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Research Article

An Experimental Investigation on the Effect of Different Reagents on Gold Ore Recovery Efficiency

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ABSTRACT

In this study, the effects of different collector and frother reagents on gold ore recovery were experimentally investigated. A total of ten flotation tests were conducted under constant stirring speed (1,200 rpm), pH (7), and solid ratio (30% PKO) conditions, using various reagent types and dosages. The effects of these reagent combinations on the flotation behavior of the ore were evaluated, and the amounts and compositions of the obtained concentrates were analyzed. As a result of the tests, while flotation success was achieved with some reagent combinations, the ore did not float in others. Overall, 4 out of 10 tests yielded successful flotation, highlighting the importance of reagent–ore compatibility. The highest gold content of 7.36 ppm was obtained in the test using the Tomamine M73 + Aerofroth 76A combination, while the highest silver content of 398.99 ppm was achieved with the KEX-Aero 3477 + MIBC combination. These results indicate that not only the type of reagent but also its dosage and synergistic combination significantly affect flotation efficiency. For example, certain reagents required higher dosages to produce flotation, and tests without frothers generally failed to generate sufficient concentrate. The findings emphasize that careful reagent optimization, tailored to the mineralogical structure of the ore, is essential for achieving maximum recovery efficiency in gold ore flotation.

1. Introduction

Gold has played an important role throughout history as a metal with high economic and strategic value. It has been one of the most valuable and sought-after metals throughout human history, not only in the production of ornaments and jewelry, but also due to its importance in economic and industrial areas.

It is an important mineral used in many areas today due to its properties such as being easy to process, not corroding, and easily conducting electricity and heat (Doğan, 2005). It is widely used in electronics, space, the energy sector, medicine and other advanced technology fields. (Marsden & House, 2006) It plays a critical role as a reserve asset and investment tool in international financial systems.

This demand for gold necessitates the efficient and sustainable evaluation of ore reserves. This versatile use of gold increases the importance of the processes of extracting and processing the metal from nature. However, the gradual decrease or even depletion of high-grade gold deposits around the world has made it necessary to make low-grade ores economically processable. This situation increases the importance of the methods applied in the recovery of gold and the chemical reagents used (Çopur, 2005).

The extraction of gold from its ore is carried out by methods using various chemical reagents, which is a complex and costly process. Anonymous. (2024). The effectiveness of the reagents used in the recovery of gold ore may vary depending on many factors such as the mineralogical composition of the ore, grain size, pH, temperature, and the presence of oxidants. The reagents used during the processing of gold ore directly affect the recovery efficiency.

Flotation is a physicochemical enrichment method that allows the separation of gold-containing sulphide minerals (e.g. pyrite, arsenopyrite) in water with the help of air bubbles according to different surface properties. It is applied in ores where gold is not directly, but mostly in the sulphide mineral matrix (Arhan, 2024). The flotation process is carried out by using reagents that change the chemical properties of the mineral surfaces. Flotation is a widely used method in the enrichment of gold ores. Flotation reagents play a vital role in gold mining, especially in improving gold recovery while reducing operational costs through the selectivity of flotation processes. (MarketResearch, 2024).

The type, quantity and combination of reagents used in this process directly affect the recovery efficiency achieved. There are traditional reagents frequently used in gold flotation. New generation collectors, frothers and reagents are being investigated to provide higher efficiency and selectivity. It is of great importance to find environmentally friendly and economically advantageous reagents in the sector.

Reagent optimization is a critical strategy to increase efficiency, improve selectivity and reduce costs in flotation processes. This process is achieved by the correct selection and precise dosing of reagents. In modern flotation plants, the integration of digital technologies such as artificial intelligence and machine learning allows real-time monitoring of reagent performance, thus increasing recovery rates (MarketResearch, 2024)

In various studies conducted in Türkiye, the effects of different leaching reagents were tested at laboratory scale along with mineralogical characterization of domestic gold deposits and significant differences were observed in terms of efficiency (Yıldız, 2014; Sönmez, 2020).

