

# Enrichment of cobaltite bearing magnetite-rich ore with the flotation method: The effect of anionic sulfhydryl collectors at different pHs

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## ABSTRACT

The concentration of sulfide minerals can be achieved through various methods, and one such method is flotation. In the case of cobaltite, a mineral composed of cobalt sulfoarsenide, its ability to float is attributed to the presence of sulfur within its lattice structure. Cobalt, a versatile element with historical applications in dyeing, has gained strategic importance in recent times due to its utilization in alloys and lithium batteries. However, the scarcity of cobaltite in the Earth's crust has limited the extent of research conducted on its flotation. Nonetheless, previous studies have indicated that under specific conditions, cobaltite can indeed be floated. The objective of this particular study was to separate cobaltite minerals from magnetite and other associated minerals through the process of flotation. Initially, preliminary tests were conducted using Minitab software and Taguchi analysis. These tests revealed that the highest recovery rate, approximately 71%, was achieved at acidic pH levels (pH=4) using PAX as the collector. Subsequent additional tests were carried out, resulting in a recovery rate of 75% and a grade of 22.3%. One of the significant findings of this study was the influence of pH on the recovery of cobaltite when sulfhydryl collectors were employed. It was observed that cobaltite exhibited a considerably low recovery rate when the pH approached neutral or alkaline values.

**Keywords:** *Enrichment, Cobalt, Cobaltite, Flotation, Sulfhydryl collectors.*

## 1. Introduction

Cobalt serves various purposes and holds a crucial role in the industry due to its properties, such as a high melting point, ferromagnetism, and multiple oxidation states. These attributes perfectly account for the extensive utilization of cobalt (Barceloux & Barceloux, 1999; Fisher, 2011; Haldar, 2016; Hawkins, 2001). In ancient times, Egyptian craftsmen employed cobalt metal for coloring their creations (Haldar, 2016). Industries experiencing rapid growth, such as electronics and automotive, heavily rely on cobalt as a vital component (Harper et al., 2012; Mohapatra et al., 2020). Cobalt finds its primary usage in batteries and is a prevalent metal in superalloys and magnets (Roberts & Gunn, 2014). Due to the swift advancement of mobile devices and new energy vehicles, the demand for lithium-ion batteries (LIBs) has witnessed a significant surge (Qiu et al., 2021). Moreover, cobalt (Co) stands as a pivotal ingredient in the production of various catalysts, aircraft engine blades, integrated circuits, semiconductors, and pigments (Abdollahi et al., 2021). Cobalt stands as a crucial micronutrient discovered in ocean. Eukaryotic phytoplankton replace zinc (Zn) in the metalloenzyme carbonic anhydrase (Bundy et al., 2020). Merely 3% of the total cobalt utilization has been directed towards the production of permanent magnets, despite batteries constituting 54% of the overall cobalt consumption (Mohapatra et al., 2020). Catalytic processes consume 10% of the entire cobalt supply, with one of the primary applications being the enhancement of polymerization and oxidation rates in the production of plastic resins. (Roberts & Gunn, 2014).

Cobalt is a relatively scarce element, constituting approximately 0.001% of the Earth's crust (Lison, 2015). During 2018, the worldwide cobalt mining production totaled around 168,000 tons (Horn et al.,

2021). Presently, the Democratic Republic of the Congo (DRC) contributes over 65% of the global cobalt mining output, extracting over 10 times the amount produced by China, which stands as the world's second-largest producer (Horn et al., 2021; Roberts & Gunn, 2014). Cobalt is present in various deposit types, including subsea nodules and crusts, Ni-Co laterites, magmatic Ni-Cu sulfide deposits, and sedimentary rock-hosted deposits (Cailteux et al., 2005; Hitzman et al., 2017; Mudd et al., 2013; Petavratzi et al., 2019). Lateritic ores, responsible for constituting 70% of the nickel deposits in the lithosphere, also encompass substantial amounts of cobalt (typically ranging between 0.025 and 0.18%) (Berger et al., 2011; Gleeson et al., 2003). It has been reported that the seafloor holds abundant deposits of cobalt (Horn et al., 2021; Sverdrup et al., 2017). Substantial regions of the elevated slopes on certain seamounts and ridges are coated with a layer of black oxide, primarily composed of manganese and iron. This layer, approximately 2 to 4 cm thick, also encompasses cobalt along with various other minor elements (Manheim, 1986; Schulz, 2017).

