 6. The water samples are analyzed as soon as possible to get the chemical properties of the water.

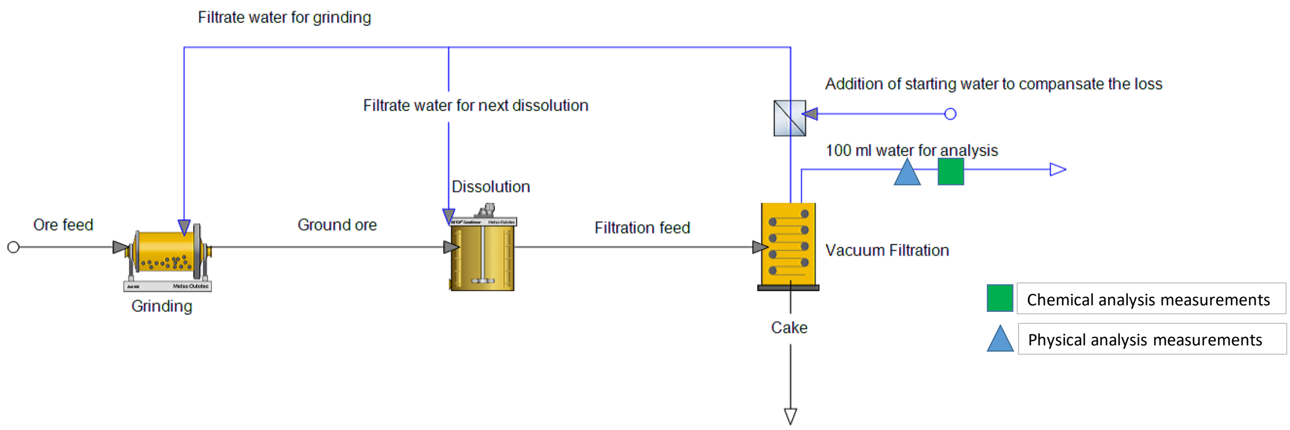

Fig. 6. Dissolution loops general diagram

The procedure for each round of the dissolution loops test consists of eight rounds:

1) Measuring the physical chemistry parameters of the tap water (for the first round).
2) Grinding the ore with the tap water for 24 minutes to reach an approximate P_{80} of 100 µm. The percentage of solid during grinding is 65 wt.%.
3) Recover the slurry and adjust the solid percentage with the tap water (for the first round) of interest for one hour of dissolution.
4) Measure the physical chemistry parameters of the slurry.
5) After one hour of dissolution, the slurry is filtered with a vacuum to prevent the decomposition of thiosulfate compounds.
6) The physical properties of created water are measured. A 100 ml water sample is taken for chemical analysis.
7) The next round is started.
8) The dissolution step repeats the stages except for adding the tap water but recycled water from the previous rounds.

The steps are repeated until the physical properties of the recycled waters are stabilized. The physical chemistry parameters such as temperature, pH, Eh (oxidation-reduction rate), specific conductance (SPC), conductivity, and dissolved oxygen (DO%) were analyzed with the YSI Pro DSS multi-meter probe. The sensors were checked before each round of tests and calibrated when needed.

2.2.4. Simulation method

The simulation model was created for the Dragon Mining flotation circuit to compare the mass balance using dissolution loop-created water and Pori tap water. For this purpose, a slurry sample was taken from the conditioner discharge to conduct a hot flotation test and determine the scale-up factor.

The kinetic models were created separately for each mineral. A rectangular distribution model was used to fit the experimental kinetic curves, and the models were calculated using the HSC Sim 10 Model Fit® tool. In addition, the Klimpel flotation model for batch flotation was used to calculate kinetic parameters such as the infinitive recovery and the flotation rate constant. Mass balances were calculated, including grades and recoveries for each mineral in each stream. In the Klimpel model (Equation 1), Rmax shows the highest possible recovery for each mineral, and the k of rectangular distribution reveals how fast each mineral is floated (Metso Outotec, 2021):

$$R = R_{max}\left\{1 - \frac{1}{kt}\left[1 - e^{-kt}\right]\right\} \tag{1}$$

where t is the cumulative residence time, Rinf is the infinitive recovery, Kmax is the flotation rate constant, and Rmax ≤1.