In this study, reagents such as Aerofroth 76A, Aerophine 3418A, Hostafloat X231, MIBC, KEX-Aero 3477, Tomamine M73, Maxgold 900, SBX and Oreprep X133 were used alone or in combination to investigate gold ore recovery under ten different experimental conditions. The aim of the study is to clearly determine the most efficient reagent combination for the given ore type and to compare its performance with alternative reagents in terms of both gold and silver recovery. The working hypothesis is that the synergistic use of amine-based collectors with selective frothers will significantly increase flotation efficiency.

Compared to previous studies in the literature, which mostly focused on leaching reagents or single-collector systems, this study provides an original contribution by systematically testing a wide range of collector–frother combinations under controlled laboratory conditions. The results are intended to guide reagent selection and optimization strategies for similar low-grade sulphide gold ores in Türkiye and elsewhere

2. Materials and Methods

The gold ore used in this study was specially prepared for flotation experiments in a laboratory environment. In the experiments, a pulp of 30% solid content (PCO) was formed using 900 grams of ore and 2,100 ml of water for each test. The pulp was mixed at 1,200 rpm to obtain a homogeneous structure.

While preparing the pulp, 0.55 grams of lime (CaO) was added, the pH value was adjusted to 7 and kept constant.After the determined pH value was reached, the collector was added, and the conditioning process was carried out for 7 minutes.(Figure 1)

Figure 1. Process performed during reagent addition

At the end of the conditioning period, frother was added, air was supplied, and flotation was carried out for 3 minutes.Concentrates obtained from the foam formed during flotation were collected and analyzed.(Figure 2)

Figure 2. Foam formation during the flotation process

Aerofroth 76A, Aerophine 3418A, Hostafloat X231, MIBC, KEX-Aero 3477, Tomamine M73, Maxgold 900, SBX, and Oreprep X133 reagents were used in this study. Reagents were applied singly or in various combinations. The main characteristics and selection rationale of the reagents are as follows: Aerofroth 76A is an alcohol-based frother producing moderately stable foam; Aerophine 3418A is a thionocarbamate-based selective collector for copper and precious metal sulfides; Hostafloat X231 is a modified xanthate collector with high selectivity; MIBC is a classic frother that generates low-density, fast-forming bubbles; KEX-Aero 3477 is a potassium ethyl xanthate-based collector with high activation energy; Tomamine M73 is an amine-based collector with strong affinity for sulfide minerals; Maxgold 900 contains thiocarbonate derivatives specifically designed for gold recovery; SBX is a highly hydrophobic sodium butyl xanthate; and Oreprep X133 is a foam stabilizer and conditioner. These reagents were selected based on their documented performance in similar sulphide gold ores reported in the literature.

At the end of the experiments, the gold contents in the concentrate and residual products obtained were analyzed and the recovery percentages were determined. Gold (Au) and silver (Ag) contents were measured using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES, following ASTM E1479-16 standards), while copper (Cu), zinc (Zn), and sulfur (S) contents were determined by X-ray fluorescence (XRF) analysis. All analyses were performed in duplicate to ensure accuracy, and calibration was done using certified reference materials (CRMs). Accordingly, the performances of different reagent combinations were evaluated.

2. Findings

In this study, the effects of different reagent combinations used on gold ore were investigated experimentally.

Test 1

- ✓ **Experiment Parameters**
- ✓ Solid: 900 g
- ✓ Water: 2,200 ml
- ✓ 1,200 rpm
- ✓ PKO ≅%30
- ✓ pH ≅ 7 (0.55 g lime)

- ✓ Aerophine 3418A: 120 g/t
- ✓ Aerofroth 76A: 80 g/t

Experiment Result

The collector was added and a 7-minute conditioning period was given. At the end of the 7 minutes, the frother was added and the air was released, but the material did not float and the experiment failed.

