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IMPROVEMENT OF HEAP LEACHING PRACTICES IN UŞAK KIŞLADAĞ GOLD MINE USING LIMESTONE

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ABSTRACT

This study focuses on improving gold recovery from ore samples from the Uşak Kışladağ Gold Mine, specifically those sized -18+0 mm. The ore was crushed below 2.36 mm and mixed with locally abundant alkaline limestone to enhance permeability and gold dissolution efficiency. Permeability tests were conducted on the -18+0 mm and -2.36+0 mm sized ores, with results of 1.28 x 10^{-3} cm/s and 0.62 x 10^{-3} cm/s, respectively. Additionally, the -2.36 mm ore was mixed with various limestone sizes (-18+10 mm, -10+5 mm, and -5+0 mm) at ratios of 15%, 50%, 100%, 150%, and 200%. The best permeability results were observed with the -2.36+0 mm ore and -10+5 mm limestone mixture. Consequently, leaching experiments were conducted with 1:1 and 1.5:1 ratio of the -2.36+0 mm sample mixed with limestone, resulting in gold dissolution efficiencies of 63% and 53%, respectively. Furthermore, bottle-roll tests were performed on -2.36+0 mm and -75+0 µm samples for 48 hours, with gold recoveries of 64% and 83%, respectively.

1 INTRODUCTION

Gold and silver extraction methods vary depending on ore quantity, mineralogy, and grade [1]. However, as high-grade ores decline and costs rise, cyanide leaching has become the primary method for low-grade ores, despite its environmental and health risks [2].

Yet, refractory gold ores, where gold is trapped in sulfide minerals like pyrite or arsenopyrite, hinder cyanide leaching due to micron-sized particles and high reagent consumption [3, 4]. Thus, pre-treatments such as roasting at 550°C, pressure oxidation at 225–245°C, and biooxidation—applied since 1986—are used to enhance recovery [5, 6].

Moreover, in heap leaching, permeability is critical, as fine materials can block solution flow. Therefore, agglomeration with coarser particles improves permeability and recovery [7]. In this context, Robertson et al. [8, 9] highlight the role of agglomeration, while Yılmaz et al. demonstrate that nut shell additives enhance permeability and recovery at Uşak Kışladağ Gold Mine [10]. This effect is illustrated in Figure 1, where fine particles exhibit clay-like behavior, impeding uniform solution and gas flow, whereas agglomeration improves permeability and enhances extraction efficiency [11].

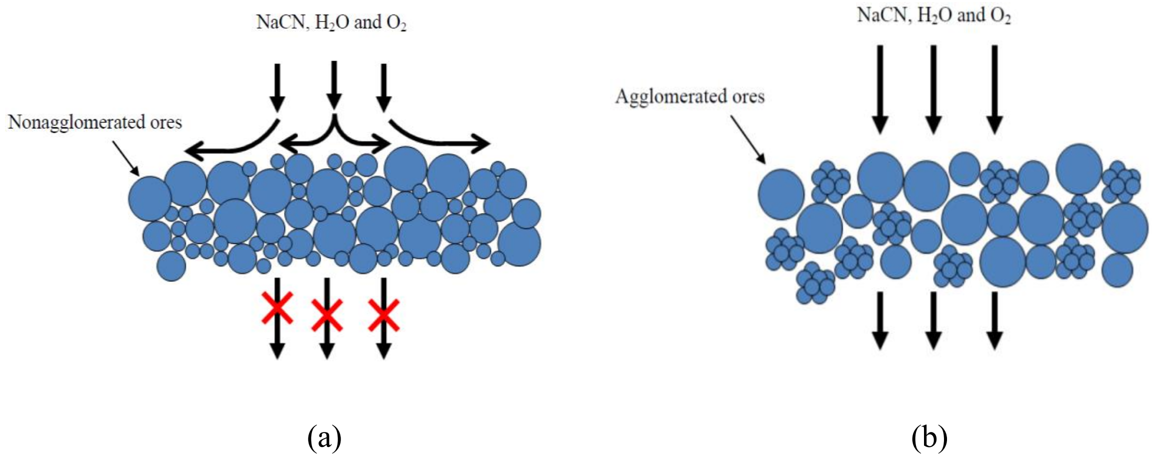

***Figure 1**. Schematic Diagram (a) Illustrating How Fine Particles Exhibit Clay-Like Behavior, Impeding the Uniform Flow of Solution and Gas During Heap Leaching, (b) More Uniform Flow of Solution and Gas in Agglomerated Ore [11].*

Vethosodsakda conducted permeability tests on agglomerated ores, showing increased permeability and reduced leaching times [11]. The results indicated that both particle size and moisture content are key factors in determining permeability. Ores with coarse particles and 6-8% moisture content exhibited high permeability due to the agglomeration process. In this context, Figure 2 illustrates the distribution of ore within the heap, highlighting the difference between actual and desired distribution, with the latter promoting better permeability and solution flow [10].

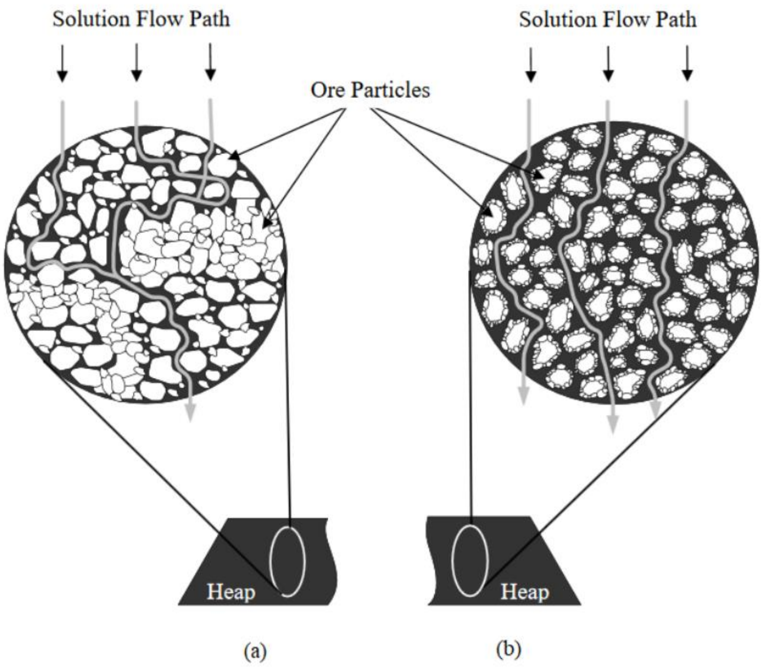

Figure 2. *Distribution of Ore Within the Heap: (a) Actual Distribution, (b) Desired Distribution [10].*

As illustrated in Figure 2, the distribution of ore within the heap can significantly impact permeability. In Figure 2a, fine-grained ore creates an impermeable layer, obstructing the flow of the cyanide solution. However, in Figure 2b, when fine and coarse particles are uniformly distributed, the solution can flow smoothly, thereby increasing gold recovery efficiency [10].

Several factors, including rock type, heap height, and NaCN solution concentration, affect permeability in heap leaching. Excessive fine-grained ores negatively impact permeability due to their clay-like behavior and the formation of channels [12]. Permeability values for materials vary, with fine sands having a permeability of 10^{-5} cm/s, clay-rich soils ranging from 10^{-7} to 10^{-8} cm/s, and sand mixtures and alluvium exhibiting a permeability of 10^{-6} cm/s [13]. Uhrie et al. [14]

noted that increased clay content reduces permeability, with the relationship between clay amount and permeability being inversely proportional.

Finally, as discussed in the Corelab report, changes in water permeability based on clay content and salinity are illustrated in Figure 3 [15]. Kinard and Schweizer [16] also highlighted that heap density is inversely proportional to permeability, with densities ranging from 1.19 to 1.43 t/m³ corresponding to permeabilities from 10^{-4} to 4 x 10^{-7} cm/s.

