separations

Article

Technology for Aiding the Cyanide Leaching of Gold Ores

Jiahong Han [1,2,3,4], Shujuan Dai [3,*], Jiushuai Deng [1,*], Shandong Que [5] and Yugao Zhou [6]

1 School of Chemical & Environmental Engineering, China University of Mining and Technology (Beijing), Beijing 100083, China; hjh@cync.edu.cn
2 Department of Scientific and Technology, Chaoyang Normal University, Chaoyang 122000, China
3 School of Mining Engineering, University of Science and Technology Liaoning, Anshan 114051, China
4 Postdoctoral Research Station, Guangxi Huatin Group Co., Ltd., Liuzhou 545200, China
5 Guangxi Senhe High Technology Co., Ltd., Nanning 530022, China; queshandong888@163.com
6 Guangxi Nandan Nanfang Metal Co., Ltd., Hechi 547299, China; ygaozhou@163.com
* Correspondence: dsj@ustl.edu.cn (S.D.); jsdeng@cumtb.edu.cn (J.D.); Tel.: +86-15149937449 (S.D.); +86-18811172965 (J.D.)

Abstract: Cyanide leaching technology was studied for low-grade oxidized gold ores in Guangxi Province. The gold grade of the raw ores was 1.32 g/t. The gold leaching rate was 90.91% under the optimal conditions for the following conventional leaching process: using steel forging as the grinding medium, a grinding fineness of −0.074 mm accounting for 92.53%, a stirring speed of 1500 r/min, a pulp leaching concentration of 28.57%, a pH value of 10.5, a temperature of 25 °C, a leaching time of 24 h, and a potassium cyanide consumption of 4 kg/t. A new type of mixed aid-leaching agent (0.6 kg/t) was used, with a dosage of potassium cyanide of 2 kg/t. All else being equal, the gold leaching rate increased by 2.17% to 93.20% after 18 h of aid leaching compared to that of conventional leaching for 28 h. Meanwhile, the amount of potassium cyanide used was reduced by 50%. The aid-leaching agents restored the surface activity of passivated gold particles and depressed the adsorption of gold and its complexes by gangue minerals. This approach could shorten the leaching time and increase the gold leaching rate.

Keywords: gold ores; leaching behavior; cyanidation; adsorption; separations

Citation: Han, J.; Dai, S.; Deng, J.; Que, S.; Zhou, Y. Technology for Aiding the Cyanide Leaching of Gold Ores. *Separations* **2024**, *11*, 228. https://doi.org/10.3390/separations11080228

Academic Editors: Guoquan Zhang and Ki Hyun Kim

Received: 29 May 2024
Revised: 17 July 2024
Accepted: 22 July 2024
Published: 26 July 2024

1. Introduction

Gold has good corrosion resistance, heat resistance, and ductility. The demand for gold has gradually increased with the progress of science and technology [1]. Cyanide leaching in gold technology occupies an important position in gold extraction, having the advantages of low production costs, high stability, and good adaptability to ores [2]. Cyanide leaching of gold has been a concern for researchers [3]. Cyanide leaching is a chemical reaction in an aqueous cyanide solution under aerobic conditions. Elsner [4] thought that the reaction process is a one-step reaction (Equation (1)); however, Bodländer [5] and Kameda [6] believed that it involves a two-step reaction (Equations (2) and (3)). At present, the presence of hydrogen peroxide in the cyanide leaching of gold has been proven. A small amount of hydrogen peroxide can accelerate the leaching efficiency of gold [7].