Figure 3. Test 1 experiment images

Test 2

Experiment Parameters

- ✓ Solid: 850 g
- ✓ Water: 2.100 ml
- ✓ 1,200 rpm
- ✓ PCO ≅30%
- ✓ pH ≅ 7 (0.55 g lime)
- ✓ Aerophine 3418A: 120 g/t
- ✓ Hostafloat X231: 130 g/t
- ✓ MIBC: 20 g/t

Experiment Result

Collectors were added and a 7-minute conditioning period was given. At the end of 7 minutes, frother was added, air was released and flotation was performed for 3 minutes. The resulting 184 g of concentrate was given for analysis.

Tablo 1. Mineralogical Composition Table

% Cu	% Zn	% S	Au (ppm)	Ag (ppm)
0,80	0,29	45,53	1,40	76,84

Figure 4. Test 2 experiment images

Test 3

Experiment Parameters

- ✓ Solid: 850 g
- ✓ Water: 2,100 ml
- ✓ 1,200 rpm
- ✓ PKO ≅%30
- ✓ pH ≅ 7 (0.55 g lime)
- ✓ KEX-Aero 3477: 214 g/t
- ✓ MIBC: 20 g/t

Experiment Result

The collector was added and a 7-minute conditioning period was given. At the end of 7 minutes, the frother was added and the air was released and the material did not float. Then, the same amount of KEX-Aero 3477 was added again and flotation was performed for 3 minutes. The 17 g of concentrate obtained was given for analysis.

Tablo2. Mineralogical Composition Table

% Cu	% Zn	% S	Au (ppm)	Ag (ppm)
2,97	0,90	36,06	4,96	398,99

Figure 5. Test 3 experiment images

Test 4

Experiment Parameters

- ✓ Solid: 900 g
- ✓ Water: 2,100 ml
- ✓ 1,200 rpm
- ✓ PKO ≅%30
- ✓ pH ≅ 7 (0.55 g lime)
- ✓ Tomamine M73: 107 g/t
- ✓ Aerofroth 76A: 80 g/t

Experiment Result

Collector was added and 7 minutes of conditioning time was given. At the end of 7 minutes, frother was added and air was released and 3 minutes of flotation was performed. The resulting 21.58 g of concentrate was given for analysis.

Tablo3. Mineralogical Composition Table

% Cu	% Zn	% S	Au (ppm)	Ag (ppm)
1,48	0,42	18,04	7,36	375,53

Figure 6. Test 4 experiment image

Test 5

Experiment Parameters

- ✓ Solid: 900 g
- ✓ Water: 2,100 ml
- ✓ 1,200 rpm
- ✓ PKO ≅%30
- ✓ pH ≅ 7 (0.55 g lime)
- ✓ Tomamine M73: 107 g/t

Experiment Result

The collector was added and a 7-minute conditioning period was given. At the end of 7 minutes, the air was turned on and flotation was performed for 3 minutes, but since the concentrate obtained was 4.03 g, it could not be given for analysis.

Figure 7. Test 5 experiment images

Test 6

Experiment Parameters

- ✓ Solid: 900 g
- ✓ Water: 2,100 ml
- ✓ 1,200 rpm
- ✓ PKO ≅%30
- ✓ pH ≅ 7 (0.55 g lime)
- ✓ Maxgold 900: 107 g/t
- ✓ MIBC: 20 g/t

Experiment Result

The collector was added and a 7-minute conditioning period was given. At the end of the 7 minutes, the frother was added and the air was released, but the material did not float and the experiment failed.

Figure 8. Test 6 experiment images

Test 7

Experiment Parameters

- ✓ Solid: 900 g
- ✓ Water: 2,100 ml
- ✓ 1,200 rpm
- ✓ PKO ≅%30
- ✓ pH ≅ 7 (0.55 g lime)
- ✓ SBX: 250 g/t
- ✓ Oreprep X133: 20 g/t

Experiment Result

The collector was added and a 7-minute conditioning period was given. At the end of the 7 minutes, the frother was added and the air was released, but the material did not float and the experiment failed.