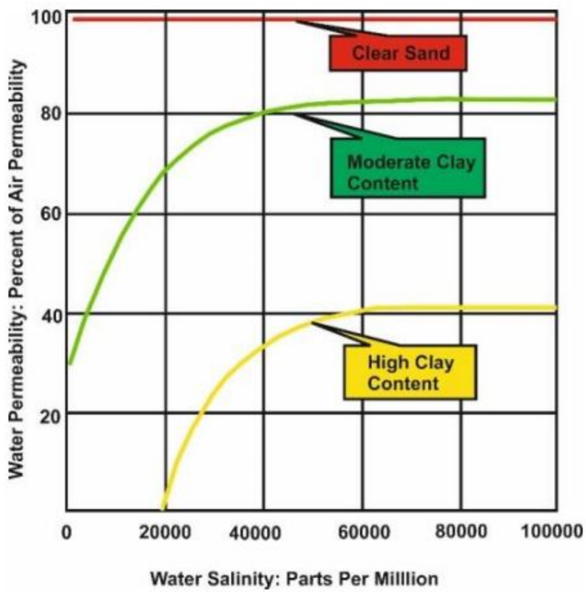

***Figure 3**. Water Permeability Based on Clay Content [15].*

Thus, proper management of particle size, moisture content, and permeability through agglomeration and other pre-treatment processes is essential for optimizing heap leaching and ensuring efficient gold recovery. The aim of this study is to investigate the effects of different ore and limestone mixtures on permeability and gold recovery, focusing on optimizing leaching efficiency through various pre-treatment methods to enhance gold extraction from Uşak Kışladağ Gold Mine ore.

The objective of this study is to evaluate the impact of different ore and limestone mixtures on permeability and gold recovery, aiming to optimize leaching efficiency for Uşak Kışladağ Gold Mine ore. By investigating the permeability variations in crushed ore samples of different sizes and limestone mixtures, the study seeks to determine the most effective combination for enhancing solution flow and gold dissolution. Through permeability and leaching experiments, including bottle-roll tests, the research assesses how particle size distribution and limestone addition influence gold recovery, ultimately providing insights into optimizing heap leaching conditions.

2 MATERIAL AND METHOD

The ore from the Kışladağ Gold Mine was crushed to increase surface area and expose gold. To improve permeability, fine ore was mixed with limestone for uniform cyanide flow, enhancing gold dissolution.

Permeability tests were conducted on gold ore samples of various sizes, followed by experiments on (-2.36+0 mm) ore mixed with limestone at different sizes and ratios. The optimal mix was selected for column leaching, and gold dissolution efficiency and rates were analyzed.

2.1 Size and Chemical Analyses Conducted on the Sample

Initially, size and chemical analyses were conducted on the material sized (-18+0 mm) that is currently being applied to the heap at the Kışladağ Gold Mine, as presented in Tables 1 and 2.

Table 1. *Sieve analysis values of material sized (-18+0 mm) currently applied to the heap at kişladağ gold mine.*

Sample Size (mm)	Weight (%)	Cumulative Passing (%)
-25+18	0.5	100.0
-18+10	12.9	99.5
-10+6.70	8.6	86.6
-6.70+4.75	13.8	78.0
-4.75+2.36	18.5	64.2
-2.36+1.00	19.0	45.7
-1.00+0.50	4.1	26.7
-0.50+0.212	6.7	22.6
-0.212+0.150	1.8	15.9
-0.150	14.1	14.1
Total	**100.0**	

Considering Table 1, it can be observed that nearly all of the samples passed through the 18 mm sieve, with approximately 50% passing through the 2.36 mm sieve.

***Table 2**. Chemical analysis values of material sized (-18+0 mm) currently applied to the heap at kişladağ gold mine.*

Element	Au	Ag	Al	As	Ba	Be	Bi	Ca	Cd	Co	Cr	Cu	Fe	Ga	K	La	Mg
Unit	ppm	ppm	%	ppm	ppm	ppm	ppm	%	ppm	ppm	ppm	ppm	ppm	%	ppm	%	ppm
Amount	1.32	1.90	7.62	172	320	3.90	8.00	0.66	3.80	25.00	121.00	142.00	3.98	20.00	3.71	50.00	1.26

Element	Mn	Mo	Na	Ni	P	Pb	S	Sb	Sc	Sr	Th	Ti	Tl	U	V	W	Zn
Unit	ppm	ppm	%	ppm	ppm	ppm	%	ppm	ppm	ppm	ppm	%	ppm	ppm	ppm	ppm	ppm
Amount	396	104	1.00	35	1090	909	3.70	13	10	604	30	0.24	10	<10	84	10	2000

The chemical analysis of the material brought from the Uşak Kışladağ Gold Mine shows that the gold grade is 1.32 ppm, the silver grade is 1.90 ppm, and the sulfur content is 3.7%. The material was analyzed across different size groups, and the results are presented in Table 3.

***Table 3**. Gold (Au) analysis values by sample size.*

Size (mm)	Amount (%)	Grade (ppm)	Distribution (%)
-25+18	0.5	0.70	0.24
-18+10	12.9	0.80	7.85
-10+6.70	8.6	0.85	5.56
-6.70+4.75	13.8	0.88	9.19
-4.75+2.36	18.5	1.10	15.35
-2.36+1.00	19.0	1.73	24.98
-1.00	26.7	1.81	36.59
Total	**100.0**	**1.32**	**100.0**

Considering Table 3, it can be observed that as the sample size decreases, the Au values increase. This increase in Au values is attributed to the growing surface area, which facilitates the liberation of gold as the size reduces. The most significant increase occurs in the ore size below 2.36 mm, which is why material under 2.36 mm is utilized in heap leaching.

Permeability Tests

Permeability in heap leaching directly affects the contact of the cyanide solution with gold in the ore, thereby increasing gold recovery efficiency.

In heap leaching, fine-sized gold ores can lead to channeling due to clay-like behavior, resulting in low permeability and diminished gold dissolution efficiency. To minimize this low gold dissolution rate, permeability tests were conducted using the "Column Leaching Test Set" method. Before conducting the column leaching tests, permeability experiments were performed on mixtures of the gold ore sized (-2.36+0 mm) with limestone in various sizes and percentage ratios. The results were analyzed to select the most suitable mixture for heap leaching. Initially, a particle size analysis of the selected (-2.36+0 mm) sample for permeability testing was conducted, and the results are presented in Table 4. Permeability tests were conducted using limestone at ratios of 15%, 50%, 100%, 150%, and 200%, while keeping the ore size constant at -2.36+0 mm. Limestone was used in three different size ranges: -18+10 mm, -10+5 mm, and -5+0 mm.

Table 4. *Size distribution of the selected -2.36 mm sized ore for permeability.*

Sample Size (mm)	Weight (%)	Cumulative Undersize Ratio (%)
-2.36+1.70	12.4	100.0
-1.70+1.00	36.5	87.6
-1.00+0.50	22.4	51.1
-0.50+0.30	7.0	28.7
-0.30+0.150	9.0	21.7
-0.150+0.075	5.5	12.7
-0.075+0.045	3.5	7.2
-0.045	3.7	3.7
Total	**100.0**	

As shown in Table 4, approximately 51.1% of the sample distribution, reduced to a size below 2.36 mm, is below the 1.00 mm size.

Permeability tests were conducted in laboratory using the Permeability Test Set, set up according to the "Constant Head Permeability Test" process of Darcy's Law. The permeability tests were performed in accordance with ASTM D2434 (ASTM, 2006) standards. The schematic representation of the Constant Head Permeability Test Set is shown in Figure 4, and an image of the permeability test set available in our laboratory is presented in Figure 5.

