Comparison of flash flotation and gravity separation performance in a greenfield gold project

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Abstract: Recovery of gold and gold-containing sulfide mineral particles requires multiple-stage recovery processes starting from the grinding circuits to avoid over-grinding of the liberated gold particles. Due to high density, these gold grains tend to follow the hydrocyclone underflow, and a significant amount of metal increases in the circulating load. Therefore, in recent years the grinding circuits have been designed to improve the recovery of free gold/gold-containing particles in the grinding circuit. Gravity separation (centrifugal gravity separators) and flash flotation processes are commonly used for gold recovery in the grinding circuit. This study used a methodology based on modeling-simulation studies to assess various flowsheet configurations involving flash flotation, gravity separation, and the conventional sulfide mineral flotation process. The standard GRG, flash flotation, and rougher kinetic tests were used for the model development of each process. The laboratory tests and simulation studies showed that gold and sulfur recoveries in flash flotation were approximately 7% and 17% higher than that of the gravity separation process. However, the grade of the gravity concentrate was considerably higher. Therefore, one of these unit processes or their combinations can be selected depending on the ore characteristics and the aim of the recovery process. Simulation studies were performed to illustrate the gold recovery performance of various flowsheet configurations. This methodology could be used effectively for flowsheet development, particularly for greenfield projects.

Keywords: gold recovery, flash flotation, gravity separation, modelling, and simulation

1. Introduction

The mining industry widely uses cyanidation and carbon adsorption processes for gold ore. Gravity separation has been utilized in gold plants as the primary recovery mechanism or ahead of other downstream processes such as flotation and cyanidation for decades (Laplante and Gray, 2005). Coarse-free gold and gold associated with complex sulfide minerals tend to complicate the cyanidation process. Besides, coarse free gold may need more residence time for leaching and quickly report to hydrocyclone underflow and can be locked in the mill. Various separation methods are widely used to overcome these problems.

After the 1980s, the development of centrifugal gravity separators boosts the use of gravity separation for gold recovery in the grinding circuits. (Burt, 1999; Das and Sarkar 2018; Falconer, 2003) In the Golden Giant mine in Ontario, 25% of the gold is recovered by gravity ahead of the cyanidation process, and reduced the operation cost in the cyanidation stage (Banisi el al ., 1991; Hendriks and Chevalier, 1994)

Nowadays, centrifugal, continuous, or batch gravity concentrators manufactured by Falcon® and Knelson® are used to recover free gold at relatively low capital and operating costs. A centrifugal concentrator can reach 200G and capture high-density particles (Will's, 2006). Hence, a standard test procedure was developed to characterize the gravity recoverable gold (GRG) potential of gold ores and provide design data for equipment sizing (Laplante, 1995). However, the confidence in equipment

sizing and flowsheet development is still not at the required level. Because, the separation mechanism of the gravity concentrator is highly complex. For a long time, researchers have been working on separation characteristics, influencing factors, modification equipment, GRG tests, mathematical models, and computer simulations to understand separation mechanisms. (Chen, Yang, Tong, Niu, Zhang and Chen, 2020)

Flash flotation is another process used to recover free gold in grinding circuits. The purpose of flash flotation is to recover fast floating and liberated minerals in the grinding circuit and minimize the over-grinding of sulfide minerals. The first industrial attempt was made in 1982 in a copper mine in Finland. Due to the natural hydrophobic nature of gold (Yarar, Aksoy, 1989), flash flotation has been used for gold ores. Although flash flotation is defined for coarse gold, it is more suitable for liberated fine gold grains. (Newcombe, 2012) Flash flotation can be considered in three conditions. Firstly, flash flotation may be preferred if there is significant GRG content in the ore. Secondly, the amount of GRG may be distributed in fine fractions. Finally, flash flotation can be easily integrated if flotation is the primary gold recovery method. (Laplante and Dunne, 2002) A simple laboratory test could determine the suitability of ore for flash flotation. (Newcombe, 2012)

Modelling and simulation become helpful tools for process plants' flowsheet design and optimization using laboratory-scale tests and plant scale survey data. Lamberg et al. (2009) has used this methodology to demonstrate the performance of different flowsheet configurations for a copper-gold project. According to this study, the gold recovery of flash flotation was higher than the gravity in lab-scale tests, particularly in the finer fraction (-37μm). The simulation studies showed that the gold recovery of flash flotation was almost 2 times higher compared to the recovery by gravity separation due to the higher capacity and better recovery of fine gold grains in flash flotation.

Accumulation of heavy minerals is a common problem in milling circuits operated in closed-circuit with hydrocyclone classification. In a milling circuit with 300% circulating load at a steady state, it has been reported that ten times the gold in the hydrocyclone feed report to the hydrocyclone underflow. (McAlister and Sprake, 2003) There is a ratio between how much gold is reported to hydrocyclone underflow and circulating load. For example, the percentage of hydrocyclone feed gold grade to hydrocyclone downstream gold grade was determined as 83% in a mill circuit with 300% recirculating load. (Grewal, Kleek and McAlister, 2009)

In most applications, centrifugal gravity separators or a flash flotation cell are selected to recover liberated gold/sulfide mineral particles in the grinding circuit. A few examples involve using both gravity separation and flash flotation processes. Gravity and flash flotation was used in MSV, Chimo, and Eskay Ck mines (Laplante and Dunne, 2002). The flash concentrate is upgraded by gravity separation in these process plants to produce high-grade gold concentrate for direct smelting. In the Morro de Ouro Gold Mine, low-grade gold ore was floated, and the flotation concentrate was fed to the gravity concentrator for upgrading and then subjected to cyanidation for gold extraction(Suttill, 1990). It is cleaner that selection of one of these processes or a combination is critical, particularly for greenfield projects.

Determining the GRG recovery in grinding circuits, flowsheet design, and selection/sizing of the required equipment are still significant challenges for the gold-containing sulfide ores. This study used a methodology based on modeling-simulation studies to assess various flowsheet configurations involving flash flotation, gravity separation, and the conventional sulfide mineral flotation process.

2.   Materials and method

The ore was taken from a project located 50km northwest of Eskişehir in Turkey's inner west Anatolian region. Samples were taken from 36 drill holes and 111 drill intervals to prepare a representative sample of the ore deposit. The drill core samples were crushed to -24mm with a jaw crusher, homogenized, and split into sub-samples for ore characterization and testwork using a rotary splitter.