In the simulation model, the same flotation cell configuration was used. Therefore, a 6x16 m3 Outokumpu flotation cell was selected in the model.

A gas hold-up of 10% and a froth volume reduction of 5% were used in the simulation work. Based on the hot flotation and mass balance calculation, the scale-up factor was calculated as 2.7 for the flotation circuit. Moreover, the residence time was calculated based on the volumetric pulp feed to the flotation bank. The infinitive recoveries and maximum grades of the conducted tests can be seen in Table 4.

Table 4. R_{inf} and K_{Max} values of the conducted tests

Tests	Parameter	Arsenopyrite	Gold	Pyrrhotite	Quartz
Tap water	R Inf	66.237	77.184	89.449	9.279
	k Max	2.356	0.844	1.509	0.0124
Dissolution water	R Inf	63.435	81.231	92.084	6.789
	k Max	2.966	1.299	2.141	0.0025

The feed mineralogy was simplified for simulation study to allow for the simulation's better stability and reliability. Pyrrhotite and arsenopyrite were selected as the primary sulfur carrier for the mineral conversion. The remaining feed material was summed as quartz based on the mineralogical study.

2.2.5. Plant survey and mass balancing methodology

The Dragon Mining plant survey was conducted within 5 hours. First, all the sampling points were checked, cleaned, and tagged. Then, sampling was started from the grinding circuit to the flotation cells. In total, six samples were collected into the sample buckets. Sampling points on the flowsheet can be seen in Fig. 7.

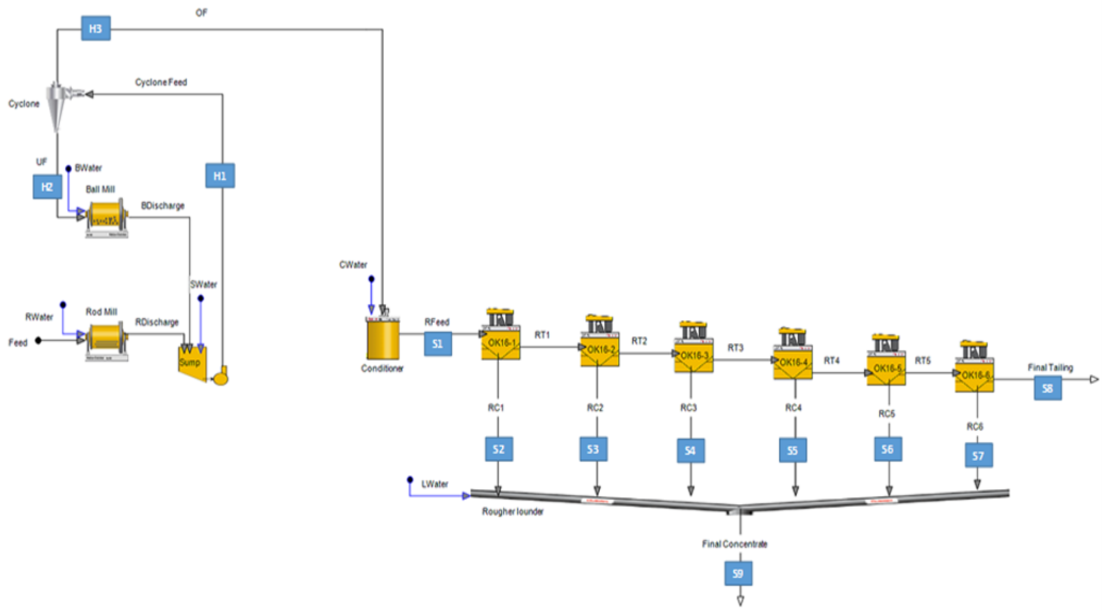

Fig. 7. General flowsheet of the plant and sampling points

All the concentrate samples were sampled by lip sampler, except the final concentrate. Additionally, conditioner discharge, final concentrate, and final tailings samples were taken by cutter samplers.