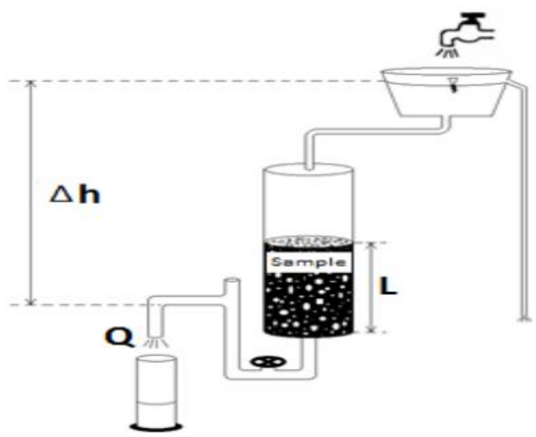

Figure 4. *Schematic representation of the constant head permeability test set [2].*

***Figure 5**. Image of the permeability test set taken during permeability experiments.*

The permeability value is mathematically calculated using the formula (1):

$$K = \frac{Q * L}{A * t * \Delta h} \quad \textbf{(1)}$$

Where:

K: Permeability value (cm/s)

Q: Volume of discharged water (cm^3)

L: Sample height (cm)

A: Sample surface area (cm^2)

t: Discharge time (60 s)

Δh: Distance between the discharge point in the bucket and the discharge point at the bottom of the column (cm).

In all permeability tests conducted in ore preparation laboratory, the ore size was kept constant at (-2.36+0 mm), while the limestone size was varied.

2.2 Bottle Roll Tests

Gold dissolution efficiency tests were conducted on two different sample sizes (-2.36+0 mm and -75+0 μm) using an Atomic Absorption Spectrophotometer

(AAS). The Bottle Roll experiments, shown in Figure 6, involved periodic sampling at 2, 4, 8, 24, and 48 hours to analyze gold dissolution efficiency. The tests were performed on ore from the Uşak Kışladağ Gold Mine, and dissolution values were calculated using AAS to evaluate the effectiveness of the process.

Figure 6. *Image of the "bottle-roll" experiment setup.*

To determine gold dissolution efficiency, the following materials were used in the "Bottle-Roll" experiment conducted in our laboratory with 2.5-liter bottles:

- **Sample Amount**: 500 g
- **Water Volume**: 1 L
- **pH Adjustment and Value**: Adjusted with lime powder/$Ca(OH)_2$ to 10.5
- **NaCN Amount**: 1 g

2.3 Column Leaching" Experiments Conducted in Columns

The gold ore was thoroughly mixed with limestone sized (-10+5 mm). To create a basic environment (pH=10.5), hydrated lime was added to the sample and mixed well. Approximately 10% water was added to ensure proper agglomeration of the sample and limestone. The prepared sample was placed into the column leaching set available in our laboratory. A sodium cyanide (NaCN) solution was prepared at a concentration of 1 g/L, totaling 5 liters. After 24 hours, a loaded solution (gold solution) formed at the bottom of the columns, which was then transferred to activated carbon. The resulting barren solution was recycled back into the system, creating a closed-loop for the column leaching experiments. Samples were taken from both the loaded and barren solutions over a month (30 days) to calculate gold values. Initially, activated carbon was loaded at the start of the experiment, with a second loading performed on the 10th day. Samples from the activated carbon were collected at the end of the 10th and 30th days, dried, and prepared for analysis to determine the amount of gold absorbed by the activated carbon. In the column leaching experiments, the initial focus was on ores sized (-18+0 mm) and (-2.36+0 mm) (Figure 7).

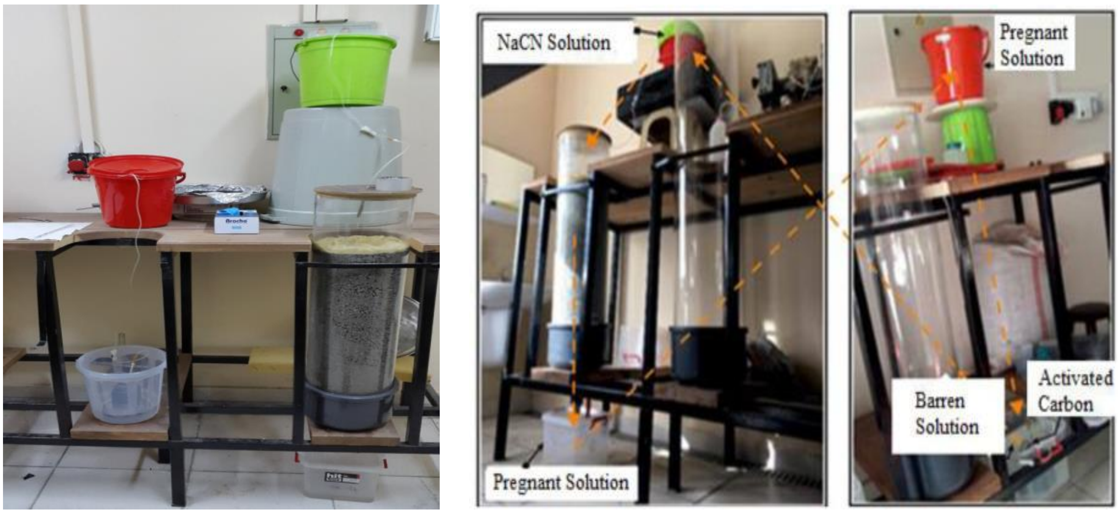

Figure 7. *Image of the Pilot-Scale "Column Leaching Set.".*

2.4 Column Leaching Experiments with Limestone Mixture

In the experiments conducted, the gold particles within the ore brought from the Uşak Kışladağ Gold Mine were liberated after the ore was crushed to a size of -2.36+0 mm. The ore was then mixed with limestone in two different ratios: 1:1 and 1.5:1. Additionally, limestone sized -10+5 mm was used in the experiments due to its better mixing properties. In the column leaching experiment using the 1:1 limestone mixture, the -2.36+0 mm ore was homogeneously mixed with -10+5 mm limestone and approximately 10% water. The mixture was then fed into the columns for the experiments.

3 RESULTS AND DISCUSSION

In this section, permeability tests, bottle roll experiments, and column leaching experiments are addressed separately, with results discussed alongside corresponding figures are provided accordingly. Trends and cause-and-effect relationships are explicitly identified, such as the impact of particle size on permeability and gold dissolution efficiency. Additionally, key findings are summarized at the end of each subsection as in the following.

3.1 Permeability Tests

The permeability test conducted on the ore with a size of (-2.36+0 mm) without the addition of limestone resulted in a permeability value of 0.62×10^{-3} cm/s, while the permeability value for the ore with a size of (-18+0 mm) was determined to be 1.28×10^{-3} cm/s.

Permeability tests were conducted using limestone at 15%, 50%, 100%, 150%, and 200% ratios. The resulting values from these experiments are presented in the graphs between Figure 8 and Figure 12.