Many factors affect the cyanidation leaching of gold, including cyanide concentration, oxygen concentration, pH value, temperature, pressure, size and shape of gold in ores, grinding fineness, ore pulp concentration, slime content, stirring strength, films formed on the surface of gold particles, cyanidation leaching time, and associated minerals [8]. The cyanide concentration and oxygen concentration are mutually restricted in gold cyanide leaching. The mechanical and chemical losses of cyanide should be increased in the production process. The cyanides used in cyanidation leaching are mainly KCN or NaCN. When the pH value of the solution is acidic or neutral, cyanide decomposes according to Equation (4) to produce the highly toxic gas HCN, which pollutes the environment [9]. NaOH, KOH, $Ca(OH)_2$, or CaO should be added to the cyanide solution as a "protective base" to avoid the production of HCN. When CaO or $Ca(OH)_2$ is used as a "protective base", hydrogen peroxide is generated during the cyanidation reactions (Equation (5)). The CaO_2 films generated on the surface of gold particles hinder the dissolution of gold.

$$4Au + 8CN^- + O_2 + 2H_2O = 4[Au(CN)_2]^- + 4OH^- \quad (1)$$

$$2Au + 4NaCN + 2H_2O + O_2 = 2NaAu(CN)_2 + H_2O_2 + 2NaOH \quad (2)$$

$$2Au + 4NaCN + H_2O_2 = 2NaAu(CN)_2 + 2NaOH \quad (3)$$

$$CN^- + H_2O = OH^- + HCN\uparrow \quad (4)$$

$$Ca(OH)_2 + H_2O_2 = CaO_2 + 2H_2O \quad (5)$$

High temperatures reduce the dissolved oxygen content in the system as well as the gold reaction speed. When ores are treated with the same gold content and the gold particles are of different sizes, the larger the gold particle size, the lower the leaching efficiency. Therefore, pre-separating coarse gold particles before cyanidation can significantly shorten the cyanidation leaching time and improve the gold leaching rate.

Gold often appears in microscopic/submicroscopic form or as lattice gold in fine-grained gold ores, which can form a solid solution with sulfide. It is wrapped by pyrite, arsenic pyrite, chalcopyrite, and other sulfide minerals, or by quartz, carbonate and silicate gangue minerals. Gold ores need to be oxidized in advance, or aid-leaching agents are added to destroy the inclusions before cyanide leaching. The effect of gold leaching time on the leaching efficiency is determined by the change in the gold particle area covered by passivation films. A reasonable cyanide-leaching time should be selected according to the technological process and economic benefits to achieve the optimal cyanide leaching efficiency and leaching rate. Increased stirring intensity is beneficial for breaking the saturated solution layer on the gold surface and strengthening the diffusion of the leaching agent in the leaching system. The diffusion rate increases with the stirring speed. Ore pulp viscosity depends on slime content and pulp concentration.

A higher ore pulp viscosity leads to a smaller contact area and a lower diffusion coefficient and diffusion speed for CN^- and O_2 molecules. It reduces the gold dissolving speed [10]. Minerals containing iron [11], copper [12], silver [13], lead [14], arsenic [15], antimony [16], mercury [17], sulfur [18], carbon [19], and silicon [20] have different effects on the cyanidation leaching of gold within the cyanidation leaching system of gold ores, which changes the cyanidation leaching environment [21]. Different leaching conditions and different aid-leaching agents have been investigated to enhance the cyanidation leaching process for gold ores with different ore properties [22]. Yang et al. [23] performed alkali preprocessing and conventional leaching. The aid-leaching agents enhance leaching on a high-arsenic gold concentrate based on mineralogy research. The enhanced leaching of heavy metal salts can improve the gold leaching rate and accelerate the process, with obvious enhancements. Oraby et al. [24] accelerated the leaching efficiency of Au, Ag, and Cu by using glycine co-cyanidation leaching for copper-gold ores. The formation of glycine complexes inhibits the decomposition of cyanide under weak acids. Eksteen et al. [25] used amino acids and hydrogen peroxide to improve the leaching efficiency of gold under alkaline conditions for low-grade gold ores. Raphulu et al. [26] used titanium dioxide as a catalyst to improve the activity of oxygen as well as the interaction between cyanide ions and gold. Guzman et al. [27] used potassium persulfate as an oxidizer under alkaline conditions. Thallium ions were added to improve the gold-dissolving speed.