Figure 9. Test 7 experiment image

Test 8

Experiment Parameters

- ✓ Solid: 900 g
- ✓ Water: 2,100 ml
- ✓ 1,200 rpm
- ✓ PKO ≅%30

- ✓ pH ≅ 7 (0.55 g lime)
- ✓ Aerophine 3418A: 120 g/t
- ✓ Hostafloat X231: 130 g/t
- ✓ MIBC: 20 g/t

The same parameters were repeated for the control of Test 2.

Experiment Result

Collectors were added and a 7-minute conditioning period was given. At the end of the 7 minutes, the frother was added and the air was released, but the material did not float and the experiment failed.

Figure 10. Test 8 experiment image

Test 9

Experiment Parameters

- ✓ Solid: 850 g
- ✓ Water: 2,100 ml
- ✓ 1,200 rpm
- ✓ PKO ≅%30
- ✓ pH ≅ 7 (0.55 g lime)
- ✓ Aerophine 3418A: 120 g/t
- ✓ Hostafloat X231: 130 g/t
- ✓ MIBC: 20 g/t

The same parameters were repeated for the control of Test 8.

Experiment Result

Collectors were added and a 7-minute conditioning period was given. At the end of the 7 minutes, the frother was added and the air was released, but the material did not float and the experiment failed.

Figure 11. Test 9 experiment image

Test 10

Experiment Parameters

- ✓ Solid: 900 g
- ✓ Water: 2.100 ml
- ✓ 1,200 rpm
- ✓ PCO ≅30%
- ✓ pH ≅ 7 (0.55 g lime)
- ✓ Maxgold 900: 50 g/t
- ✓ Hostafloat X231: 100 g/t
- ✓ MIBC: 20 g/t

Experiment Result

Collectors were added and a 7-minute conditioning period was given. At the end of 7 minutes, frother was added, air was released and flotation was performed for 3 minutes. The resulting 86.31 g of concentrate was given for analysis

Tablo4. Mineralogical Composition Table.

% Cu	% Zn	% S	Au (ppm)	Ag (ppm)
1,82	0,56	43,36	2,29	129,76

Figure 12. Test 10 experiment images

4 out of 10 tests were successful. (Test 2, Test 3, Test 4 and Test 10)

The highest gold grade (7.36 ppm) was obtained in Test 4 with the combination of Tomamine M73 + Aerofroth 76A.

The highest silver (Ag) content (398.99 ppm) was achieved with KEX - Aero 3477 in Test 3.

In many tests (especially in combinations of Aerophine 3418A and Hostafloat) the material did not float, indicating that the reagents were less effective on gold minerals.

In some tests (Test 5), analysis could not be performed due to the low amount of concentrate.

In some tests ("material did not float"), no concentrate was obtained. The combination of **Aerophine 3418A + Hostafloat** was particularly unsuccessful. The possible mineralogical and chemical reasons are as follows:

Reagent-mineral interaction: Aerophine 3418A and Hostafloat X231 may not have interacted sufficiently with the gold ore minerals tested. For example, proper surface activation may not have been achieved for gold sulfide minerals.

pH effect: pH is critical in froth flotation. If the pH is not suitable for the target minerals, collection and froth formation will not occur.

Reagent dosage too low or too high: Excessive or insufficient amounts of collector/pH regulator can hinder flotation.

Froth stability: Frothers such as MIBC or Aerofroth 76A may not produce a stable froth if they do not interact properly with the mineral surfaces.

Test 4 (Tomamine M73 + Aerofroth 76A): The highest gold content (Au: 7.36 ppm) was obtained. This combination appears to have an optimal balance of collector and frother for gold minerals.

Test 3 (KEX-Aero 3477 + MIBC): The highest silver content (Ag: 398.99 ppm) was achieved. This indicates that KEX-Aero 3477 selectively collected the silver minerals.

The obtained results are summarized in Table 5.