2.1. Ore characteristics

Microscopic gold in primary ores occurs as pristine grains of varied size and shape in fractures and microfractures or as attachments to and inclusions in other minerals. Microscopic gold, also known as visible gold, comprises gold alloys, gold tellurides, gold sulfides, gold selenides, gold sulfoselenides,

etc. Qemscan analysis was used for microscopic gold. Gold is invisible under an optical microscope, and Sem (Scanning Electron Microscope) is referred to as submicroscopic gold or invisible gold. (Zhou, Jao, Martin, 2004) For submicroscopic gold determination, d-sims analysis was used in this study. Qemscan and D-sims methods were used to determine the microscopic and submicroscopic gold. The most abundant Au minerals are native gold and calaverite ($AuTe_2$). According to the microscopic study, 524 gold grains were identified. The diameter of the gold grains ranges from 0.6 µm to 153.1 µm and averages 7.7 µm. The average sizes of the liberated, exposed and locked gold minerals are 19.8 µm, 11.7 µm, and 3.2µm. The exposed and locked gold grains are mainly associated with pyrite, melonite, gersdorffite, coloradoite, and trace with tetrahedrite, sphalerite, Fe-Ti oxides, silicates, and carbonates. The distribution of the gold is presented in Table 1. Liberated and locked gold minerals in the SEM study are shown in Fig. 1.

Table 1. Distribution of gold in master composite

Sample	Locked Gold	Exposed Gold	Liberated Gold	Sub-Microscopic Gold	Total
Master Composite	12.3%	12.9%	41.0%	33.7%	100%

When sub-microscopic gold, which contains 33.7% of the gold in the ore, was examined, it was observed that most of the gold was associated with pyrite and a small amount of arsenopyrite mineral. It shows that the major sub-microscopic Au carrier mineral is pyrite. Sub-microscopic gold accounts for %34 of total Au head assay, of which is 27% is concentrated in pyrite and 7% in arsenopyrite. Microscopic gold accounts for 66%, of which 41% is liberated, 13% is exposed, and 12%is locked. The head assays of the ore used in the study are presented in Table 2.

2.2. Test methodology

The basic flowsheet of the test program is given in Fig. 2. The representative sub-samples were prepared by crushing and splitting the master composite ore sample. The sub-samples were used for chemical-mineralogical analysis, E-GRG tests, and flash flotation tests using a Retsch Sample Divider PT-100. One

Spectrum	In stats.	O	S	Fe	Ag	Au	Total	Mineral
1	Yes		55.8	44.2			100.0	Pyrite
2	Yes	4.2		1.6	14.3	79.8	100.0	Gold
3	Yes				21.6	78.4	100.0	Gold
4	Yes			2.0	16.5	81.5	100.0	Gold

Spectrum	In stats.	S	Fe	Au	Total	Mineral
1	Yes	55.9	44.1		100.0	Pyrite
2	Yes		3.1	96.9	100.0	Gold
3	Yes		4.5	95.5	100.0	Gold
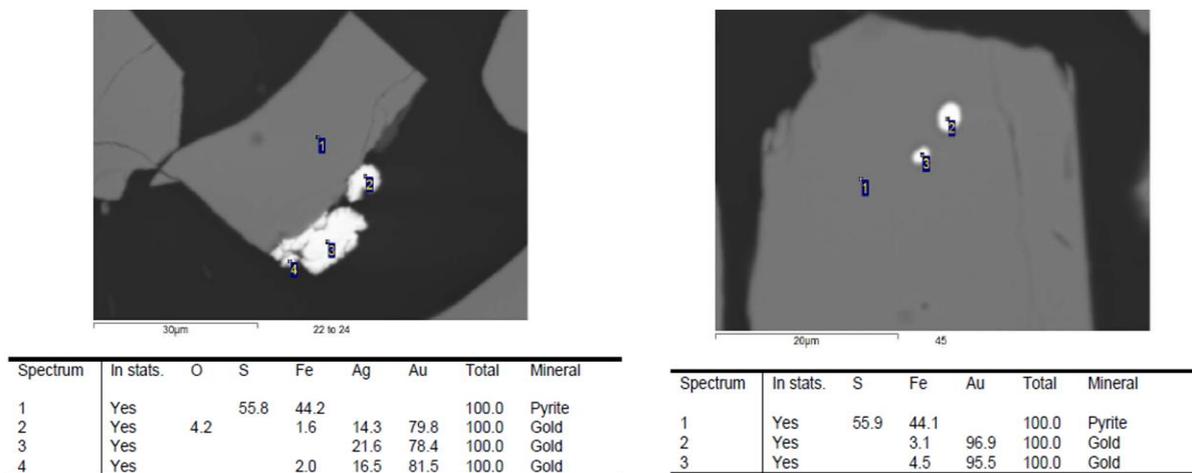
Fig. 1. SEM analyses of the gold grains

Table 2. Head assays

Analysis	Au (g/t)	Ag (g/t)	Cu (g/t)	As (g/t)	Fe g/t	%S
Method	*FA*	*AAS*	*ICP*	*ICP*	*AAS*	*Leco*
Head Assay 1	14.85	2.25	147	1265	66.539	3.21
Head Assay 2	15.33	2.23	297	1215	64.409	3.44
Head Assay 3	16.32	2.22	137	1273	68.676	2.86
Average Head	**15.50**	**2.23**	**194**	**1251**	**66.541**	**3.17**

of the sub-samples was crushed to p100=850 microns for the E-GRG test and another one to p100=600 microns for flash flotation. Knelson MD-3 model gravity concentrator was used for the E-GRG tests, and a Denver flotation machine with a 2-liter cell was used for both flash and rougher flotation tests. The results obtained were used in modeling and simulation studies.
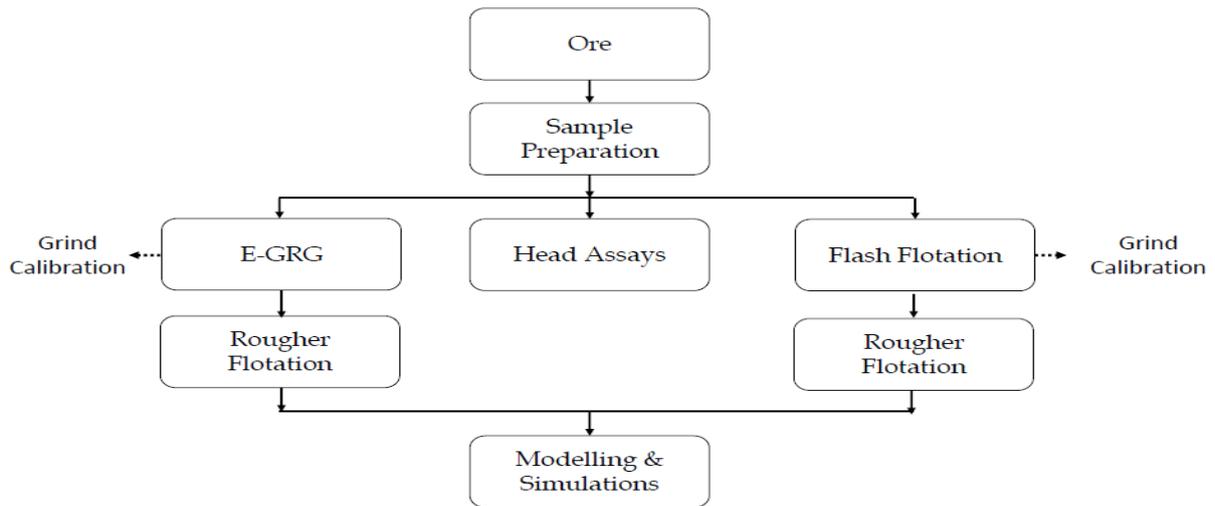
Fig. 2. Basic flowsheet of the test program

2.2.1. E-GRG and rougher flotation tests

The E-GRG test is used to predict the amount of gold recovered by gravity in the ore. Laplante developed the test procedure in 1995. The standard method for a GRG test using a centrifugal concentrator is presented in Fig. 3.