Pure cobalt is a rare occurrence in nature. However, due to its affinity for sulfur and its strong attraction to iron, nickel, copper, and sulfur, cobalt primarily forms associations with these elements. Instead of bonding with oxygen, cobalt tends to create various sulfide and sulfoarsenide phases, as noted by (Azevedo et al., 2018; Hazen et al., 2017; Roberts & Gunn, 2014). The most commonly extracted primary cobalt ore minerals are cobalt sulfides, including Carrollite ( $\text{CuCo}_2\text{S}_4$ ), Cattierite ( $\text{CoS}_2$ ), and linnaeite ( $\text{Co, Ni}_3\text{S}_4$ ), according to (Dehaine et al., 2021). Within the sulfarsenides category, cobaltite ( $\text{CoAsS}$ ), erythrite [ $\text{Co}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$ ], Skutterudite ( $\text{CoAs}_3$ ), and Safflorite ( $\text{CoAs}_2$ ) are

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prominent minerals associated with cobalt, as highlighted by (Anthony et al., 2001; Hazen et al., 2017; Lison, 2015; Roberts & Gunn, 2014).

A method has been developed for the separation of target minerals based on their varying particle densities and the effects of gravity and other forces on their acceleration, as documented by (Burt, 1984). Particles containing cobalt arsenide or cobalt sulphide demonstrate significantly higher specific gravity in comparison to gangue minerals (Dehaine et al., 2021). The extraction of cobalt from Bou Azzer ore involves the application of gravity separators specifically designed for cobalt arsenide minerals, such as skutterudite and safflorite. Techniques such as jigs, spirals, and shaking tables are employed, resulting in recovery rates reaching up to 96% (Formanek & Lauvernier, 1963; Swartz et al., 2009). Additionally, the dense media separation (DMS) is commonly utilized in the Central African Copper belt (CAC) to concentrate finely dispersed Cu-Co ores with complex gangue before entering the flotation circuit (Shengo et al., 2019). Nevertheless, the primary methods for cobalt extraction are hydrometallurgical, with acid leaching, high-pressure acid leaching, and reduction roasting-ammonia leaching being fundamental processes for recovering cobalt from its source minerals (Kaya & Topkaya, 2011; Ma et al., 2013; Thubakgale et al., 2013; Zhang et al., 2019).

In a study in the Democratic Republic of Congo (DRC) (Musuku et al. 2013) the collector SIPX (sodium isopropyl xanthate) was utilized at a concentration of 32 g/t for micro flotation of pure Carrollite material extracted from Konkola-Nchanga. The pH was adjusted to 9, resulting in a recovery rate of 95.2%. Similarly, another study conducted on an unexplored deposit in Zambia, using pure minerals, conducted micro flotation experiments with the collector SEX (sodium ethyl xanthate), yielding recovery rates ranging from 70% to 95% (Kemal et al., 1996). Additionally, (Moyer et al. 1948) in Carrollite flotation in Carrollite flotation, Moyer et al. (1948) used  $\text{CuSO}_4$  (0.9 kg/t) in a pH range from 4.5 to 5 with SEX (70 g/t) as an activator and collector. The findings revealed that the optimal system recovery was between 60 and 65%. Chemical reagents, including 0.25kg/t  $\text{Na}_2\text{SiO}_3$ , 0.05kg/t  $\text{Na}_2\text{CO}_3$ , NaSH (6-7kg/t), at natural pH, and 600-700g/t PAX as a collector, were used to treat cobalt mineral heterogenite in one of the oxide ores of Luiswishi, DRC, achieving a recovery of 52-83% (Lutandula & Maloba, 2013). Another study aimed to float heterogenite using 6 kg/t NaSH/( $\text{NaH}_4$ )<sub>2</sub>S with 1/1 ratio, 350 g/t PAX, and 350 g/t 90/10 Gas/Palm oil emulsion, and the results revealed 60-80% recovery (Kongolo et al., 2003). In another study focusing on heterogenite, kolwezite, and carrollite of Mutanda mixed ore flotation, a combination of NaSH, 30 g/t SIPX, and 30 g/t DTP (sodium dithiophosphate) yielded flotation responses in the range of 38-48% (Musuku, 2013). Carrollite from the Kolwezite sulphide ore was floated with 1.82 kg/t Na<sub>2</sub>S, 50 g/t PAX, 80 g/t SEX, 100 g/t Gas oil, and 10 g/t Tall Oil, resulting in a 70% industrial scale recovery. Although carrollite crystals floated with over 85% recovery when mixed with SIPX and PAX (3/1) (Konkola), DTP (Mutanda), and SEX (Nkana, Zambia) (Mainza et al., 1999; Musuku, 2013; Tremolada et al., 2010). Studies on the Bou-Azzer Morocco ore with skutterudite, erythrite, and safflorite minerals showed a 70% flotation recovery on an industrial scale using 0.2-0.6 kg/t  $\text{CuSO}_4$ , 1-2 kg/t Na<sub>2</sub>S, Na<sub>2</sub>SiO<sub>3</sub>, and PAX as a collector (Formanek & Lauvernier, 1963).