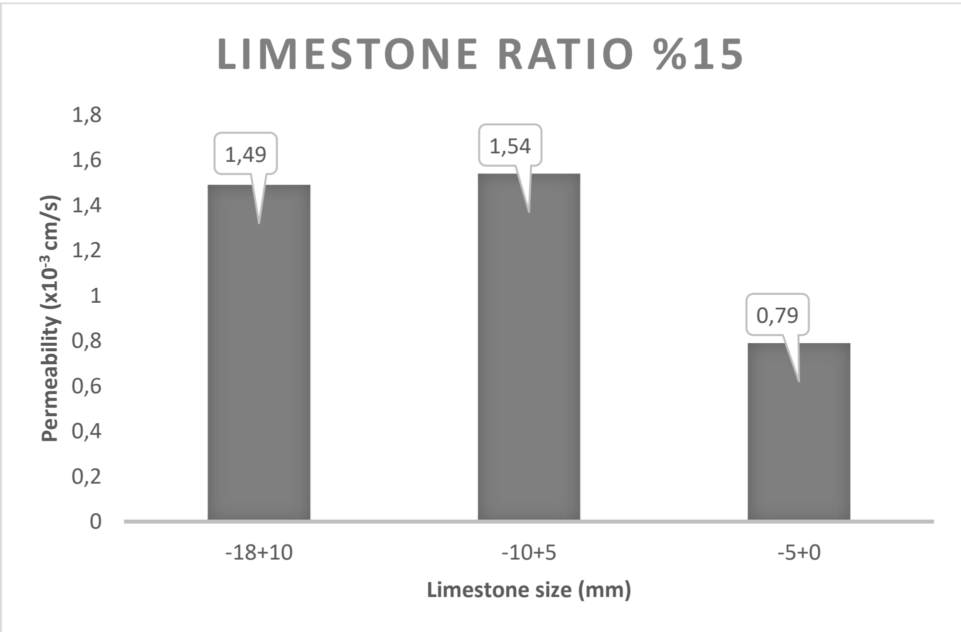

***Figure 8**. The effect of permeability with the mixture of limestone of different sizes at a 15% ratio.*

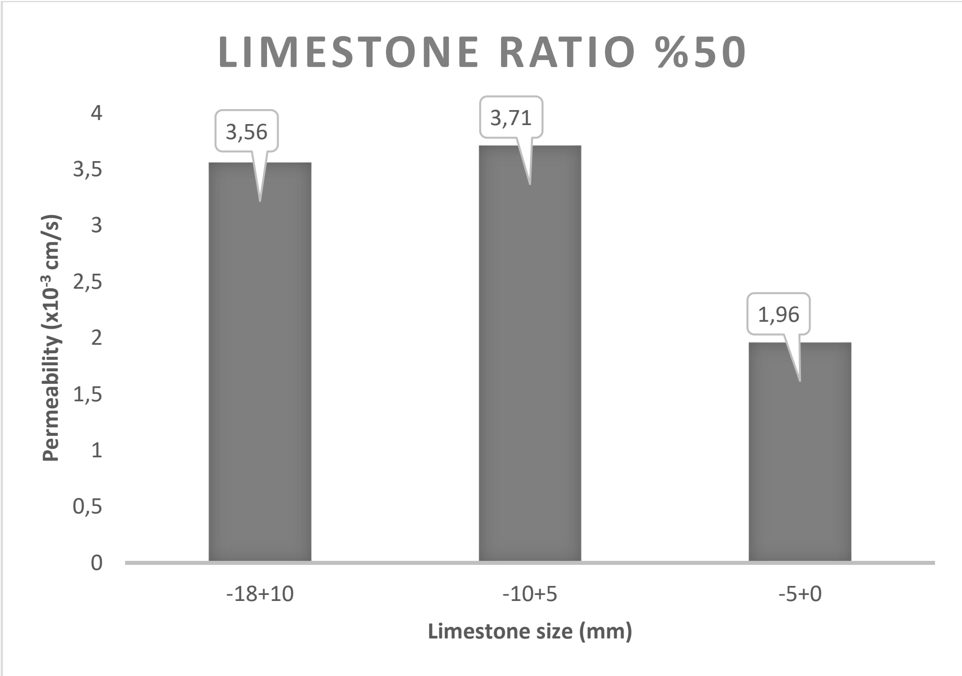

Figure 9. *The effect of permeability with the mixture of limestone of different sizes at a 50% ratio.*

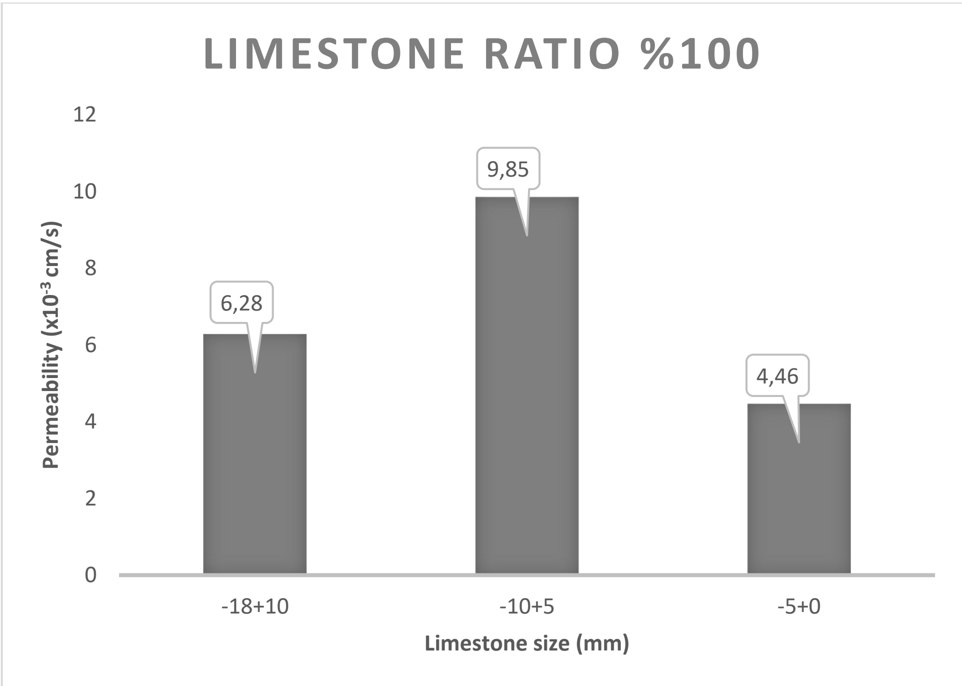

Figure 10. *The effect of permeability with the mixture of limestone of different sizes at a 100% ratio.*