Standard 60G centrifugal force and 35% solid were applied for the gravity process. A 20 kg ore sample was crushed to p100:850 µm. An additional 10kg was used for grind calibration. The ore was ground at various times in a laboratory-scale rod mill. The particle size distribution of the ground material was determined as p80=543 µm for the first stage, p80=313 µm for the Second Stage, and p80=72 µm for the Third Stage. Gold and sulfur analysis of each product was done on a size-by-size basis.

The rougher kinetic flotation tests were performed on the tailing material of the E-GRG test. The flotation tests were conducted at 35% w/w solids content using 2 kg representative sub-samples crushed to -2mm. The details of the flotation conditions are given in Table 3.

Analytical purity CuSO4 (98%) and sodium silicate (99%) were used from Merck. The collecter, PAX (potassium amyl xanthate), was from China (Y & X) with 90% purity. Oreprep F549, which includes both alcohol and glycol-based frother, was used as delivered from the manufacturer (Solvay).
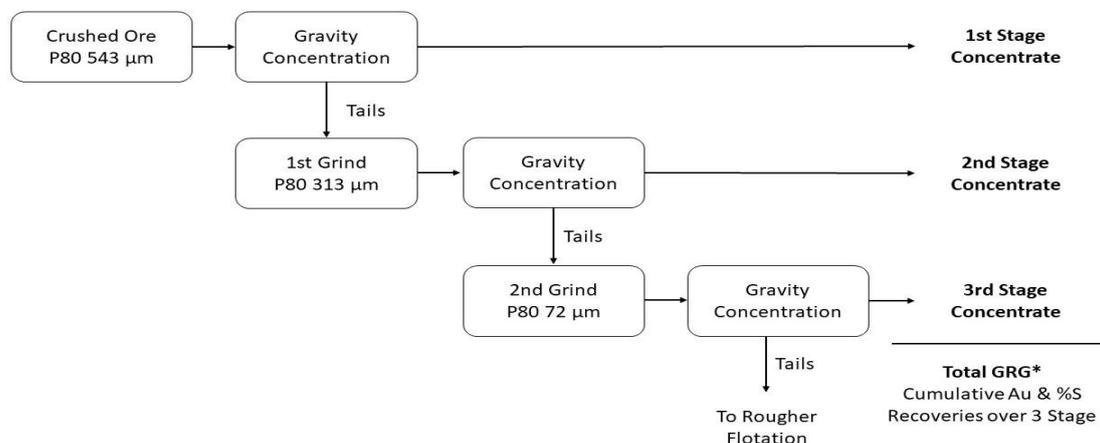
Fig. 3. E-GRG procedure (*Laplante, 1995)

Table 3. Rougher flotation conditions

Stage	Reagents added (g/t)				Time (minutes)		
	Na_2SiO_3	CuSO4	PAX	F549	Cond.	Ind.	Cum.
Condition	500				5		
Condition		100			2		
Rougher 1			30	16.6	1	3	3
Rougher 2			15	12.6	1	4	7
Rougher 3			15	12.6	1	5	12
Rougher 4			10	12.6	1	8	20
Rougher 5			10	12.6		8	28
Rougher 6			10	12.6		8	36
Total	500	100	90	79.6	15	36	42

2.2.2. Flash flotation and rougher tests

Flash flotation tests were conducted to determine gold recovery at coarse particle size. The test flowsheet consists of Flash flotation and rougher flotation applied on the Flash tailings, as shown in Fig. 3. The testing flowsheets were similar in both gravity-rougher flotation and Flash-Rougher flotation options. The testing flowsheet is presented in Fig. 4.

The pulp was conditioned with $CuSO_4$ as an activator. A mixture of PAX and Aero 5100 was used for the flotation of gold and gold-containing sulfide minerals. Flash flotation test conditions are given in Table 5. Aero 5100 from Solvay was used as a promoter in the flash flotation tests to improve gold recovery. The rougher flotation was conducted using the same conditions as applied on the E-GRG tailings (Table 4).
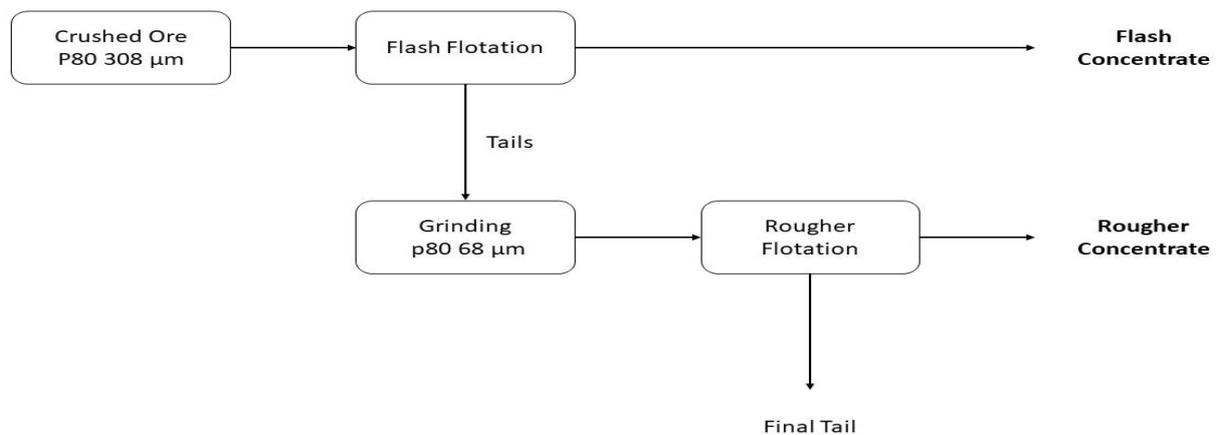
Fig. 4. Flash & rougher flotation test program

Table 4. Flash flotation conditions

Product	Reagents added, g/t					Time(minutes)		
								Froth
	Na_2SiO_3	$CuSO_4$	PAX	AERO 5100	F549	Cond.	Ind.	Cum.
Condition	-	50	-	-	-	5		
Flash Conc 1	-	-	10	10	20	10 sec.	0.5	0.5
Flash Conc 2	-	-	-	-	-		0.5	1
Flash Conc 3	-	-	-	-	-		0.5	1.5
Flash Conc 4	-	-	-	-	-		0.5	2
Total	0	50	10	10	20	5.17	2	

2.2.3.   Process modelling and simulation

Outotec® Chemistry HSC 10 program was used for the process simulation studies. Some assumptions have been made for this study based on literature studies. (Grewal, Kleek ve McAlister 2009) It is believed that more than%80 of the gold and sulfur minerals (chalcopyrite) report the hydrocyclone underflow (Lamberg, Bourke, Kujawa, 2009). Similar research conducted on PGMs (platinum group minerals) showed that %80 of these minerals were reported to the hydrocyclone underflow. (Xiao, Laplante, Tan and Finch 2021) Therefore, in the simulation studies, it was assumed that %80 of the gold and sulfide minerals (pyrite) were reported to hydrocyclone underflow. A typical grinding circuit consisting of a primary mill and a secondary mill with hydrocyclone classification was considered for the simulation studies. The mass balance of an operating gold plant in Turkey was taken as a benchmark. The circulating load was assumed to be %300, and the size by size mineral classification model was used for the hydrocyclone.