Because of its alignment with the principles of "Green Chemistry," flotation has garnered significant interest (Akl & Alharawi, 2018). Sulphide minerals are generally more amenable to flotation than oxide minerals (Dehaine et al., 2021). Furthermore, most sulphide minerals carry a charge within their functional pH range, preventing the adsorption of commonly used anionic chemicals (Kohad, 1998). Experimental findings indicated the stability of cobaltite at a pH of 4, with an increase in the negative charge on its surfaces as pH levels rose and vice versa (Abeidu, 1976). Cobaltite can be effectively floated at acidic pH using ethyl xanthate after activation by copper sulfate (Rao, 2000). Introducing nitrogen to generate bubbles enables efficient cobaltite flotation with xanthate collectors, achieving high recoveries at pH 4-5 without activation (Smith, 1953). Similar outcomes are observed when air is employed in the flotation process; approximately 80% of cobaltite is recovered, reaching up to 82% at pH 4-5 with xanthate (Rao, 2000; Teoh et al., 1982). The flotation of arsenosulfide cobaltite mineral

(CoAsS) may be improved by the application of collectors based on nitroso naphthol. Nitroso naphthol flotation of cobaltite from Mount cobalt ore showed optimal responses between pH 8 and 9, achieving approximately 88% recovery (Rao, 2000).

The flotation of cobalt-containing magnetite ore from Qamsar, Iran, was examined in this work using two distinct carbon chains, xanthate and a dithiophosphate collector family under both acidic and alkaline flotation conditions. The influential factors and the levels under examination were collected from prior studies, and the tests were designed using the Taguchi statistical technique. To achieve optimal results, five parameters, including pH, collector concentration, frother concentration, pulp density, and RPM, were selected at four levels.

Additionally, testing was carried out in accordance with the results of previous studies and the tests that were done. One of the fascinating findings of this study was how pH and particle size affected the cobaltite recovery.

## 2. Materials and methods

### 2.1. Sample preparation and characterization

The cobaltite-enriched specimen was sourced from a mining site in the Isfahan province of central Iran, situated approximately 7 km northwest of Qamsar. This sample originated from an abandoned ore heap subjected to leaching during underground mining. Initially, jaw and roller crushers were employed to crush the sample, resulting in a size fraction below 3.36 mm. Subsequent wet milling further reduced the size to less than 75  $\mu\text{m}$ . After the crushing and milling processes, the sample attained a d80 value of 54  $\mu\text{m}$ , preparing it for the flotation process. The mineralogical composition and content were validated through semi-quantitative X-ray diffraction (XRD) analysis using a CuK beam (see Figure 1 and Table 1). Table 2 outlines the primary oxide compounds identified through Li-fusion findings. The sample comprises 0.46% Co, >10% Fe, 0.28% Mg, 0.53% Al, 0.01% As, 0.006% Pb, 0.90% Ca, 0.058% Mn, 0.60% S, and 0.04% Na. Additionally, Figure 2 displays the SEM and EDAX analysis of the sample in which the mineral elements of cobaltite (which are cobalt, arsenic, and sulfur), were detected, and the amount of cobaltite was reported to be 4.3%. Also, due to the coexistence of cobalt and iron peaks in the EDAX diagram, we can conclude the possibility of the presence of Alloclasite [(Co,Fe)AsS] mineral.