Cyanidation leaching was tested on low-grade gold ores in Guangxi Province to reduce the influence of gangue minerals containing silicon on the cyanide leaching of gold. This work investigated the effects of grinding time, grinding fineness, cyanide dosage, pH, temperature, stirring speed, and leaching time on gold leaching. The gold leaching rate was calculated by measuring the change in gold concentration in the leaching solution and the gold content in the leaching residue before and after leaching. The leaching efficiency and rate of gold were increased to reduce the interaction between silicon-containing minerals and gold. Additionally, new aid-leaching agents were studied.

2. Materials and Methods

2.1. Materials

The mill used in the test was an XMQ-φ240 × 90, with a filling rate of 35.83%. Steel forgings with diameters of 3 cm, 2.5 cm, and 2 cm were used as the grinding media. The specific parameters are shown in Table 1.

Table 1. Mill-specific parameters.

Name	Conical Ball Mill
Model	XMQ Φ-240 × 90
Feeding size/mm	≤3
Discharge/mesh	200
Reference grinding capacity/kg	≤1
Cylinder volume/L	6.25
Motor power/kW	0.55

Oxidized gold ores were extracted from Guangxi Province. Leaching test samples, spectral analysis samples, and chemical multiple analysis samples were obtained through a series of operations, including crushing, screening, agitation, and division. The chemical composition and content of the raw ores were determined using X-ray fluorescence spectrometry (XRF) and chemical multi-element analysis. X-ray diffraction (XRD) was used to analyze the mineral composition of samples (Figure 1).

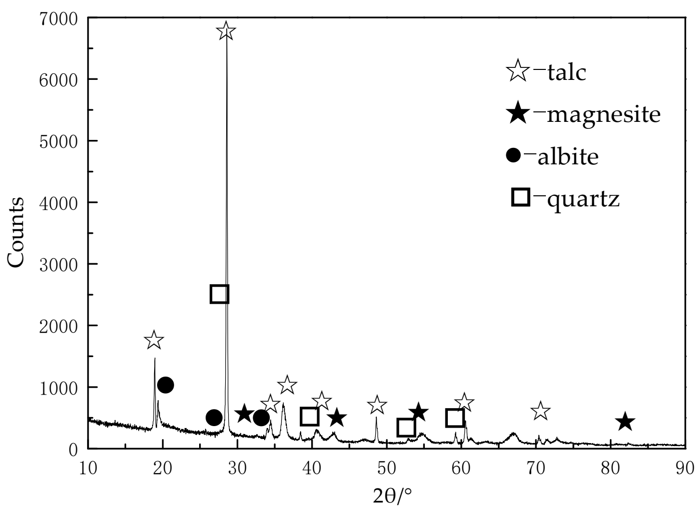

Figure 1. XRD analysis of gold ores.

Tables 2 and 3 and Figure 1 show that the gold grade is 1.32 g/t, and the main useful element of gold ores is gold, with low contents of harmful elements such as arsenic. The main gangue minerals are quartz, albite, talc, and magnesite, and gold mainly occurs in quartz gangue. Si, Ca, Mg, and Al are the dominant elements, with a SiO_2 content above 90% and an Al_2O_3 content above 6%. These gold ores were deemed suitable for cyanidation leaching.

Table 2. XRF analysis of raw ore.

Composition	**Na_2O**	**MgO**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**SO_3**	**K_2O**
content/%	0.035	0.193	6.872	90.222	0.022	0.194	0.683
Composition	CaO	TiO_2	Cr_2O_3	MnO	Fe_2O_3	CuO	ZnO
content/%	0.195	0.085	0.019	0.013	1.356	0.008	0.021
Composition	As_2O_3	Rb_2O	SrO	ZrO_2	BaO	Ag	PbO
content/%	0.003	0.005	0.004	0.003	0.023	0.028	0.016

Table 3. Chemical analysis of raw ore.

Composition	**Au ***	**Zn**	**TFe**	**MgO**	**Al_2O_3**	**CaO**	**S**	**SiO_2**
content/%	1.32	0.008	1.597	0.185	6.876	0.172	0.112	91.050

* Unit g/t.