A size-reduction model was used for the primary and secondary mills to transfer mass from one size to another. The mineral assay and water content of the entire flow were conserved with this model. Gold, sulfur, and quartz (gang minerals) recoveries defined in the size fractions were used for gravity separation, flash flotation, and rougher flotation models.

3.   Results and discussion

3.1. E-GRG and rougher flotation test results

The E-GRG (Extended GRG) test was conducted at three stages as described in section 2.2.1. The results are given in Fig. 5 for gold and Fig. 6 for the sulfide minerals. In the first stage, mass pull, the gold, and sulfur recoveries were determined as 0.73%, 9.67%, and %2.91, respectively. Gold and sulfur grade of the 1st stage concentrate were 205.7 g/t and 12.59%, respectively. With finer grinding in the Second
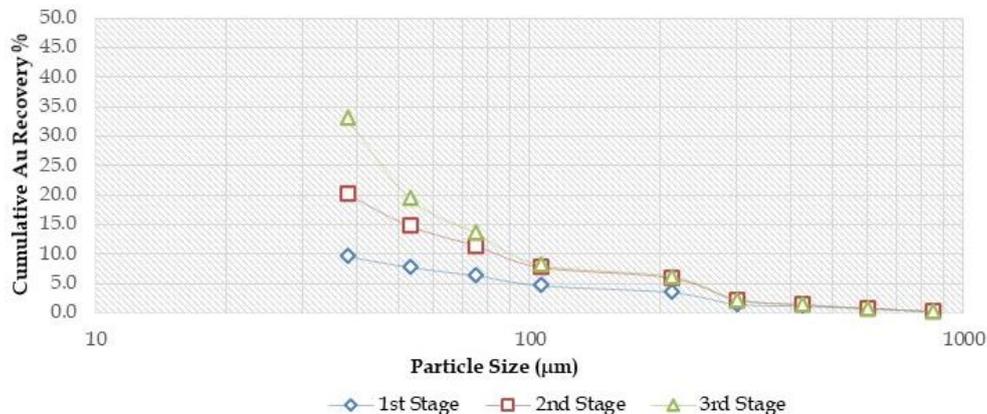
Fig. 5. E-GRG test results – Au recoveries as a function of particle size
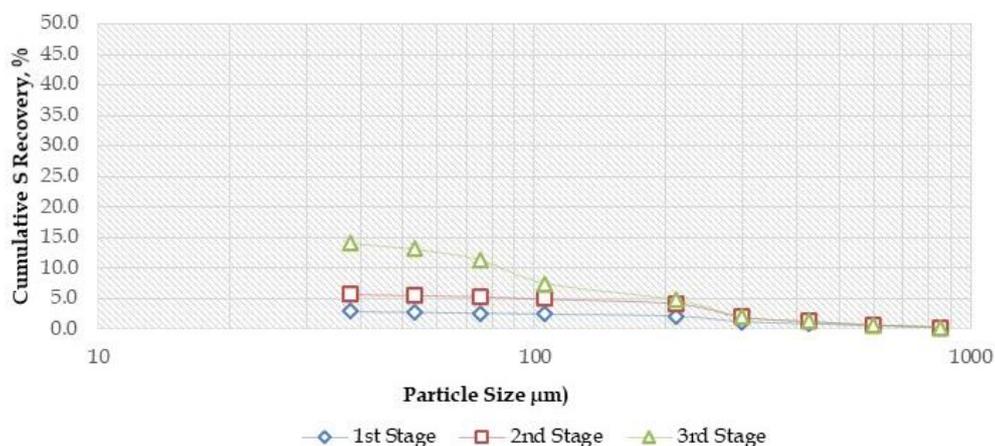
Fig. 6. E-GRG test results - S recoveries as a function of particle size

Stage, the mass pull decreased to 0.56% while the gold recovery increased. A concentrate was produced assaying 293 g/t Au, 16.11%S at recoveries of 10.53% and 2.85%, respectively. The cumulative gold recovery was calculated as approximately 20%. The highest gold and sulfur recoveries were obtained at the finest size fraction in the 3rd stage, and the gold recovery increased to 33.13%.

The results showed that gold and sulfur recoveries were very low at >300 μm particle size. The recoveries increased with finer particle size, particularly in the 3rd stage. There was a direct correlation between gold and sulfur recoveries. The gold recovery was higher, indicating preferential recovery of liberated gold particles and pyrite particles containing relatively coarse grain gold particles. In other words, liberation has a more positive effect on gold grains in all stages. But the impact of the liberation in the third stage was also seen to some extent for sulfur grains. According to the results of the E-GRG test, it can be said that a significant amount of GRG is dispersed in fine fractions.

The remaining gold and sulfide minerals in the gravity tailings were recovered by flotation. Fig. 7 shows the cumulative gold recovery as a function of flotation time for different size fractions. Flotation rate and recovery increased with finer particle sizes. The flotation behavior of the gold particles was similar at -53+38 μm and -38 μm particle size fractions, indicating that the required liberation could be achieved at -53 μm size fraction. The highest gold recovery was 80.47% in the -38 micron fractions. According to Fig. 7 and Fig. 8, flotation of gold grains may require a longer time than sulfur flotation.

Fig. 8 shows the cumulative sulfur recoveries as a function of flotation time. The flotation rate and sulfur recovery were higher than gold (Fig. 7). The highest flotation rate and recovery were obtained at -53+38 μm size fraction. The gold recovery in this size fraction was 96.0% but decreased to 91.53% in the -38 μm fraction. The flotation rate was low at -38, μm presumably due to the difficulties in the flotation of fine particle sizes in sulfide flotation. The rougher flotation mass pull was determined as 15.50%.