**Table 1.** The mineral composition of the sample including cobaltite and magnetite: Semi -Quantitative XRD analysis.

Phase/mineral	Chemical formula	Content (%)
Magnesioferrite	$\text{Mg}(\text{Fe}^{3+})_2\text{O}_4$	91.4
Quartz	$\text{SiO}_2$	3.1
Calcite	$\text{CaCO}_3$	3.6
Cobaltite	$\text{CoAsS}$	1.9

**Table 2.** The primary oxide compounds of the sample, the Li-fusion method.

Oxide compound	Content (%)	Oxide compound	Content (%)
$\text{SiO}_2$	4.37	MgO	0.48
$\text{Al}_2\text{O}_3$	1.21	MnO	0.09
CaO	1.64	$\text{Na}_2\text{O}$	0.07
$\text{Fe}_t$	69.39	$\text{P}_2\text{O}_5$	0.05
$\text{K}_2\text{O}$	0.06	$\text{SO}_3$	1.20

### 2.2. Flotation experiments

The experimental design followed the Taguchi statistical method and was executed using Minitab software. Throughout the experiments, collectors such as potassium amyl xanthate (PAX), potassium ethyl xanthate (SEX), and dithiophosphate, along with methyl isobutyl carbonyl (MIBC) as a frother reagent, were employed. Sulfuric acid ( $\text{H}_2\text{SO}_4$ ) and calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ) were used to adjust the

acidic and alkaline pH, respectively. The conditioning time for the collector, frother, and froth skimming from the cell was set at 3, 1, and 3 minutes, respectively. The design and conditions of the preliminary flotation experiments with PAX as the collector are detailed in Table 3, while Table 4 provides information on tests with the main reagent, dithiophosphate, as the collector. Furthermore, these tests specifically focused on fine particle sizes with a  $d_{80}$  of 38  $\mu\text{m}$ . The analysis of cobalt concentration in the concentrate was conducted using atomic absorption spectroscopy (model: AA 20-varian).

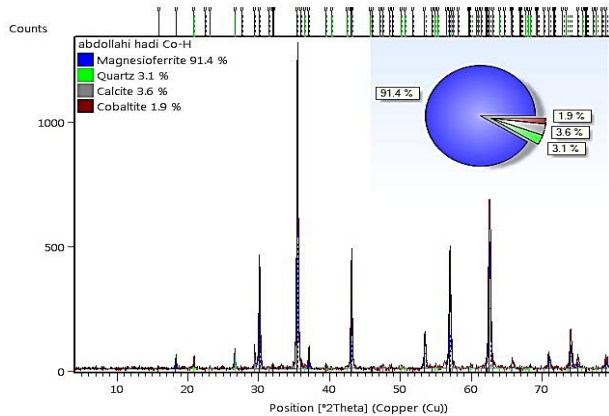


Figure 1. The X-ray diffractogram of the cobaltite bearing magnetite-rich sample.

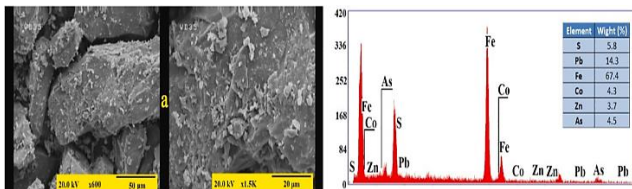


Figure 2. The SEM micrographs and EDAX analysis of the sample.

## 2.1. Statistical analysis and optimization

The Taguchi method of quality control is an engineering strategy that emphasizes the contributions of product design and development, as well as research and development (R&D), to reduce the incidence of flaws and failures in produced items (Keerthi et al., 2023). Using Minitab software, Taguchi's approach was first applied in this research to identify the ideal conditions, which were determined based on the parameters (pH, pulp density, collector concentration, frother concentration, and stirring speed) and chosen levels (four levels). The following sections provide information on the test findings and analyses.

Potassium amyl xanthate was found to have the greatest recovery and grade. Although some of these conditions were tested with dithiophosphate, the outcomes were unsatisfactory. Subsequently, due to successful preliminary tests employing a potassium ethyl xanthate collector, further tests were conducted under optimal conditions using this collector, resulting in a substantial recovery.

## 3. Results and discussion

### 3.1. Mineralogical study

A representative sample was taken from crushed specimens (Figure 3a) and then meshed to six size fractions (+1000, -1000+297, -297+149, -149+100, -100+75, -75 micron). Subsequently, the polished blocks and thin sections were prepared for ore microscopy and petrography in reflected and transmitted polarized light. Observations in optical microscopy revealed that magnetite with massive – microgranular texture, is the main mineral phase (> 95 vol%). Magnetite crystals are almost fresh; however, they are partially replaced by secondary hematite and goethite along with crystallographic planes, and microcracks are observed (Figure 3b). The interstitial spaces between magnetite grains which are less than 2 mm, are occupied by minor phases that include cobaltite (1-2 vol%), quartz, calcite, erythrite, chalcopyrite, pyrite, as well as rarely arsenopyrite and bornite. Cobaltite occurs as idiomorphic to subhedral grains ranging in size from less than 15 microns to crystal aggregate of 400 microns.