Table 5. Experimental Results

Test No	Reangents	Concentrate Amount (g)	% Cu	% Zn	% S	Au (ppm)	Ag (ppm)	Explanation
1	Aerophine 3418A + Aerofroth 76A	-	-	-	-	-	-	The material did not float.
2	Aerophine 3418A + Hostafloat X231 + MIBC	184	0,80	0,29	45,53	1,40	76,84	Successful
3	KEX-Aero 3477+MIBC	17	2,97	0,90	36,06	4,96	398,99	Success (with additional collector)
4	Tomamine M73+ Aerofroth 76A	21,58	1,48	0,42	18,04	7,36	375,53	Successful
5	Tomamine M73+	4,03	-	-	-	-	-	Concentrate was not analyzed.
6	Maxgold 900+ MIBC	-	-	-	-	-	-	The material did not float
7	SBX+ Oreprep X 133	-	-	-	-	-	-	The material did not float
8	Aerophine 3418A+ Hostafloat X231+ MIBC (Tekrar)	-	-	-	-	-	-	The material did not float
9	3418A+ Hostafloat X231+ MIBC (Tekrar)	-	-	-	-	-	-	The material did not float
10	Maxgold 900+ Hostafloat X231+ MIBC	86,31	1,82	0,56	43,36	2,29	129,76	Successful

3. Argument

In this study, the flotation recovery efficiencies of different reagent combinations on gold ore were evaluated. The results obtained varied depending on both the interaction potential of the reagents with the mineral surfaces and the structural properties of the ore. In most of the tests performed with Aerophine 3418A, the material did not float (Tests 1, 8, 9), indicating that this collector alone or in combination with certain frothers could not provide sufficient surface activation. Possible reasons for these failures include reagent-mineral interaction issues, inappropriate pH for target minerals, incorrect reagent dosage, and insufficient froth stability**.** However, in Test 2, where the same reagent was used together with Hostafloat X231 and MIBC, the material floated successfully and the gold content in the analyses was found to be 1.40 ppm. However, the failure in the repetitions of the same combination (Tests 8 and 9) indicates that the flotation performance may be inconsistent in terms of reproduction. This inconsistency may be attributed to the heterogeneous structure of the ore or the sensitivity of the reagents to minor variations in preparation and dosing conditions**.**

One of the most successful results was obtained with the combination of Tomamine M73 + Aerofroth 76A (Test 4). In this test, both gold (7.36 ppm) and silver (375.53 ppm) recovery was high. Tomamine M73, as an amine-based collector, may have provided high flotation efficiency by showing a strong interaction with the sulphide minerals in the ore. In Test 5, where the same reagent was used without frother, a very low concentration was obtained. This situation emphasizes the effect of frothers on flotation efficiency.

In Test 3, which was conducted with KEX - Aero 3477, no flotation occurred in the first attempt, but after the same amount of collector was added again, concentrate could be obtained. This demonstrates that certain reagents require a minimum threshold dosage to become effective. In Test 3, the gold content was found to be 4.96 ppm and the silver content was quite high (398.99 ppm).

Combinations containing Maxgold 900 gave mixed results. Only in Test 10, when used with Hostafloat X231 and MIBC, a significant recovery was achieved (Au: 2.29 ppm; Ag: 129.76 ppm). This shows that Maxgold 900 alone is insufficient, but can create synergy with the right frother and auxiliary reagents.

In Test 7, with SBX and Oreprep X133, the material did not float. This indicates that this combination is not suitable for the mineralogical characteristics of the current ore.

As a result, the highest gold recovery among the reagents used was obtained with the Tomamine M73 + Aerofroth 76A combination. However, the effect of each reagent depends not only on its chemical structure but also on many factors such as dosage, pH, frother type and mineralogical properties of the ore. Therefore, optimization studies specific to the ore type should be carried out when selecting the reagent.

The results have not been compared with literature data. Moreover, inconsistencies between tests (for example, Test 2 versus Tests 8 and 9) have not been sufficiently explained. It is recommended that the results be compared with similar studies in the literature, and that possible reasons for these inconsistencies—such as ore heterogeneity, experimental conditions, or reagent sensitivity—be discussed in detail.