Mass balancing was completed for both grinding and flotation circuits. The solid ratio by weight was used as the primary input for the grinding circuit. The solid ratio by weight, sulfur, gold, and iron assays was used for the mass balancing in the flotation circuit. The mass balancing weighted sum of squares method was used in the HSC Mass balancing tool.

3. Results and discussion

3.1. Dissolution loop results

In Fig. 8, concentrations of cations are increasing by each loop. The SO_4^{-2} anions concentration rises from 64 to 161 mg/L. However, $S_2O_3^{-2}$ anions concentration is relatively stable and limited. The concentration versus loop number plots also indicates that the silicon and silicate-associated elements' concentration is not stabilized by the end of the test because of the continuous dissolution of the silicate minerals. The last water loop was used as a water resource for the flotation test. The comparison of plant process water and dissolution water properties can be seen in Fig. 9.

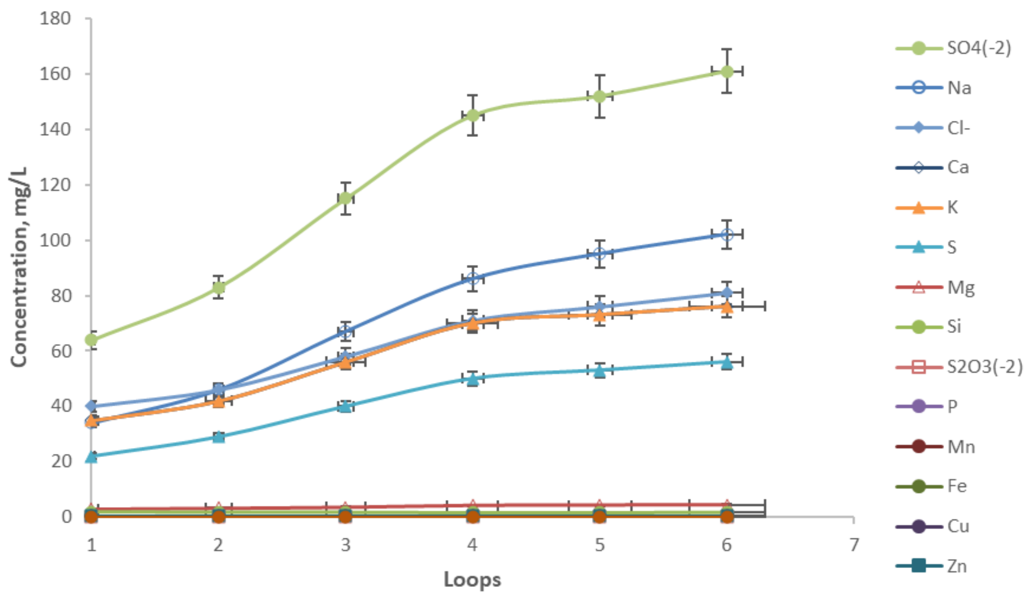

Fig. 8. Chemical properties of the dissolution loop results

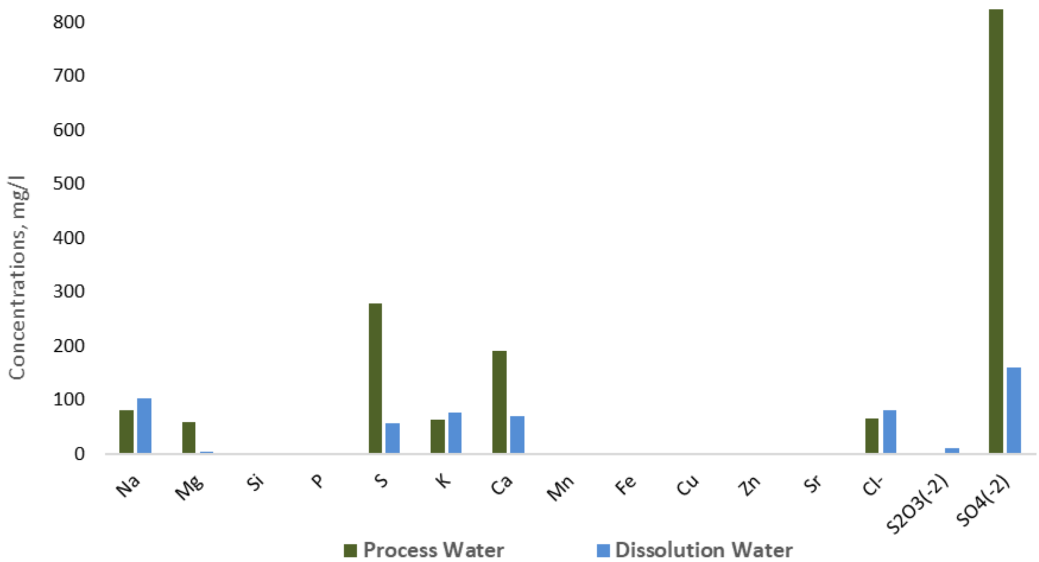

Fig. 9. Chemical comparison of the water samples

Fig. 9 shows that overall anions` concentrations between process water and dissolution water are the same except for SO_4^- concentration. The chemical comparison chart shows that the SO_4^- ions are six times higher in the process