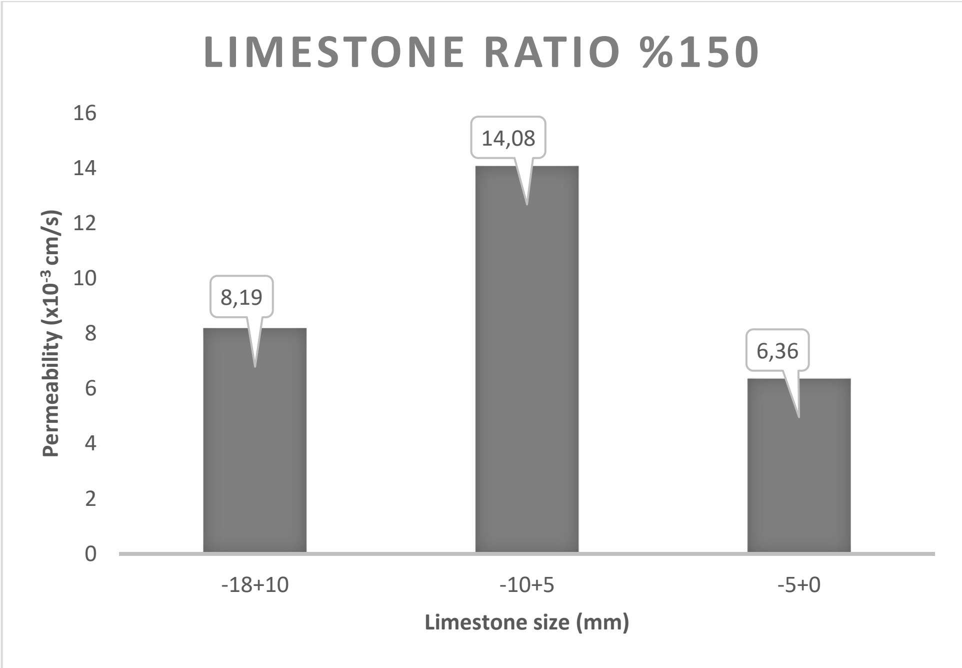

***Figure 11**. The effect of permeability with the mixture of limestone of different sizes at a 150% ratio.*

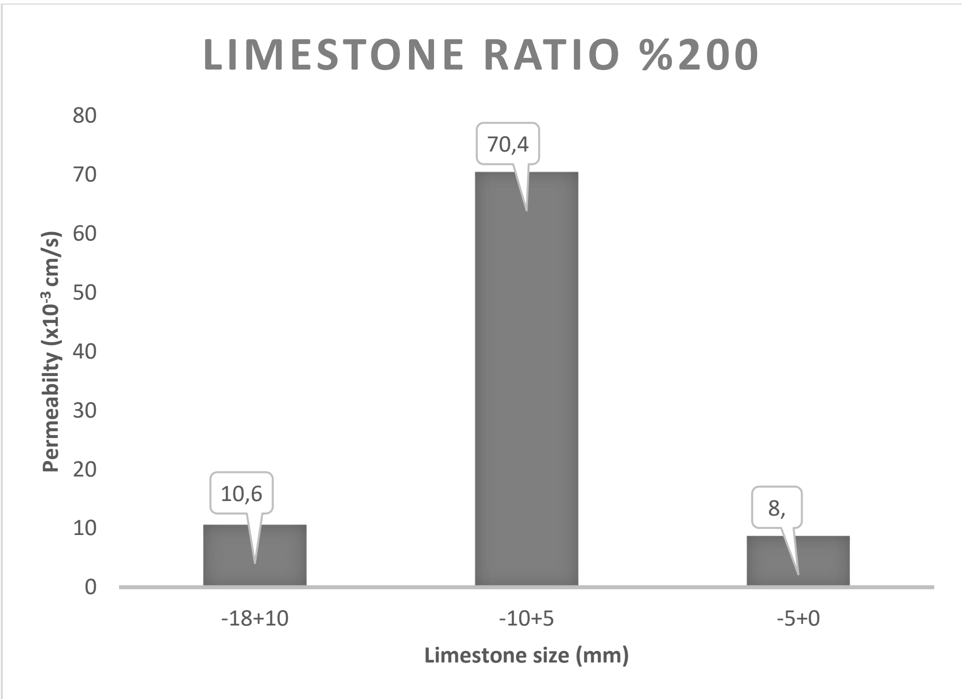

***Figure 12**. The effect of permeability with the mixture of limestone of different sizes at a 200% ratio.*

As a result of the permeability tests conducted with the sample and limestone mixture:

- It was observed that as the limestone particle size decreased, permeability also decreased; even the dust generated from smaller limestone particles adversely affected permeability.
- An increase in limestone particle size led to an increase in permeability; however, excessively large particles did not yield efficient results in permeability tests due to disaggregation.
- An increase in the percentage of limestone in the mixture resulted in higher permeability test results, while a decrease in the percentage led to reduced permeability.
- Among the permeability tests conducted with different limestone sizes, the best results were observed with the mixture of the sample and limestone of size (-10+5 mm).

The limestone of size -10+5 mm, which demonstrates a better mixing structure with the sample, is of significant importance to our study because it yields better results in permeability tests compared to the limestones of sizes -18+10 mm and -5+0 mm.

3.2 Bottle Roll Experiments Results

In this study, Bottle-Roll experiments were performed on two different gold ore sizes: (-2.36+0 mm) and (-75+0 μm) to evaluate gold dissolution efficiency. The results obtained from these experiments provide insights into the leaching behavior of different particle sizes. The dissolution trends and efficiency values for both ore sizes are illustrated in Figure 13 and Figure 14, where Figure 13 presents the dissolution behavior of the -2.36+0 mm sample, while Figure 14 displays the results for the -75+0 μm sample. These figures highlight the impact of particle size on the dissolution process and provide a comparative analysis of the leaching performance under the experimental conditions.

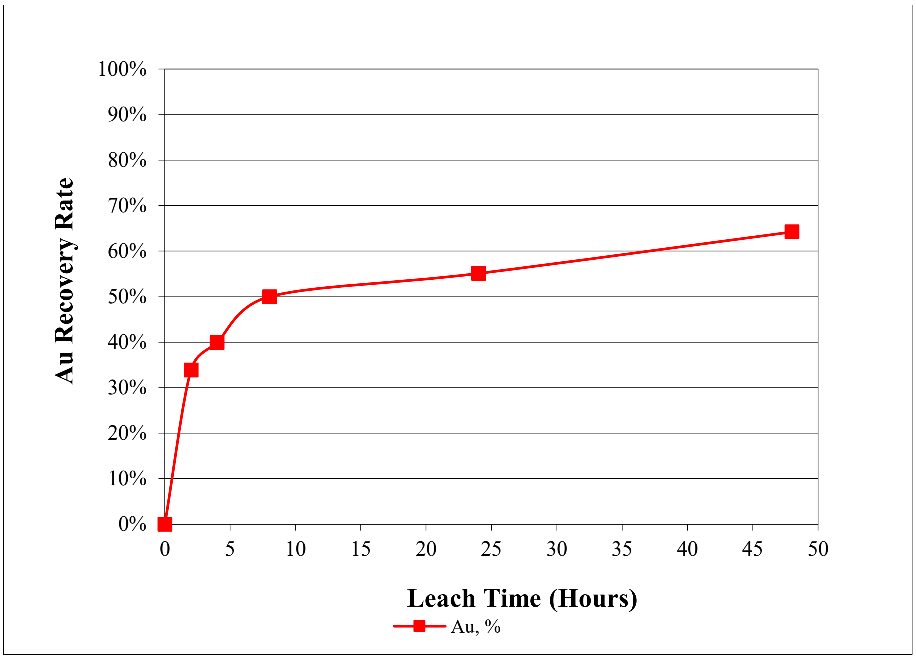

Figure 13. *Graph of the "Bottle-Roll" experiment conducted with the sample of size -2.36+0 mm.*

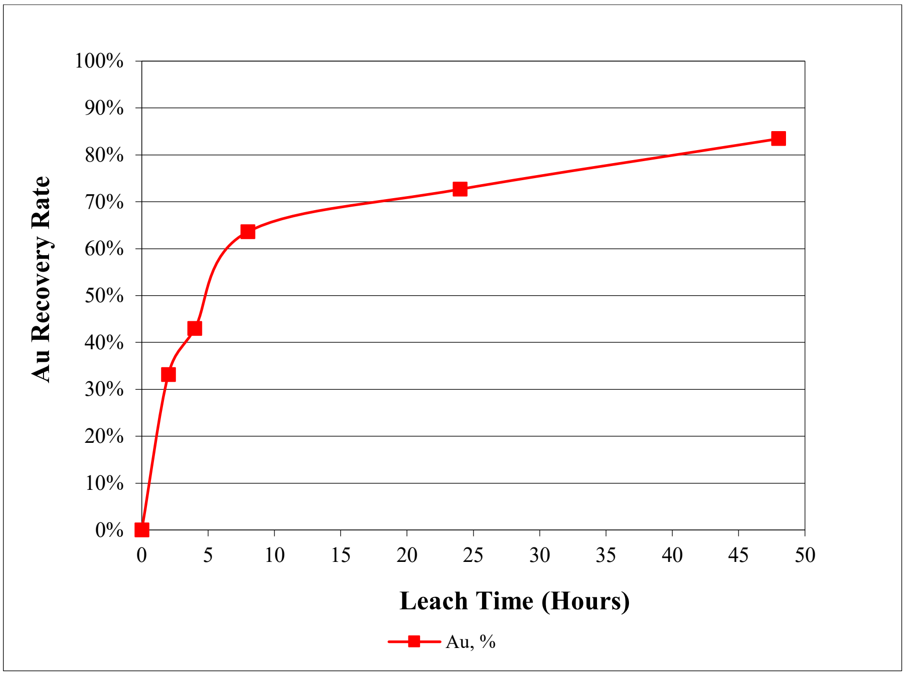

Figure 14. *Graph of the "Bottle-Roll" experiment conducted with the sample of size -75+0 μm.*

The results of the conducted experiments are as follows:

- The gold recovery rate for the (-2.36+0 mm) gold ore was found to be: 64%
- The gold recovery rate for the (-75+0 μm) gold ore was determined to be: 83%

From the analysis of these results, it was observed that as the size of the ore increases, the gold recovery rate decreases. Conversely, a decrease in ore size leads to an increase in gold recovery efficiency. This is because the finer the gold ore is subjected to crushing or grinding, the more gold particles become liberated, allowing for better contact with the cyanide solution and subsequently improving dissolution.