2.2. Methods

Cyanidation leaching was tested using a single factor to investigate the effects of grinding time, grinding fineness, KCN dosage, pH value of ore pulp, temperature, stirring speed, and aid-leaching agents on leaching. Each grinding and agitation process utilized 400 g of sample, aid-leaching agent, alkali, and leaching agents. The gold leaching rate was calculated through centrifugation, filtration, sampling, and testing after reaching the leaching time. Each experiment was performed three times. Figure 2 shows the process of cyanide leaching.

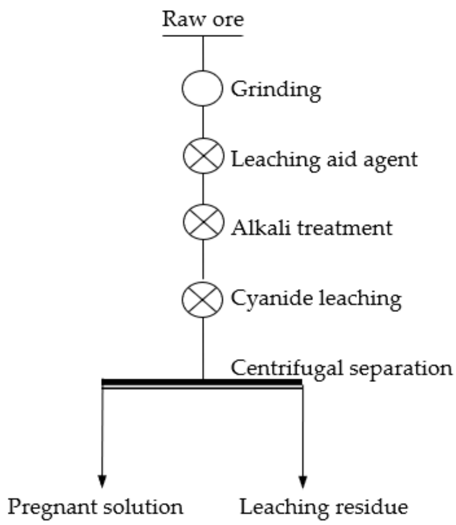

Figure 2. Process of the cyanide leaching of gold.

3. Results

3.1. Grinding Time Test

The size of gold ores significantly affects cyanidation leaching. The optimal grinding fineness is due to the minimum fineness of dissociation of gold particles and the economic benefit [28]. The grinding concentration was set at 66.67%. The relationship between grinding time and grinding fineness was investigated (Figure 3). Various hues symbolize distinct outcomes in varying circumstances (same as below).

Figure 3 shows that the −0.074 mm content in the grinding curve increases with time. The fineness of the raw ore of −0.074 mm accounts for 18.77%. This increases to 92.53% after grinding for 6.5 min because of the different mechanical properties of gold ores. Coarser grain sizes means more microcracks, lower mechanical strength, and easier milling. Smaller particle sizes indicate higher ore strength, which hinders milling [29]. The macroscopic and microscopic cracks in the ore decrease with a uniformly finer grain size. The probability of steel forging collision and grinding coarse particles is greater than that for fine particles, which reduces the production of fine particles [30]. Therefore, it is essential to select an appropriate grinding time, energy consumption, and optimal value to achieve the desired the gold leaching effect.

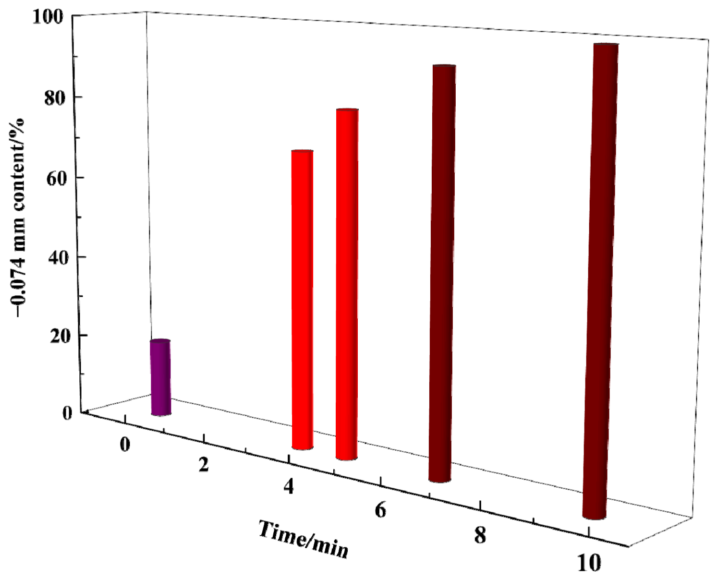

Figure 3. Relation curve between grinding fineness and time.