water, which may negatively affect sulfide flotation performance. Although six dissolution loops were completed, the process water thiosulfate concentration was not reached in the dissolution water compared to the process water. These tiny differences in the concentration levels may affect the flotation performance.

3.2. Laboratory scale flotation results

The lab-scale flotation tests were conducted within Dragon Mining plant conditions. Moreover, the exact dosages were applied to get the same flotation conditions as the plant. Some collectors, like the plant, were added to the cell after the third concentrate was taken. Moreover, the flotation conditions can be seen in Table 5.

Table 5. Rougher flotation conditions of the conducted experiments

Conditions	Reagents				Streams
	SIBX/ PAX g/t, 1%	Danafloat 571 g/t, 100%	Danafloat 468 g/t, 100%	DF250 g/t, 1%	
JS13 (P_{80}=100 µm, PW)	43	28		18	RC1
					RC2
					RC3
					RC4
	8	28	8		RC5
					RC6
JS14 (P_{80}=100 µm, DW)	43	28		18	RC1
					RC2
					RC3
					RC4
	8	28	8		RC5
					RC6
JS15 (P_{80}=100 µm, TW)	43	28		18	RC1
					RC2
					RC3
					RC4
	8	28	8		RC5
					RC6

The main aim of the flotation experiment is to see the effect of different water qualities on the metallurgical performance and create data for the simulation model. Results can be seen in Fig. 10 and Fig. 11. All the flotation conditions are the same except for the water qualities used during the tests.