There was no direct correlation between gold and sulfur recoveries, particularly at coarse particle sizes. The gold recovery was lower per unit sulfur recovery, indicating that a portion of the gold was associated with non-sulfide gangue minerals.
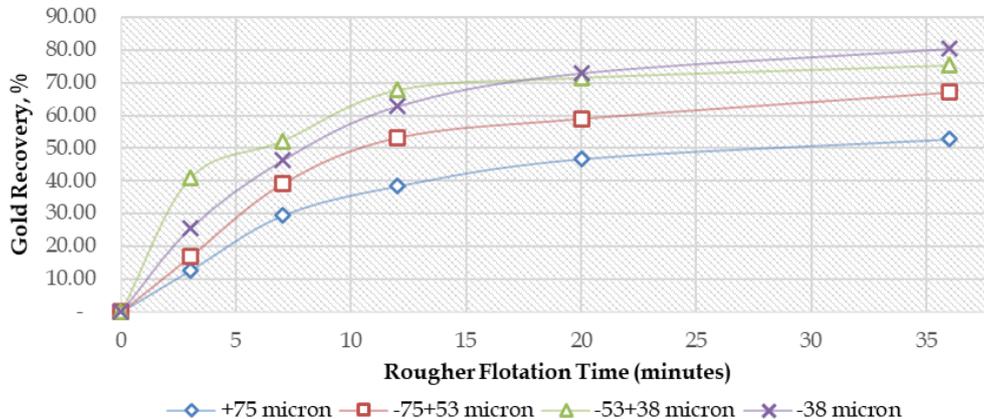
Fig. 7. Cumulative gold recoveries in different particle size fractions (E-GRG tailing rougher)
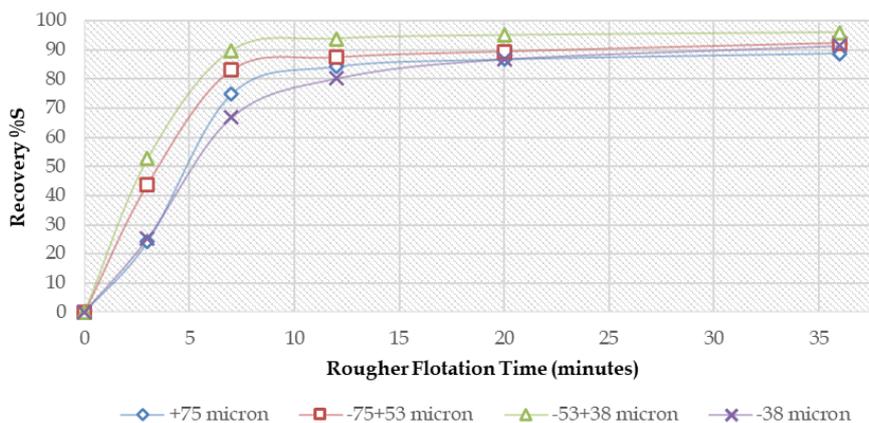
Fig. 8. Cumulative sulfur recoveries in different particle size fractions (E-GRG tailing rougher)

3.2. Flash and rougher flotation tests results

The Flash flotation aims to recover the liberated gold and sulfide minerals at coarse grind size and minimize the over-grinding of the gold/gold-containing particles in the grinding circuit. Gold and sulfur recoveries to the Flash flotation concentrate were illustrated as a function of flotation time for different size fractions in Fig. 9 and Fig. 10, respectively. There was no direct relationship between particle size and gold recovery. The highest flotation rate and recovery were obtained at -75+53 μm size fraction. The recoveries at finer and coarser fractions were 40% and 50%. The lowest gold rate and recovery were observed at +212 μm size fraction due to insufficient liberation of the gold and sulfide mineral particles.

The highest sulfur flotation rate and recovery were observed with particles in -212+53 μm size fraction. The flotation performance decreased at finer particle sizes. This was due to the presence of liberated sulfide mineral (mainly pyrite) particles in this size range. Besides, the Flash flotation conditions (conducted at high percent solids in a very short time) were favorable for liberated coarse particles.

According to the studies on flash flotation, +212 micron GRG particles showed slow flotation kinetics in the tests. In general, it is similar to the trend in the flotation of sulfide grains larger than +150 micron. (MacKinnon, 2002 and Newcombe, 2012) Similar results were obtained in this study as well.

Comparison of the separation performances of the GRG and Flash flotation laboratory tests showed that the Flash flotation achieved higher recoveries, 7% for gold and 17% for sulfur. A similar observation was reported by Laplante and Dunne (2002), where flash flotation performs between 3% and 12% higher gold recovery in ores with gold grains associated with sulfur compared to centrifugal force concentrators. However, the gold grade of the GRG concentrate (254.49g/t) was much higher than that produced by Flash flotation (149.88 g/t). Because the GRG was distributed in fine fractions, higher gold
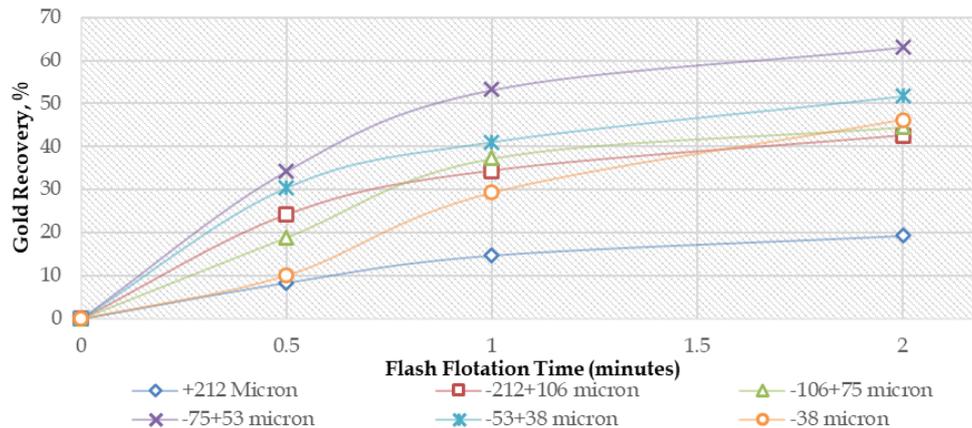
Fig. 9. Cumulative gold recoveries in flash flotation test as a function of flotation time
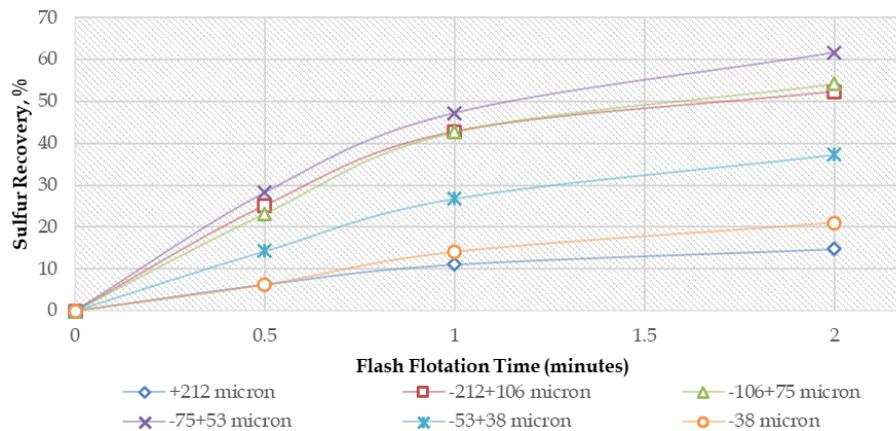
Fig. 10. Cumulative sulfur recoveries in flash flotation test as a function of flotation time

recovery was achieved in flash flotation. The sulfur minerals in the ore also responded well to flotation. Although the flash flotation test was carried out in short a time, the sulfur recovery was 31.06%