3.2. *Effect of Grinding Fineness on Gold Leaching*

Grinding fineness determines the degree of dissociation or exposure of gold ores [31]. The finer the grinding fineness, the more conducive it is to the dissociation of gold ores and the enhancement in the contact area between gold and the leaching liquid. However, finer grinding fineness means higher ore pulp viscosity, which is not conducive to the diffusion of cyanide ions and gold cyanide complexes. Moreover, it hinders solid–liquid separation and wastes energy. Therefore, proper grinding fineness is important to ensure a leaching effect and a reasonable production cost.

For the leaching tests, 400 g of gold ore was used, with a pulp leaching concentration of 28.57%, a potassium cyanide dosage of 5 kg/t, and a NaOH dosage of 1.25 kg/t (pH 10.5). The stirring speed was set at 1500 r/min, with an ore pulp temperature of 25 °C and a leaching time of 24 h. This work investigated the impact of different particle contents (70.66%, 81.16%, 92.53%, and 98.99%) on gold leaching, with a −0.074 mm grinding fineness for each sample (Figure 4).

Figure 4 shows that the gold leaching rate increases with grinding fineness. Detailed grinding is beneficial to the gold leaching rate. When the −0.074 mm grinding fineness content increases from 70.66% to 92.53%, the gold leaching rate increases from 74.84% to 91.82%. Meanwhile, the leaching rate of gold increases linearly with grinding fineness. When grain content with −0.074 mm grinding fineness is 98.99%, the gold leaching rate is 92.92%. The gold leaching rate decreases, but the grinding time increases. Moreover, the grinding fineness determines the ore pulp viscosity under the same conditions, such as slurry temperature.

A hydration film forms on the surface after particles dissolve in water. It is difficult to produce the relative flow between the hydration membrane and particles due to adsorption and hydration. The arrangement of water bodies is dense, with a large number of particles and smaller particle sizes. In particular, a large number of fine particles of slime are highly dispersed in the ore pulp due to the high fineness of grinding. The composition of ore pulp close to the colloids significantly increases the viscosity of the ore pulp, which affects the leaching effect of gold [32].

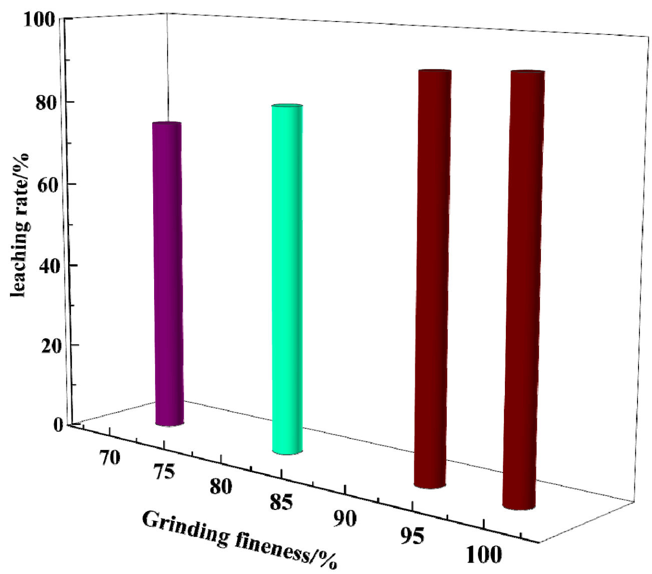

Figure 4. Effect of grinding fineness on the gold leaching rate.

More secondary slime is generated in suspension for a long time with increased grinding fineness, which makes it difficult to precipitate the gelatinous material. It reduces the gold dissolving speed and causes difficulties in the slurry washing process. Thus, dissolved gold is lost in the tailing slurry. Meanwhile, the fine particle size is increased to activate silicon-containing minerals, produce silica gel components to adsorb gold and its complex, and reduce the gold rate. Based on the factors of grinding cost and leaching effect, the −0.074 mm grinding fineness proportion was determined to be 92.53%.

3.3. Effect of Potassium Cyanide Dosage on Gold Leaching

Cyanide concentration in the solution significantly affects the gold leaching rate. The test used 400 g of gold ore, a granule content of 92.53%, a grinding fineness of −0.074 mm, a stirring speed of 1500 r/min, a pulp leaching concentration of 28.57%, a pH of 10.5 adjusted with NaOH, an ore pulp temperature of 25 °C, and a leaching time of 24 h. The influence of potassium cyanide dosage within 1–5 kg/t on gold leaching effectiveness was studied (Figure 5).