3.3 Column Leaching Experiments

In column leaching experiments, the ores with sizes (-18+0 mm) and (-2.36+0 mm) were initially used. The Au dissolution yield was determined over a period of 30 days. After another 30-day leaching period, the Au recovery efficiency was calculated. The Au dissolution rate as a function of leaching time for the ore sized -18+0 mm is presented graphically in Figure 15.

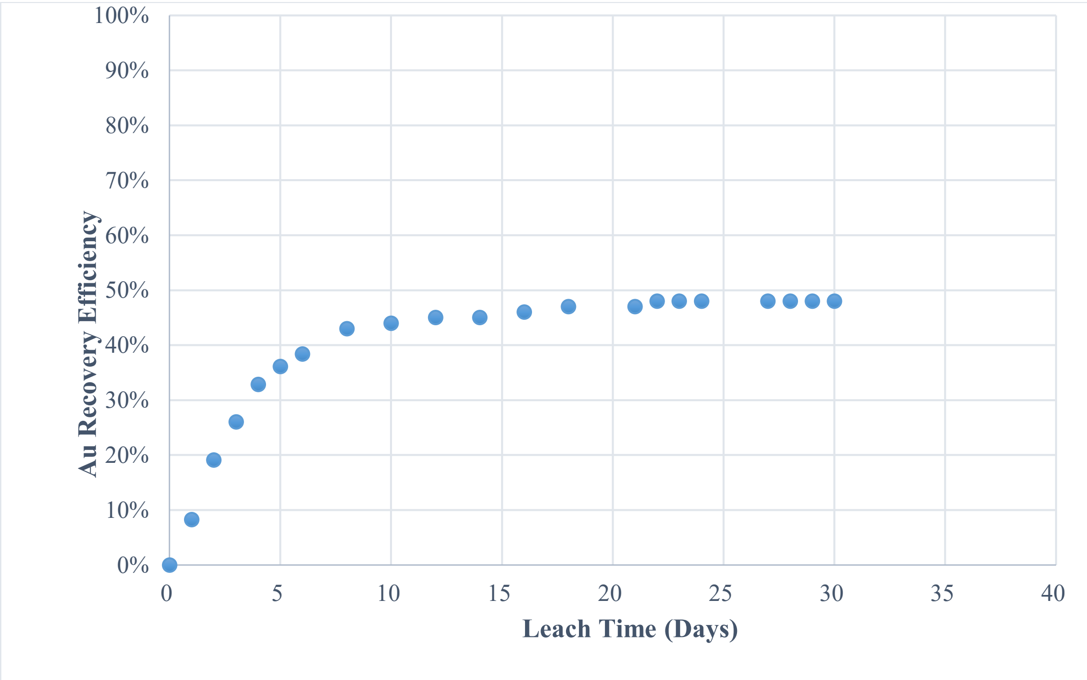

***Figure 15**. Graph of Au Recovery Efficiency Based on Leaching Time for (-18+0 mm) Gold Ore.*

At the Uşak Kışladağ Gold Mine, after a leaching period of 30 days for the ore sized (-18+0 mm):

- The gold recovery efficiency (Au dissolution rate) was determined to be 48%.

Subsequently, to enhance particle liberation, the ore was crushed to a size of -2.36+0 mm, and a second column leaching experiment was conducted. The Au dissolution yield was calculated at the end of the 30-day leaching period. The Au dissolution yield of the ore with a size of -2.36+0 mm as a function of leaching time is presented in the graph in Figure 16.

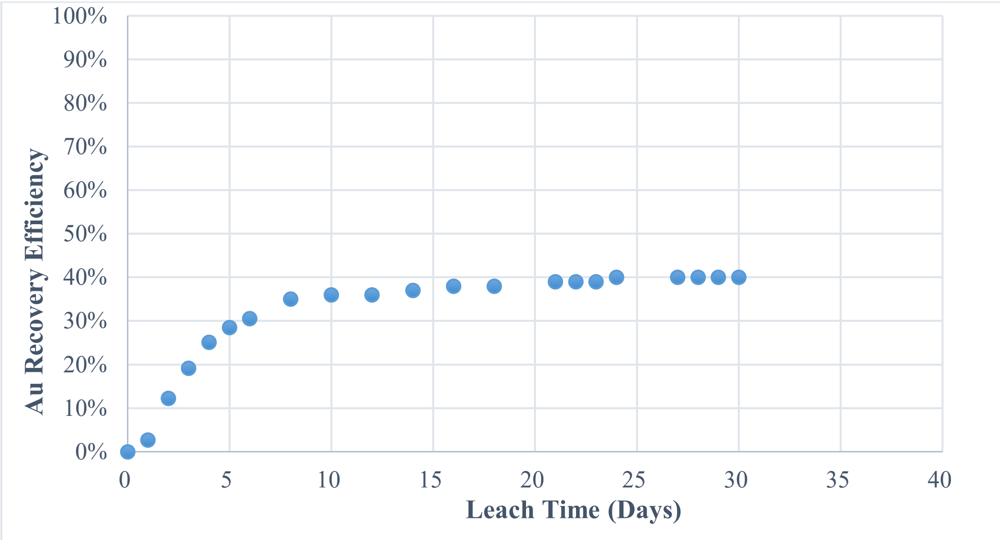

Figure 16*. Graph of Au dissolution efficiency as a function of leaching time for ore sized -2.36+0 mm.*

At the Uşak Kışladağ Gold Mine, the Au dissolution yield of the ore fed to the heap with a size of -2.36+0 mm was determined to be 42% after a 30-day leaching period.

Based on the graphs in Figures 15 and 16, it can be observed that the Au dissolution efficiency for ore sized -2.36+0 mm has decreased compared to that of -18+0 mm ore. This decline is attributed to the increased presence of fine particles within the ore, which leads to reduced permeability and Au dissolution efficiency. Consequently, the solution fails to effectively contact the gold particles within the ore.

To enhance both permeability and Au dissolution efficiency for the -2.36+0 mm ore, subsequent column leaching experiments were conducted using mixtures with limestone. This approach allowed for a thorough investigation of the effects on Au dissolution.

3.4 Column Leaching Experiments with Limestone Mixtures

In this study, experiments were conducted using ore from the Uşak Kışladağ Gold Mine, where the gold particles within the ore were released by crushing the ore to a size of -2.36+0 mm. The crushed ore was mixed with limestone in two different ratios: 1:1 and 1.5:1. The -10+5 mm sized limestone was utilized in the experiments due to its better mixing properties with the ore.

In the column leaching experiment conducted with the 1:1 limestone mixture, the -2.36+0 mm sized ore was homogeneously mixed with 10% moisture and -10+5 mm sized limestone. This mixture was then fed into the columns for the leaching process. The experiment was conducted in a closed-loop system over a period of 30 days. The results regarding the leaching duration and gold dissolution efficiency are illustrated in Figure 17.

This approach aimed to optimize gold recovery through effective mixing and interaction of the cyanide solution with the ore particles.