In summary, this study highlights that reagent performance in gold ore flotation is highly dependent on ore mineralogy, reagent compatibility, dosage optimization, and process parameters. While Tomamine M73 + Aerofroth 76A achieved the highest gold recovery and KEX-Aero 3477 achieved the highest silver recovery, the inconsistent performance of some reagents—particularly Aerophine 3418A—indicates that further optimization and ore-specific testing are essential. Integrating these findings with literature comparisons and conducting systematic parameter studies would improve the reliability and applicability of the results.

4. Conclusion

In this study, the effects of different collector and frother reagent combinations on gold recovery from ore were investigated experimentally. In total, 10 tests performed with the flotation method, only 4 were successfully concentrated. In the remaining tests, the material did not float or sufficient concentrate was not formed, so analysis could not be performed.

In light of the obtained data, the following conclusions were reached:

The highest gold recovery was obtained with 7.36 ppm in the Tomamine M73 + Aerofroth 76A reagent combination.

The highest silver content was observed with 398.99 ppm in the KEX - Aero 3477 + MIBC reagent combination.

While some combinations containing Aerophine 3418A provided floating in one go, the fact that floating did not occur in repeat tests performed under the same conditions revealed the heterogeneity of the ore and the sensitivity of the experimental conditions.

It was observed that the addition of frother had a decisive effect on flotation efficiency, and that no flotation occurred in tests where no frother was used or insufficient dose.

Reagent dosage is of critical importance, especially for some collectors such as KEX - Aero 3477. Although no flotation was observed in the first trial, successful results were obtained with increasing dosage.

In general, the flotation performances of the reagents used varied according to the ore structure. Therefore, it is recommended that comprehensive optimization studies supported by mineralogical analyses be carried out in order to determine the most suitable reagent combinations for gold ore recovery.

The laboratory-scale results obtained in this study suggest that the combination of Tomamine M73 and Aerofroth 76A can enhance flotation efficiency in low-grade, sulfide-containing gold ores. However, in order to evaluate the feasibility of applying these findings at an industrial scale, the following considerations should be addressed:

Economic Evaluation: A cost analysis per ton should be performed, taking into account the unit prices of reagents and the required dosage levels. The economic sustainability of high-performance but specialized reagents such as Tomamine M73 and KEX - Aero 3477 must be critically assessed.

Availability and Handling: Since some reagents are specially manufactured, factors such as supply chain reliability, storage requirements, and occupational health and safety considerations must be evaluated.

Process Compatibility: Results achieved under laboratory conditions may not fully translate to industrial flotation circuits. Factors such as mixing energy, settling time, and continuous feed in large-scale flotation cells can significantly influence reagent performance.

Environmental Impact: The environmental toxicity of the reagents and their effects on water treatment processes should also be considered. Reagents that are environmentally friendly and compliant with regulations should be prioritized for sustainable mining practices.

Therefore, pilot-scale test studies are recommended to verify the industrial applicability of the findings.

Based on the findings of this study, the following research directions are proposed to further improve flotation performance:

Detailed Mineralogical Analyses: The mineralogical composition of the ore (e.g., through SEM-EDS, XRD, or MLA analyses) should be characterized in detail to better understand reagent-mineral interactions.

Testing of pH and Temperature Conditions: In this study, pH was maintained at approximately neutral (~7). However, evaluating reagent performance under different pH ranges (e.g., pH 5–9) and temperatures could help identify optimal operating conditions.

Kinetic Flotation Tests: Varying conditioning and flotation times could reveal the time-dependent behavior and efficiency of reagents.

Statistical Optimization: Techniques such as Response Surface Methodology (RSM) or factorial design of experiments can be employed to optimize reagent dosages and combinations more systematically.

Environmentally Friendly Reagents: Testing of more biodegradable and eco-friendly alternatives to conventional xanthate-based collectors is encouraged to support sustainability goals.

Sequential Addition and Reagent Order: Investigating the impact of sequential or differently ordered additions of collectors and frothers could enhance overall flotation performance.

Pursuing these directions would not only contribute to the academic literature but also support the more efficient processing of low-grade gold ores in Turkey and similar deposits worldwide.

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