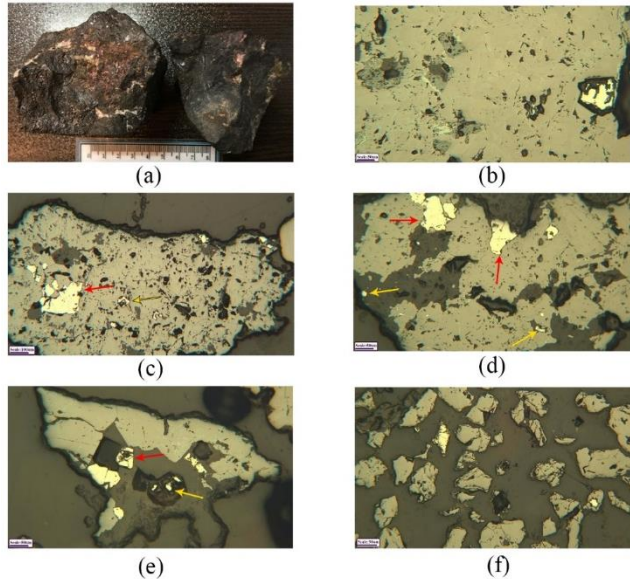
Table 3. The conditions of the preliminary flotation experiments with the PAX as collector.

Test No.	pH	Collector Conc. (g/t)	Frother Conc. (g/t)	Pulp density (%)	RPM
1	5	100	25	5	750
2	5	200	50	7.5	1000
3	5	300	75	10	1250
4	5	400	100	12.5	1500
5	7	100	50	10	1500
6	7	200	25	12.5	1250
7	7	300	100	5	1000
8	7	400	75	7.5	750
9	9	100	75	12.5	1000
10	9	200	100	10	750
11	9	300	25	7.5	1500
12	9	400	50	5	1250
13	11	100	100	7.5	1250
14	11	200	75	5	1500
15	11	300	50	12.5	750
16	11	400	25	10	1000

Table 4. The conditions of the flotation experiments with the dithiophosphate as collector.

Test No.	Size fraction (micron)	pH	Collector type	Collector (g/t)	Pulp density (%)	Frother	
						(g/t)	RPM
1	-75+38	6	Dithiophosphate	400	12.5	300	1250
2	-75+38	6	Dithiophosphate	800	12.5	300	1250
3	-38	6	Dithiophosphate	400	12.5	300	1250
4	-38	6	Dithiophosphate	800	12.5	300	1250

Cobaltite grains are rarely altered to secondary erythrite along with grain boundaries and contain fine inclusions of chalcopyrite (Figure 3c-e). The cobaltite content is founded both as a filling of interstitial spaces and fine inclusions in the magnetite and transparent gangue minerals (quartz and calcite). Microscopic examination shows that in the minus 74 microns fractions, more than 90% of the cobaltite content is liberated (Figure 3f).



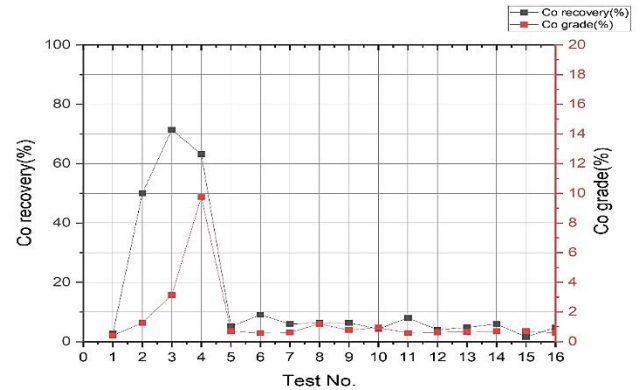
**Figure 3.** a) The representative image of cobaltite bearing magnetite sample, b) the photomicrograph image shows partially replacement of magnetite by hematite and goethite, c-e) the photomicrograph image shows idiomorphic to subhedral crystals of cobaltite as interstitial filling (red arrow) and fine inclusions (black arrow) interlocked with magnetite or transparent gangue minerals, f) the photomicrograph image of plus 74 microns fractions that shows liberated fragments of magnetite and cobaltite.