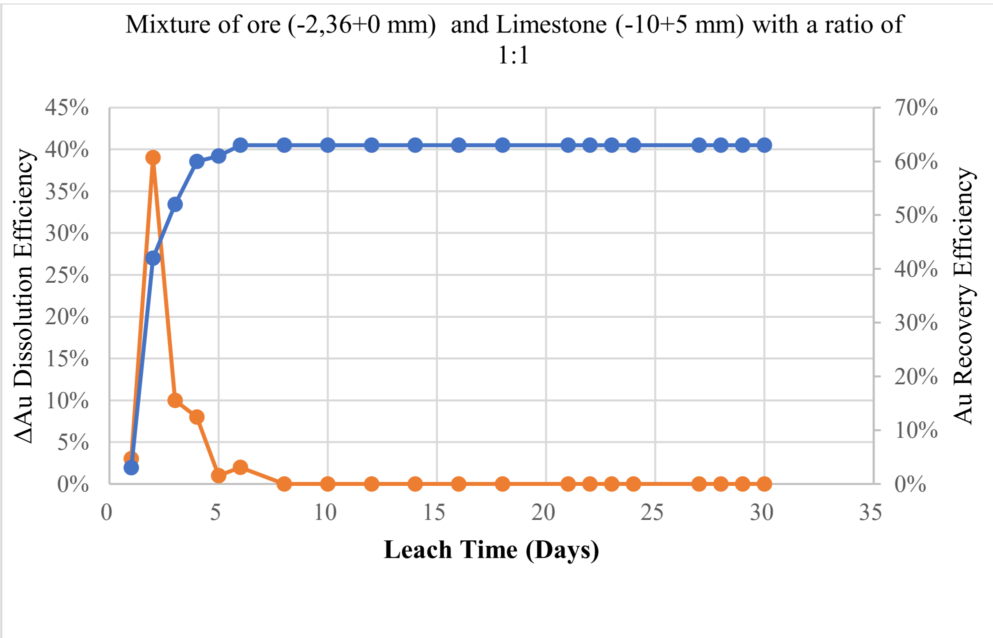

Figure 17*. Au dissolution graph of the sample sized -2.36+0 mm subjected to leaching over time with a limestone mixture in a ratio of 1:1.*

In Figure 17, after a leaching period of 30 days with a limestone mixture in a ratio of 1:1, the Au dissolution efficiency of the sample sized -2.36+0 mm was determined to be 63%. Subsequently, the results of the column leaching experiment conducted with a limestone mixture in a ratio of 1.5:1 are presented graphically in Figure 18.

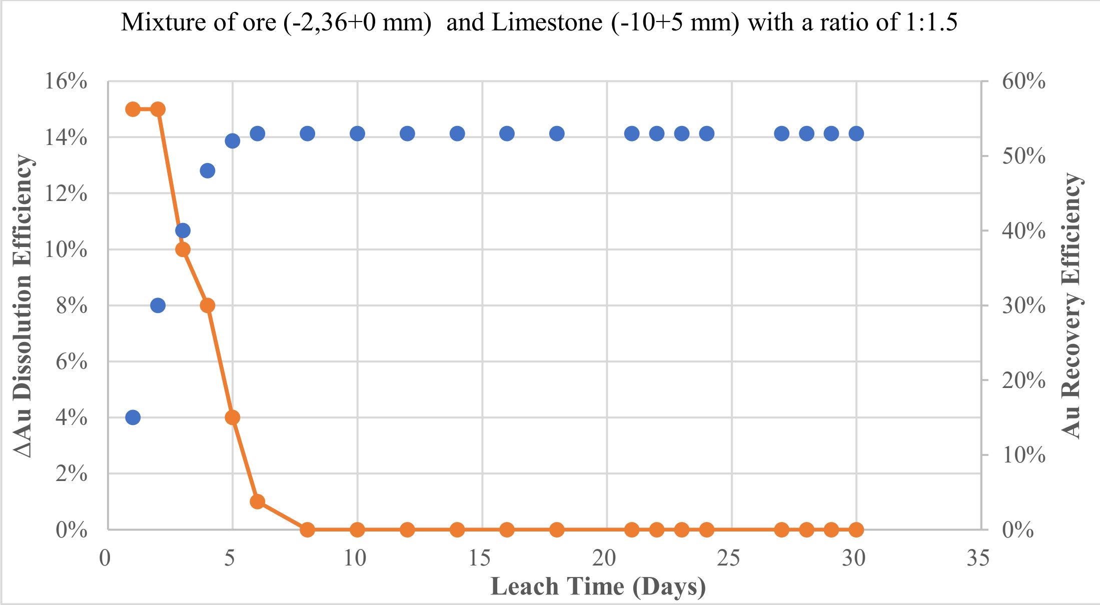

Figure 18. *Au dissolution graph of the sample sized -2.36+0 mm, conducted with a limestone mixture in a ratio of 1.5:1.*

At the end of the 30-day leaching period for the sample with a size of -2.36+0 mm mixed with limestone in a 1.5:1 ratio, the following results were observed:

- The Au dissolution efficiency was determined to be 53%.

The leaching experiments conducted with the -2.36+0 mm sample combined with limestone ores in ratios of 1:1 and 1.5:1 showed Au dissolution efficiencies of 63% and 53%, respectively. Although the leaching experiments with the -2.36+0 mm sample mixed with limestone in a 1.5:1 ratio positively affected permeability, it was noted that the dissolution efficiency of Au decreased compared to the 1:1 limestone mixture. This decrease can be attributed to the complete permeability of the medium and the leaching solution's insufficient contact with the gold particles within the ore.

3.5 Investigation of the Rate of Gold Dissolution by Cyanide Solution in the Ore

The variations in the dissolution rate of gold particles within the ore by sodium cyanide solution, based on the leaching duration, have been analyzed. The gold dissolution rate (Au dissolution rate) and gold dissolution efficiency (Au dissolution efficiency) are presented in graphical form between Figures 19-21.

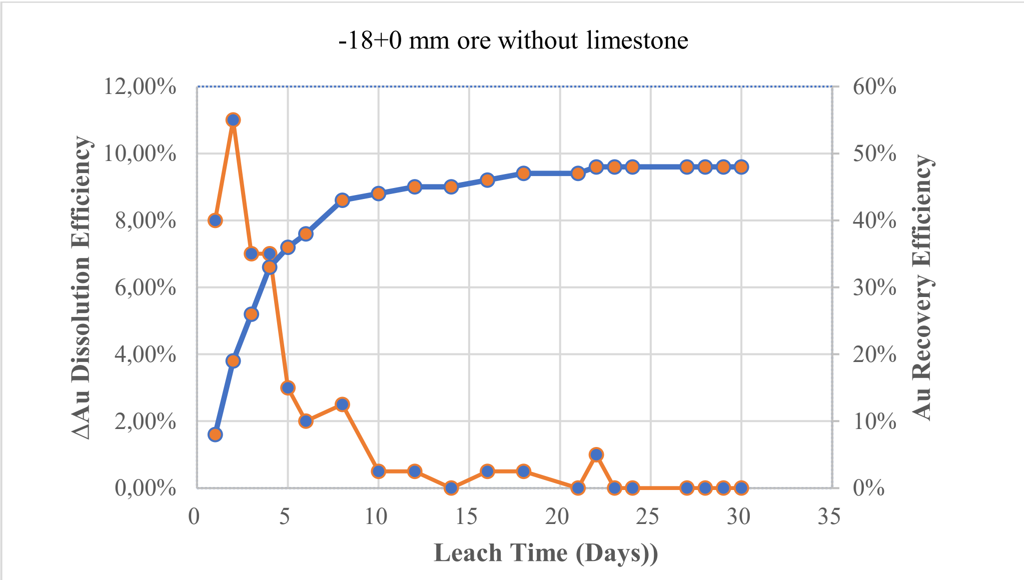

***Figure 19**. Au dissolution rate graph based on the leaching duration for the sample with a particle size of -18+0 mm.*

According to Figure 27, when examining the Au dissolution rate based on the leaching duration for the -18+0 mm sized sample from the Uşak Kışladağ Gold Mine:

- The Au dissolution rate on the first day was 8%,
- On the second day, the Au dissolution rate increased to 11% compared to the first day,
- The dissolution rates on subsequent days showed a decline.