The Flash flotation tailing was ground to p80=75 µm, and a rougher kinetic flotation test was performed. The cumulative gold and sulfur recoveries were illustrated as s function of flotation time in Fig. 11 and Fig. 12, respectively. The cumulative mass pull was 23.12%. The highest flotation rate and recovery for gold were obtained at -53 µm size fraction. The sulfur recovery was over 95% for a -75 µm size fraction. While flotation time is sufficient for sulfur flotation, additional time may be needed for gold flotation. The gold and sulfur recoveries were approximately 10% higher than obtained with the rougher flotation test applied on the GRG tailings.
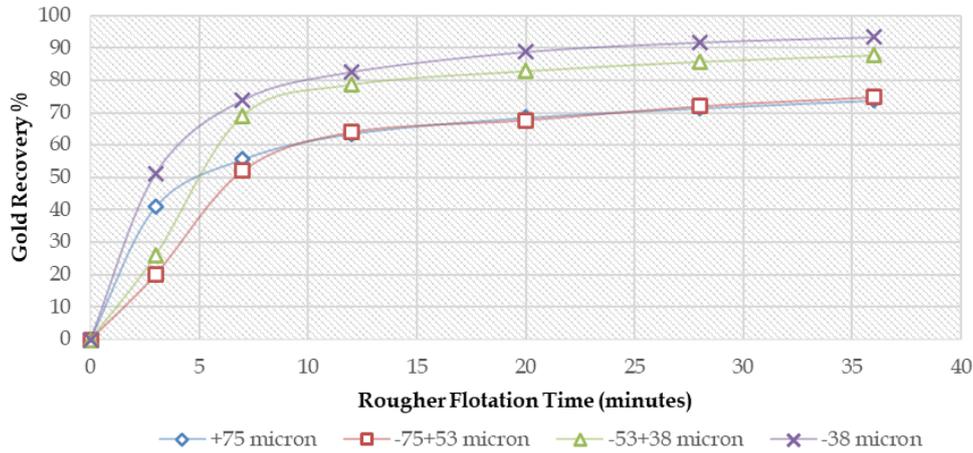
Fig. 11. Cumulative gold recoveries in different size fractions (flash tail-rougher flotation)
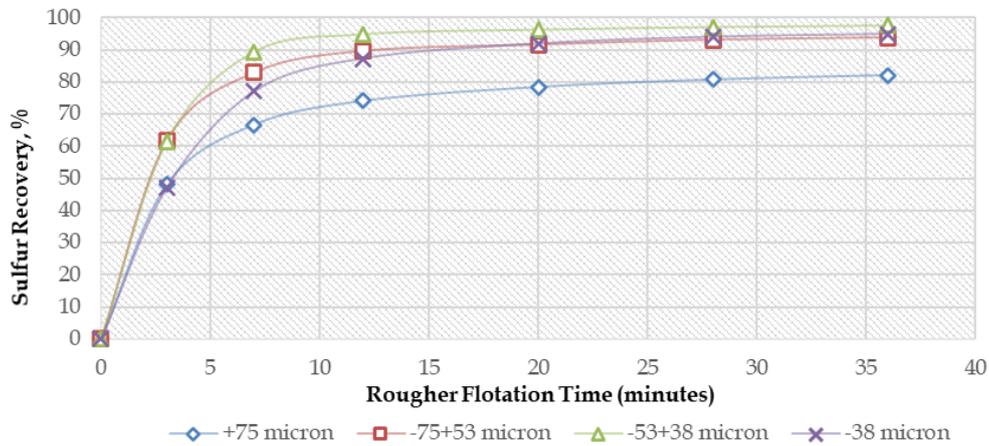
Fig. 12. Cumulative Sulfur recoveries in different size fractions (flash tail-rougher flotation)

3.3. Mass balance

Mass balance results of the combined gravity separation-rougher flotation flowsheet are given in Table 5. Head gold and sulfur grade of E-GRG and rougher flotation tests were determined as 15.5 g/t Au and 3.15% S, respectively. According to the mass balance results, 33.1% of gold was recovered by the gravity separation and 51.85% by rougher flotation. The total gold recovery was determined as 84.95%. The majority of sulfide minerals were recovered in the rougher flotation stage. The total sulfur recovery was defined as 93.14%.

Mass balance results of the combined flash flotation-rougher flotation flowsheet are given in Table 6. The gold recovery was 39.98% in the flash flotation and 54.26% in the rougher flotation stages. The sulfur recoveries were 31.06% in the flash flotation and 64.38% in the rougher flotation. The total gold and sulfur recoveries were determined as 94.24% and 96.26%, respectively. The higher gold and sulfur recoveries in the flash flotation-rougher flotation option were attributed to the approximately 10% higher mass pull.

Table 5. E-GRG and rougher flotation mass balanced results

	Weight%	Au ppm	%Au Dist	%S	%S %Dist
E-GRG Feed	100	15.5	100	3.15	100
E-GRG Concentrate	2.02	253.99	33.1	22.92	14.7
E-GRG Tail	97.98	10.58	66.9	2.74	85.3
Rougher Concentrate	15.19	52.92	51.85	16.27	78.44
Rougher Tail	82.79	2.82	15.05	0.26	6.86
Final Concentrate	**17.21**	**76.52**	**84.95**	**17.05**	**93.14**

Table 6. Flash and rougher flotation mass balanced results

	Weight%	Au ppm	%Au Dist	%S	%S %Dist
Flash Flotation Feed	100	15.13	100	3.93	100
Flash Flotation Concentrate	4.03	150.1	39.98	30.37	31.06
Flash Flotation Tail	95.97	9.46	60.02	2.83	68.94
Rougher Concentrate	22.19	37	54.26	11.44	64.42
Rougher Tail	73.78	1.18	5.76	0.24	4.52
Final Concentrate	**26.22**	**54.39**	**94.24**	**14.35**	**95.48**

3.4. Simulation scenarios

Recovery of liberated gold/gold-containing sulfide mineral particles in grinding circuits improves the overall gold recovery. Centrifugal gravity separators or flash flotation units are generally used for this purpose. Selection of the optimum unit separation is critical and requires reliable assessment of the laboratory-scale test work. Modeling and simulation studies usually are helpful tools for testing various flowsheet options. Reliable simulations require size-by-mineral data of each separation stage, gravity separation, flash flotation, rougher flotation, and grinding and classification stages.

Mass balance and model construction were performed on size by the mineral basis for each unit in the flowsheet. Assessment of various flowsheet configurations was done by simulation when the required equipment models were developed confidently. Four of these flowsheet configurations were discussed in this paper. The summary of the simulations is represented in Table 7.

In the first scenario, 50 % of the hydrocyclone underflow was treated in a gravity separation stage. The concentrate of the gravity separator was combined with the rougher flotation concentrate, and the tailing was transferred to the secondary mill (Fig. 13). A gravity concentrate was produced, assaying 949 g/t Au at 23.58% gold recovery and 0.36% mass pull. The overall gold and sulfur recoveries were 84.92% and 91.82%, respectively.