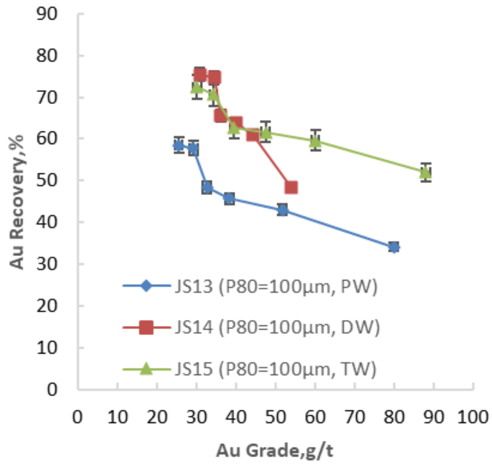

Fig. 10. Gold recovery versus grade

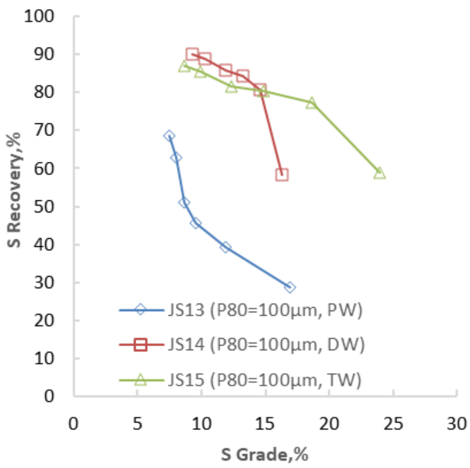

Fig. 11. Sulfur recovery versus grade

It can be seen in Fig. 10 that gold recovery and grades are lower in the process water than in the dissolution and tap water results. Test JS14 has the highest stage recovery and grade. The gold grade-recovery curves indicated that the high SO_4^- concentration in the process water negatively affected the flotation recovery and grade. However, the gold recovery and grade differences between tap and dissolution water are approximately 10%.

Overall, sulfur recoveries reached almost 90% in tap and dissolution water. However, process water sulfur recovery and grade were limited to around 70%. Nevertheless, the process water's sulfur grade and recovery are lower than the dissolution water.

3.3. Simulation results

The simulation was carried out using kinetic data from laboratory bench-scale flotation experiments. In this scope, predictions of the actual plant gold recovery and grade were conducted with tap water, process water, and the dissolution water flotation results. The simulation results can be seen in Fig. 12 and Fig. 13.

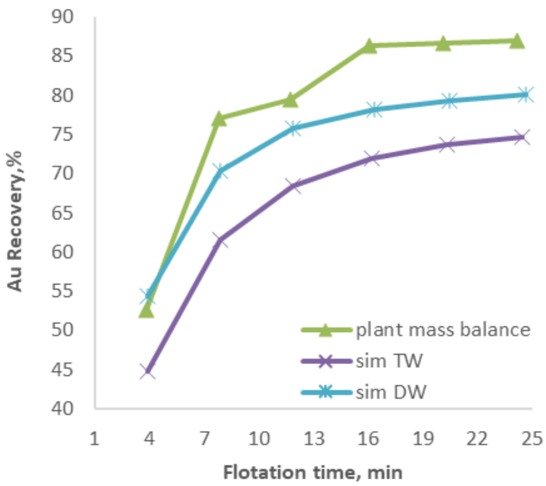

Fig. 12. Gold recovery versus flotation time

The above Figs. show that the gold recoveries with tap and dissolution water are lower than the actual plant performance. However, the simulation results based on the dissolution method are much closer to the actual plant mass balance than the tap water results. The prediction ability of dissolution water is better than tap water. On the other hand, the gold recoveries of the simulations are lower than the actual plant mass balance. One reason for gold grade differences between plant mass balance and laboratory simulations may be higher entrainment in the lab-scale flotation cell and some nugget effects in the plant survey samples.

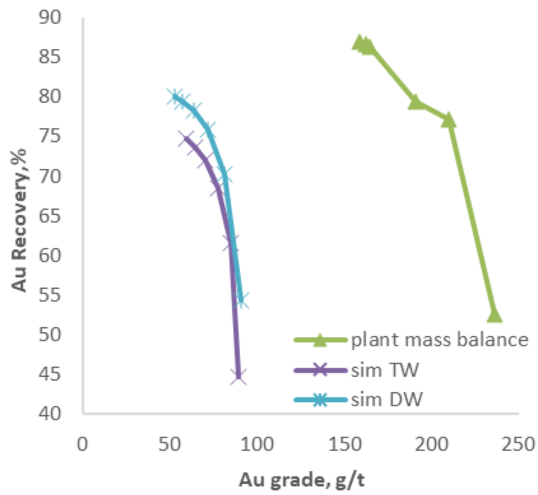

Fig. 13. Gold recovery versus grade

3.4. Mass balance results

The mass balance results of the Dragon Mining flotation circuit results can be seen in Fig. 14. The mass balance of the flotation circuit shows that 158.5 g/t gold concentrate was produced at 87% recovery. Nevertheless, the solid ratio of the individual cell concentrate was low, especially for RC3, RC4, RC5, and RC6. The solid recovery to the final concentrate was measured as 1.03%.