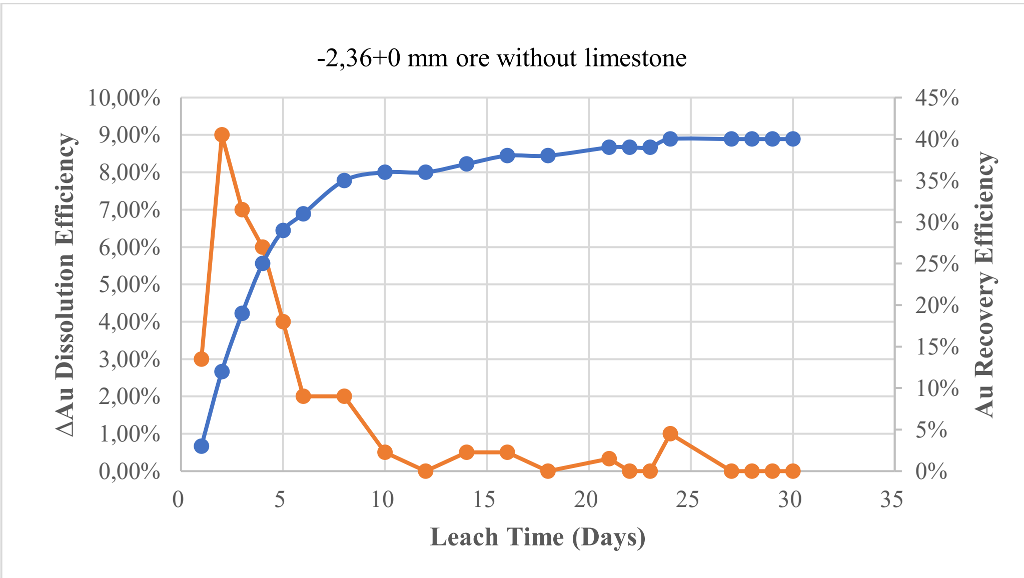

***Figure 20**. Au dissolution rate over time for the -2.36+0 mm sized sample.*

When examining the Au dissolution rate for the sample crushed to -2.36+0 mm without mixing limestone during the leaching process:

- The Au dissolution rate on the first day was 3%.
- By the second day, the Au dissolution rate increased to 9%.
- In the subsequent days, the Au dissolution rates decreased.

This reduction in both Au dissolution rate and Au recovery can be attributed to a decrease in permeability.

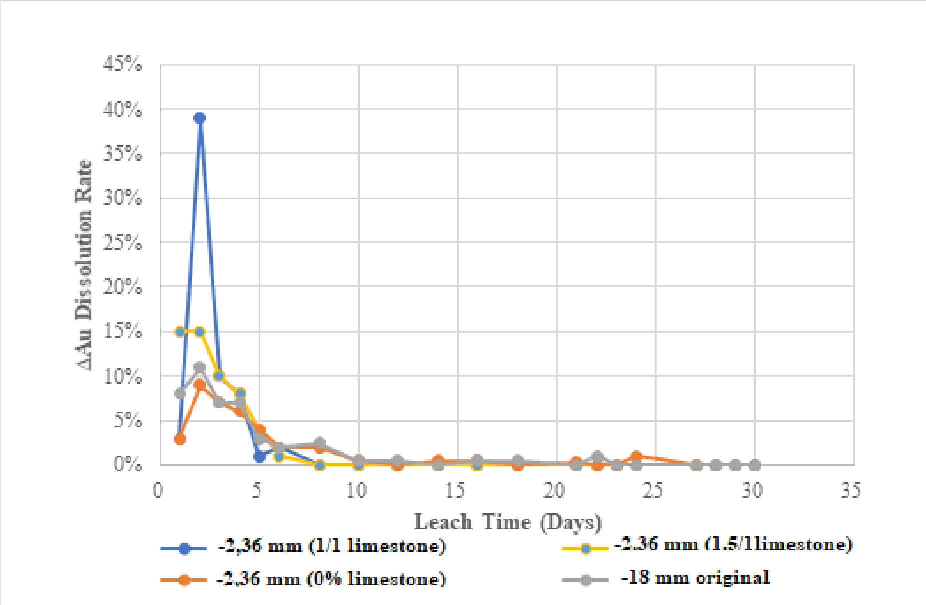

Figure 21. *Graph of the changes in gold dissolution rate by the cyanide solution throughout the leaching duration.*

When examining the graphs in Figure 21:

- The highest Au dissolution (recovery) rate on the first day occurred with the -2.36+0 mm sized ore mixed with limestone at a 1:1.5 ratio.
- On the second day, the highest Au dissolution rate was observed with the -2.36+0 mm sized ore mixed with limestone at a 1:1 ratio.
- The lowest Au dissolution rate was found in the -2.36+0 mm sized ore without any limestone, which is attributed to low permeability.
- Among the experiments, the best gold dissolution rate and overall recovery were achieved with the -2.36+0 mm sized ore mixed with limestone at a 1:1 ratio.

The findings indicate several cause-and-effect relationships influencing gold recovery efficiency. A decrease in ore size increases surface area, leading to greater gold liberation and a higher gold grade in finer particles. The addition of limestone improves permeability, enhancing cyanide solution penetration and gold recovery; however, excessively fine limestone particles can reduce permeability due to their clay-like behavior. Crushing the ore to finer sizes (-75+0 µm) significantly increases gold dissolution efficiency (83% compared to 64%), demonstrating the impact of ore fineness on recovery. Additionally, mixing the ore with limestone at specific ratios (1:1 or 1.5:1) enhances permeability, leading to improved gold dissolution efficiency (from 42% to 63%). These results highlight how modifications in ore size, permeability, and limestone composition directly affect the efficiency of gold extraction.

4 CONCLUSION

This study focused on the investigation of gold recovery efficiency and permeability in ores obtained from the Uşak Kışladağ Gold Mine. The -18+0 mm sized ore was crushed to below 2.36 mm and mixed with locally abundant alkaline limestone to enhance particle liberation. The results indicated that the size of the limestone significantly influenced the permeability; specifically, as the limestone size decreased, permeability diminished due to the formation of dust, whereas increasing the limestone size enhanced permeability. However, excessively large limestone particles also led to suboptimal results due to segregation.

The study-utilized bottle roll tests to evaluate the gold dissolution efficiency, which yielded a recovery rate of 64% for -2.36+0 mm samples and 83% for -75+0 µm samples. In column leaching experiments without any mixtures, the gold recovery rates were found to be 48% for -18+0 mm samples and 40% for -2.36+0 mm samples, demonstrating that increasing particle size enhances permeability and consequently improves gold recovery efficiency. Conversely, smaller particle sizes led to a reduction in permeability and gold recovery due to the clay-like behavior of fine particles.

Subsequent experiments involving a mixture of -2.36+0 mm ore and -10+5 mm limestone in ratios of 1:1 and 1.5:1 resulted in gold recovery rates of 63% and

53%, respectively. The 1.5:1 mixture, although beneficial for permeability, did not allow the cyanide solution to contact the gold particles as effectively as the 1:1 mixture, indicating that optimal conditions for gold recovery depend on achieving a balance between particle size and solution permeability.

Throughout all experiments, the homogeneous flow of sodium cyanide solution was maintained, effectively mitigating the negative impact of fine particle presence on permeability. This approach enhanced particle liberation, ultimately leading to high gold recovery efficiency. The findings underscore the importance of optimizing ore preparation techniques to improve the overall efficacy of gold extraction processes.

Conflict of Interest

There is no conflict of interest between the authors.

Authors Contributions

Aminullah Rashidi: Investigation, Methodology, Formal Analysis, Data Curation, Writing – Original Draft.

Serdar Yılmaz: Conceptualization, Supervision, Methodology, Writing, Review & Editing, Validation, Project Administration.

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Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

Artificial Intelligence (AI) Contribution Statement

This manuscript was entirely written, edited, analyzed, and prepared without the assistance of any artificial intelligence (AI) tools. All content, including text, data analysis, and figures, was solely generated by the authors.

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