In the second scenario, the gravity separation stage was replaced by flash flotation (Fig. 14). The mass pull increased to 3.27 % in the flash concentrate. As a result, the gold and sulfur recoveries increased to 52.02% and 36.19%, respectively. The higher mass pull resulted in a higher overall gold recovery than the gravity separation option (Fig. 13).

The ball mill discharge stream can also be considered as the feed to the gravity separation and flash flotation stages. This option can provide easier pulp density control. In Scenario 3 and Scenario 4, the ball mill discharge stream was fed to the gravity separation and flash flotation stages.

Fig. 15 shows the circuit performance when the gravity separation was used for gold recovery. The gold recovery in the gravity separation stage increased to 45.33% at 0.68% mass pull. A similar improvement was observed with the flash flotation (Fig. 16). The stage recovery of gold in the flash flotation increased to 81.4%. Performance of the rougher flotation stage increased because a significant portion of the gold was recovered in the grinding circuit. Therefore, the overall gold recovery in the gravity separation and flash flotation options increased to 89.14% and 98.68%, respectively. Higher tonnage was treated in the last two scenarios, which brought about a higher mass pull to the concentrates. Besides, the separation performance of both the gravity separation and the flash flotation stages increased with the finer particle size distribution of the ball mill discharge (McGrath, 2014; Lamberg et al., 2009).

4. Conclusions

Laboratory scale standard GRG, flash flotation, and rougher kinetic flotation tests were performed on Turkey's gold-containing sulfide ore sample. Modelling studies were performed on size by mineral basis using the tests results of each unit process. In the final stage, various flowsheet configurations,

Table 7. Summary of the gravity and flash flotation scenarios – overall recoveries

#	Process	Feed Stream	Conc Tph	Au ppm	S%	Au Rec%	S Rec%
1	Gravity	Hydrocyclone U/F 50%	11.88	104.77	23.55	84.92	91.82
2	Flash Flotation	Hydrocyclone U/F 50%	19.23	73.67	15.31	96.65	96.61
3	Gravity	Mill Discharge 100%	12.05	108.37	23.27	89.14	92.05
4	Flash Flotaiton	Mill Discharge 100%	21.30	67.88	14.01	98.64	97.91
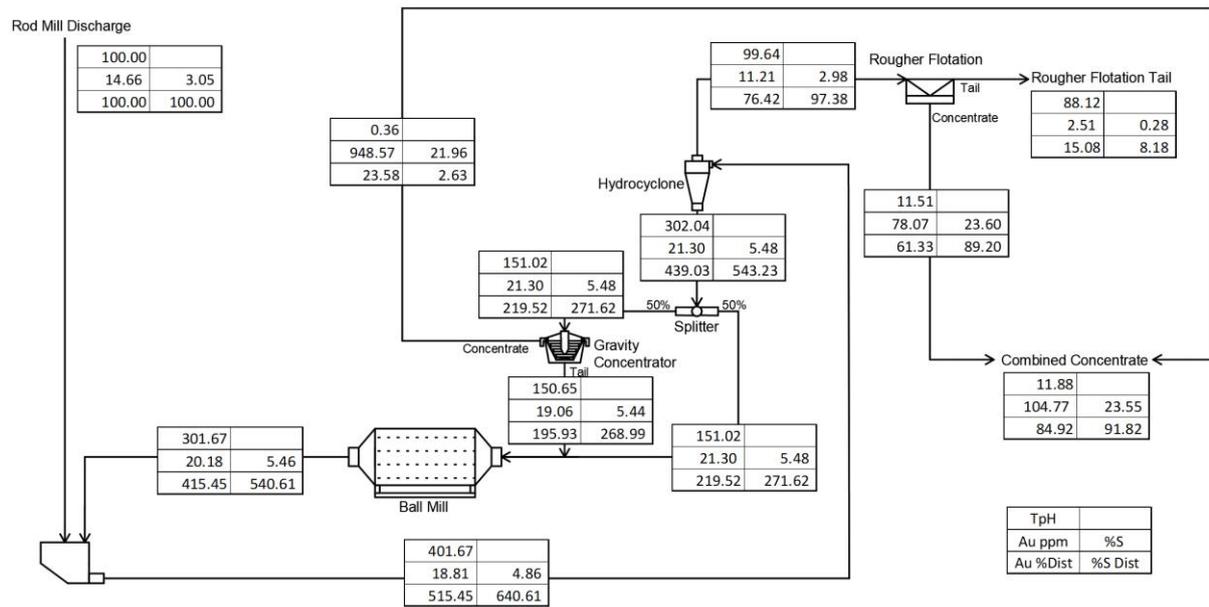
Fig. 13. Scenario #1 – gravity concentration on the hydrocyclone underflow
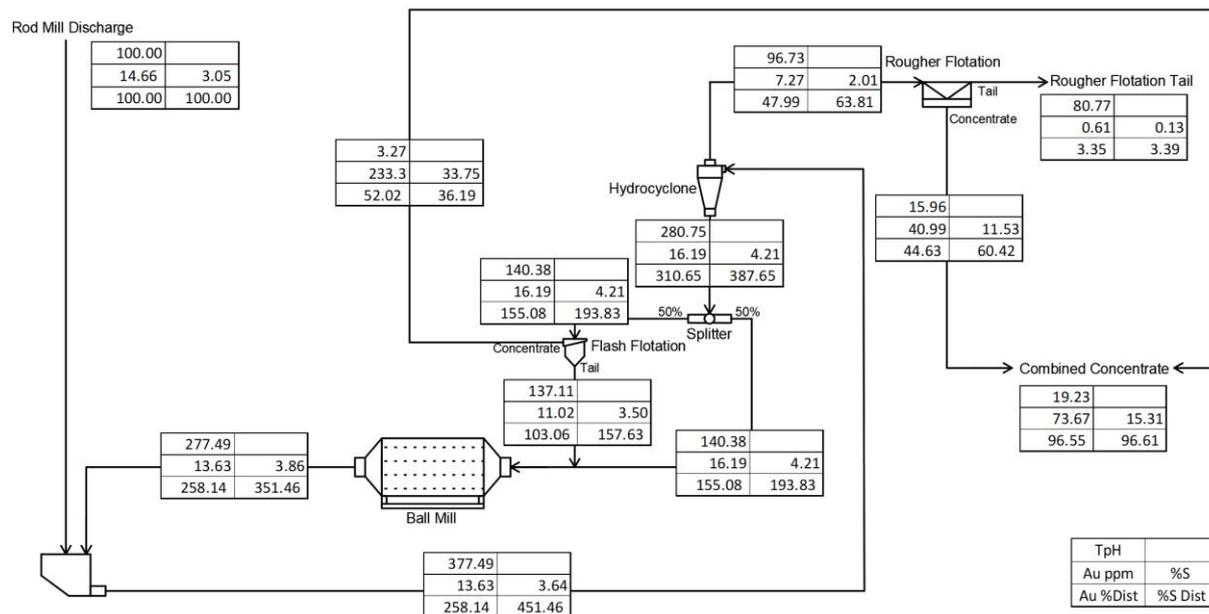
Fig. 14. Scenario #2 – flash flotation on the hydrocyclone underflow