### 3.2. Preliminary flotation by the potassium amyl xanthate (PAX) and dithiophosphate

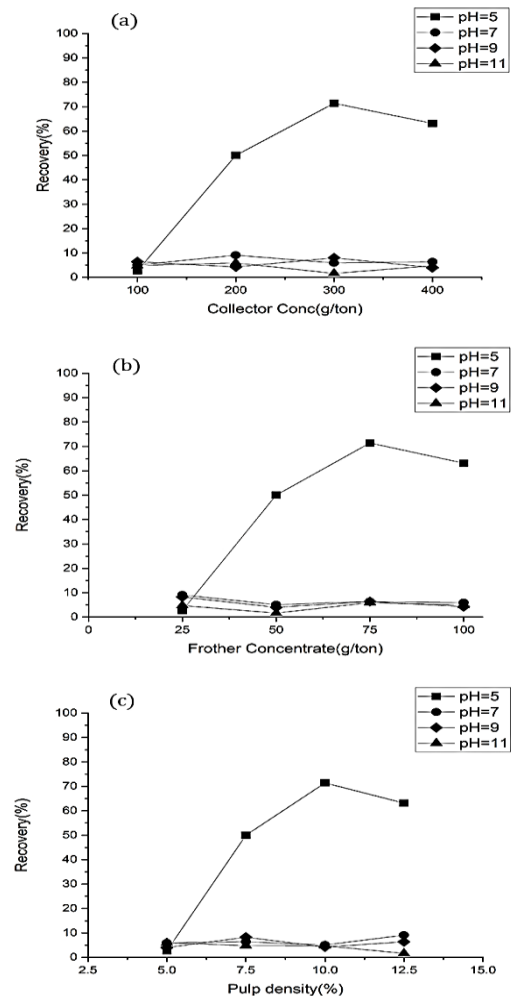
Since xanthates exhibit effective performance with sulphide minerals, experiments were conducted using four levels of potassium amyl xanthate as the collector. Consideration was given to key selection parameters, namely pH, pulp density, collector concentration, frother concentration, and stirring speed. The long hydrocarbon chain of potassium amyl xanthate makes it the most widely utilized xanthate collector. Optimal performance in neutral and alkaline pH ranges guided the selection of pH values predominantly within the range of 7 to 11, with pH 5 chosen to represent acidic conditions. Given the low grade of the sample, high recovery was not anticipated. The test design aimed to generate a very high-grade concentrate for subsequent research, leading to the choice of a low pulp density ranging from 5% to 12.5%. Collector and frother concentrations were determined based on the outcomes of previous tests. Additionally, the stirring rate was chosen to allow a comprehensive evaluation of its effects. The results of the flotation experiment with potassium amyl xanthate are presented in Figure 4.

Dithiophosphate has been utilized to assess the separation of cobaltite from various minerals, including chalcopyrite and pyrite, yielding promising results. In accordance with the findings presented by (Abeidu, 1976), sodium sulfide was introduced as an activator to evaluate the performance of diphosphate in the flotation of cobaltite from pyrite and chalcopyrite, resulting in a high recovery. However, our study did not yield noteworthy results, and the recovery was notably low when using this collector for cobaltite separation from magnetite. Additionally, two size fractions (-38 micron, +38-73 micron) were

employed to account for the release of cobaltite particles in smaller size fractions. It can be concluded that, based on the conditions outlined in Table 4, test number 3 had the best results compared to the rest of the tests, but its recovery was not significant. It can be shown from the test results and Taguchi analyses performed using Minitab software that pH variations have the largest impact on cobalt recovery and grade.



**Figure 4.** The cobalt grade and flotation recovery results obtained from the PAX collector at various conditions.



**Figure 5.** The recovery of cobalt using different, a) collector concentrations, b) frother and, c) pulp density to demonstrate the effect of pH.

In their prior studies on cobaltite flotation (Smith et al., 1976; Teoh et al., 1982), they came to the conclusion that an acidic pH is appropriate for cobaltite flotation and an acceptable recovery may be attained. The findings of the experiments performed for this study indicate that a pH of 5 is adequate for cobaltite flotation, and the recovery has increased to more than 70% (Figure 5.). The highest separation efficiency belongs to test number 4 which has about 70.43%. In (Table 5), it can be observed that the test with acidic pH has high separation efficiency.