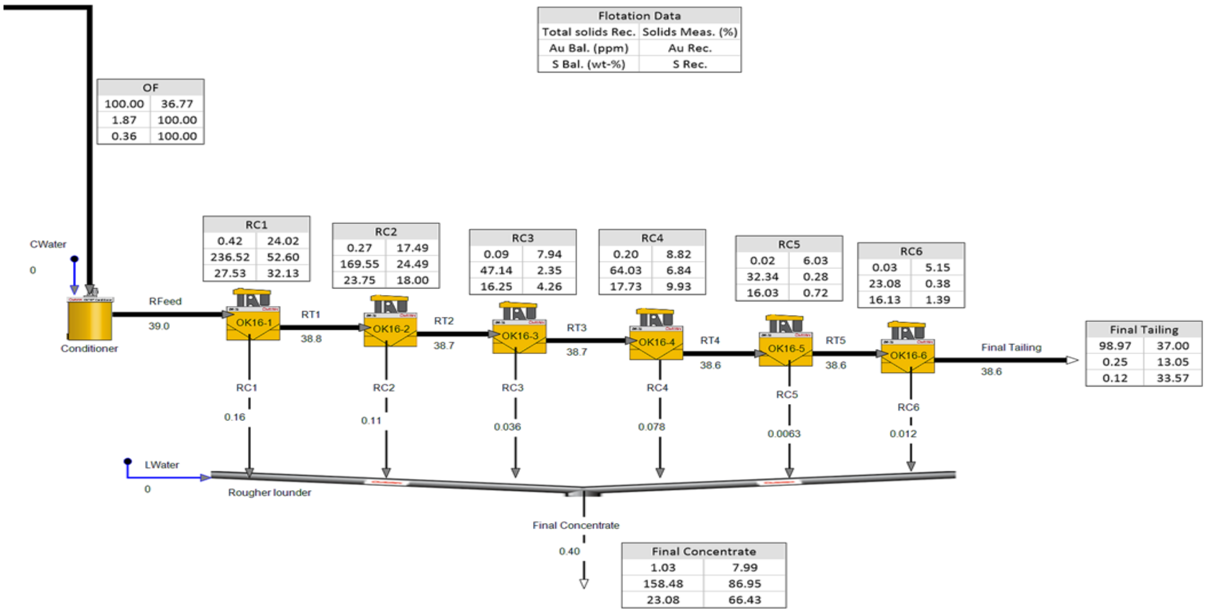

Fig. 14. The mass balance results of the Dragon Mining rougher flotation circuit

4. Conclusions

According to the dissolution loop laboratory experiments, the chemical and physical properties of process water created using the dissolution loop method were similar to the actual process water. However, the sulfate concentration in process water was much higher than in dissolution loop water. The differences in sulfate concentration may be due to the aging effect in the tailings dam.

Extending the dissolution loops numbers and improving the dissolution method by implementing actual separation tests and reagent regimes to the dissolution water production loop might provide even more precise predictions and faster mass balancing, similar to a locked cycle flotation method.

Laboratory flotation experiment results show an apparent sulfate depression effect on overall gold recoveries. The gold recovery is lower when the sulfate ions are high in the water phase.

The extensive plant survey results show that the grinding and classification units work efficiently. Moreover, the metallurgical performance of the flotation circuit is outstanding, although the froth carry rates and lip loads are low.

Comparing the simulation models with dissolution water and Pori tap water results proved many differences between plant mass balance and simulation results regarding the gold grades. Nevertheless, the gold recovery of dissolution water created simulation results is closer to the actual plant gold recovery than the Pori tap water. The gold grade differences between plant mass balance and simulation results may come from the nugget effects and unexpected entrainment at laboratory scale flotation experiments.

More extensive studies can be done, such as including reagent addition in dissolution steps to improve the predictability of the dissolution method, and the method can contribute to the predictability of the process water, especially for greenfield projects.

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