Fig. 15 flowsheet data:

Rod Mill Discharge
100.00	
14.66	3.05
100.00	100.00

0.68	
977.07	24.27
45.33	5.42

Gravity Concentrator — Concentrate / Tail

299.62	
14.51	5.34
296.57	524.90

300.30	
16.69	2.90
341.89	530.31

Ball Mill
399.62	
14.54	4.76
396.57	624.90

Hydrocyclone
300.30	
16.69	2.90
341.89	530.31

Rougher Flotation
99.32	
8.07	2.90
54.68	94.59

Tail → Rougher Flotation Tail
87.95	
1.81	0.28
10.87	7.95

Concentrate
11.37	
56.45	23.21
43.81	86.64

Combined Concentrate
12.05	
108.37	23.27
89.14	92.05

Legend:
TpH	
Au ppm	%S
Au %Dist	%S Dist

Fig. 15. Gravity concentrator on the ball mill discharge

Fig. 16 flowsheet data:

Rod Mill Discharge
100.00	
14.66	3.05
100.00	100.00

6.62	
180.12	28.20
81.40	61.30

Flash Flotation — Concentrate / Tail

258.78	
5.47	2.48
96.54	210.83

265.40	
9.83	3.12
177.94	272.12

Ball Mill
358.78	
8.03	2.64
196.54	310.83

Hydrocyclone
265.40	
9.83	3.12
177.94	272.12

Rougher Flotation
93.38	
2.92	1.26
18.60	38.70

Tail → Rougher Flotation Tail
78.70	
0.25	0.08
1.36	2.10

Concentrate
14.67	
17.22	7.60
17.24	36.61

Combined Concentrate
21.30	
67.88	14.01
98.64	97.91

Legend:
TpH	
Au ppm	%S
Au %Dist	%S Dist

Fig. 16. Scenario #4 flash flotation on the ball mill discharge

including gravity separation, flash flotation, and rougher flotation stages, were tested by simulation studies.

The results show that the highest gold recoveries were obtained with the flowsheets having flash flotation in the grinding circuit. The gold recovery in gravity increased with decreasing particle size but decreased in the -38 micron fraction. Flash flotation has a higher gold recovery than gravity in the same fraction.

According to the simulation results, the gold recovery in flash flotation was almost two times higher than that in the gravity separation stage. The gold recovery of the gravity separation was estimated as 23.58% when the hydrocyclone underflow was the feed to the gravity separation stage and 45.33% with ball mill discharge. The gold recovery was calculated as 52.02% and 81.4%, respectively, when flash flotation was used in place of the gravity separation in the same flowsheets. The sulfur recovery in flash flotation was about ten times higher than gravity separation.

However, the gold grade of the gravity concentrate was considerably higher than that of the flash flotation process, presumably due to lower mass pull and preferential separation of the gold particles and gold-containing pyrite particles.

Further studies (plant scale sampling and performance assessment) should be conducted to validate the simulation studies and improve the prediction power of the models developed for each unit process in this study.

Acknowledgments

References

AKSOY, B.S., YARAR, B., 1989, *Natural hydrophobicity of native gold flakes and their flotation under different conditions*, In Processing of Complex Ores, eds. Dobby, G.S., Rao., S.R. Pergamon Press, Halifax, pp. 19-27

BANISI, S., LAPLANTE A.R., MARIOS, J., 1991, *The behavior of gold in Hemlo Mines Ltd. Grinding circuit,* Can. Min. Metall. Bull. 84 (955), Page 72-78

BURT, R., 1999, *The Role of Gravity Concentration in Modern Processing Plants*, Miner. Eng. 12(11), Page 1291-1300

DAS, A., SARKAR B., 2018, *Advanced Gravity Concentration of Fine Particles, A Review*, Mineral Processing and Extractive Metallurgy Review, 39 (6) Page 359-394

FALCONER, A., 2003, *Gravity Separation: old technique/new method*s, Physical Separation in Science and Engineering, 12 (1), Page 31-48

GHAFFARI A., and FARZANEGAN A., 2017, *An investigation on laboratory Knelson Concentrator separation performance: Part 2: Two-component feed separation modelling*, Minerals Engineering

GREWAL I., KLEEK M. ve McALISTER S., 2009, *Gravity Recovery of Gold From within Grinding Circuits, Recent Advances in Mineral Processing Plant Design*, SME, Page 499-506

HENDRIKS, D., CHEVALIER, G., 1994. *Recovery of Gold Using Gravity Concentration the Hemlo Experience, Precious Metals Conference*, Pergamon Press, Page 209−221

LAMBERG P., BOURKE P., KUJAWA C., 2009, *Impact of Flash Flotation on Griding and Main Flotation Circuits – Design by Simulation and Case Studies*, Recent Advances in Mineral Processing Plant Design, SME

LAPLANTE, A.R., GRAY, S., 2005. *Advances in gravity gold technology, In Developments in mineral processing: Advances in gold ore processing*, ed. Adams, M.D. Elsiever B.V., Amsterdam, The Netherlands, Page 280-307.

LAPLANTE A.R., ANDREA R., 1994, *Standardized Test to Determine Gravity Recoverable Gold, Department of Mining and Metallurgical Engineering*, McGill University,

LAPLANTE A., DUNNE, R., 2002, *The Gravity Recoverable gold test and flash flotation, In Proceedings of 34th Annual Canadian Mineral Processors Operators Conference*. McGill University & Newcrest Mining Limited, Ottawa, P. Paper 7.

McALISTER C. and SPRAKE S., 2003, *Enhanced Gravity Concentration for Precious Metal Recovery*, https://seprosystems.com/wp-content/uploads/2016/09/sb-12.pdf

McGRATH, 2014, *A Study of the Behaviour of Free Gold In Flash Flotation and Gravity Recovery*, page 64.

NEWCOMBE, B., BRADSHAW, D., WIGHTMAN, 2012, E., *Development of a laboratory method to predict plant flash flotation performance*. Minerals Engineering, Page 228-238.

SGS Lakefield, 2012, Project Report 13714-001 *Au Deportment Study*, November 21.

SGS Lakefield, 2014, Project Report 13714-002 *Progress Report#1*, June 24.

SUTTILL, K., 1990. *Morro De Ouro-Brazil's Hill of Gold*. Eng Min J. 191 (6) Page 25-28.

Wills' Mineral Processing Technology, 2006, Page 267-268.

Xiao Z., Laplante A.R., Tan Y. T., and Finch J. A., 2021, *Characterizing the behavior of platinum group minerals in a griding circuit*, Min. Eng., 166(1), 106863.

ZHOU J., JAGO B., and MARTIN C., 2004, *Proceedings of the 36th annual Meeting of the Canadian Mineral Processors* (Ottawa, Canada: CMP.), Page. 199- 226.