### 3.3. Maximizing flotation performance

It was decided to use this collector under optimal conditions and compare the obtained results, which were almost similar to the PAX and approval was observed in the acidic environment, after conducting a series of initial tests and pre-tests using the PEX, resulting in interesting conclusions. The conditions and results of these tests are shown in the table below (Table 7), detailing the test condition and result of flotation for maximizing the Co grade and recovery with PEX. A high dosage of the frother agent was utilized in these studies since the frother was not stable at acidic pH. Based on the outcomes of tests carried out in previous research, these investigations demonstrate a considerable recovery of cobaltite flotation (up to 76%) at acidic pH and using potassium ethyl xanthate as collector for size fraction of -75 microns. In order to achieve a 65% recovery at pH=4, (Moyer, 1948) employs sodium ethyl xanthate. Also, test number one has accounted for the highest separation. The use of xanthate in an acidic pH produces the ideal cobaltite flotation conditions.

## 4. Concluding remarks

Given the increasing importance of cobalt in the new era of technology and its widespread applications, the demand for metallic cobalt production has surged. This study focused on generating a concentrate from cobalt-containing magnetite ore, albeit with a low grade. Among the key determinants in flotation, particularly for oxide minerals, is pH. The impact of pH was evident in this investigation, indicating that an acidic pH is optimal for cobaltite mineral flotation, delivering the highest recovery and grade within this range. Throughout this research, various xanthate collector carbon chains were evaluated, showing negligible differences among them, as they all performed at similar levels. Dithiophosphate was employed as a collector without an activator, yet it failed to yield significant results. These outcomes were successfully achieved using the magnetite and quartz companion minerals within this sample. Due to the brittleness of cobaltite, samples

featuring particles smaller than 38 microns exhibited reasonably high quality. However, the presence of tiny particles reduced recovery and grade, highlighting the optimal particle size fraction for cobaltite between 38 and 75 microns. While the typical pulp density in flotation ranges between 30% and 20%, our study aimed to produce a high-quality concentrate; hence, a low pulp density was chosen. Remarkably, the highest value of pulp density yielded the best results.

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## Conflict of Interest

The authors declare that they have no conflict of interest.

Table 5. Flotation with PAX tests results.

Test Number	Co grade (%)	Co recovery	S. E
1	0.42	2.68	0.05947
2	1.27	50.03	23.91608
3	3.15	71.42	58.01873
4	9.76	63.14	70.432
5	0.7	5.08	2.026838
6	0.58	9.1	3.284205
7	0.62	5.93	0.979031
8	1.21	6.38	2.982
9	0.78	6.39	3.620393
10	0.95	4.28	2.236197
11	0.59	8	3.316772
12	0.63	4	0.679254
13	0.67	4.84	1.359923
14	0.7	5.93	1.183333
15	0.71	1.65	0.840268
16	0.6	4.76	1.440228

Table 6. Flotation with Dithiophosphate tests result.

test No	Co grade (%)	R (%)	S. E
1	2.41	2.22	155
2	2.24	2.27	153
3	1.53	9.02	2.26
4	1.66	7.66	2.38

Table 7. Test condition and result of flotation for maximizing the Co grade and recovery with PEX.

test No	Size fraction (micron)	pH	Collector type	Collector Co. (g/t)	Pulp density %	Frother Co. (g/t)	RPM	Conc. grade (%)	Conc. recovery (%)	S.E
1	-75+38	4	PEX	400	12.5	300	800	22.3	75.92	74.93
2	-75+38	4	PEX	800	12.5	300	800	20.83	61.14	60.19
3	-38	4	PEX	400	12.5	300	800	6.81	32.96	28.26
4	-38	4	PEX	800	12.5	300	800	11.18	44.81	41.51

## Credit author statement

**Pouya Nazari:** Investigation, Software, Formal analysis, Validation

**Amir Abbaspour:** Investigation, Methodology, Software, Formal analysis, Validation, Data curation, Writing - original draft, Writing - review and editing, Visualization

**Hadi Abdollahi:** Supervision, Investigation, Methodology, Software, Formal analysis, Validation, Data curation, Writing - review and editing, Visualization

**Sajjad Tahooni Bonab:** Investigation, Methodology, Software, Formal analysis, Validation, Data curation, Writing - original draft, Writing - review and editing, Visualization

**Mirsaleh Mirmohammadi:** Resources, Funding acquisition, Mineralogy

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