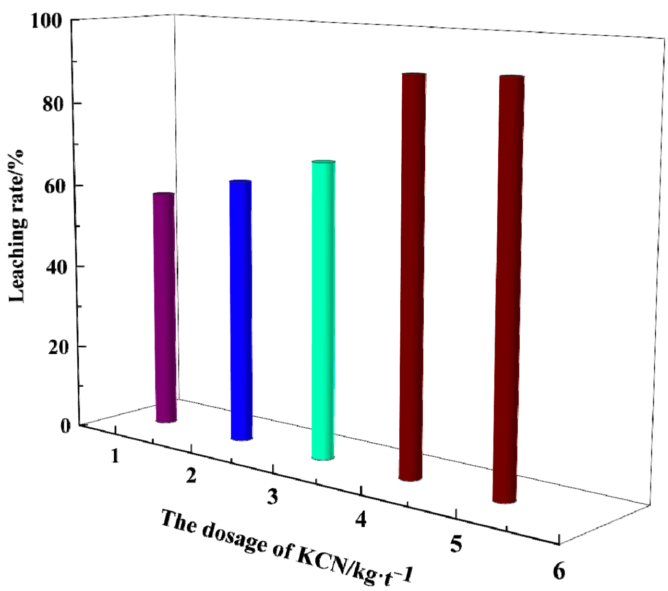

Figure 5. Effect of the potassium cyanide dosage on the gold leaching rate.

Figure 5 shows that the gold leaching rate increases significantly with potassium cyanide dosage. When the amount of leaching agent ranges from 1 to 4 kg/t, the gold leaching rate increases significantly from 57.27% to 90.91%. When the amount of the leaching agent is 5 kg/t, the gold leaching rate increases to 91.82%. The amount of potassium cyanide has reached an effective level of gold leaching. On the other hand, the saturation concentration of oxygen in water is about 8 mg/L at room temperature and pressure. When the cyanide concentration is low, the diffusion speed of cyanide in the solution is faster. The dissolution speed of gold increases rapidly with cyanide concentration. As the cyanide dosage continues to increase, the dissolution speed of gold increases slowly. Cyanide concentration is low, and the leaching rate of gold depends on cyanide concentration. When the cyanide concentration increases to a certain level, the cyanide leaching rate and speed of gold have little effect. Meanwhile, excess cyanide affects the subsequent processing cost. Thus, a dosage of 4 kg/t of the leaching agent was taken.

3.4. Effect of pH Value on Gold Leaching

When the pH of the solution is low, cyanide is hydrolyzed to produce hydrocyanic acid. Therefore, the pH value of the ore pulp is adjusted to make the ore pulp alkaline. This prevents the consumption of agents generated by the hydrolysis of cyanide during the cyanide leaching process as well as environmental pollution. The test involved 400 g of gold ores with a −0.074 mm grinding fineness of 92.53%, a KCN dosage of 4 kg/t, a stirring speed of 1500 r/min, an ore pulp temperature of 25 °C, a pulp leaching concentration of 28.57%, and a leaching time of 24 h. We slowly added the sodium hydroxide solution until the pH value was reached.

Figure 6 shows that the gold leaching rate is in a downward trend at pH 9.5–11.5. The gold leaching rate decreases from 91.64% to 90.91% at pH 9.5–10.5, which has little influence on the gold leaching rate. When the pH is greater than 10.5, the gold leaching rate significantly decreases, reaching 82.27% at pH 11.5. The concentration of hydroxide ions is high under a strong base. The existing competitive adsorption with cyanide ions reduces the contact between cyanide and gold. $[HCN]/[CN^-] = 1$ in the solution at pH 9.4, having the highest cyanide speed. When the pH is greater than 9.4, the cyanide ions are stable in aqueous solution. When the pH is lower than 9.4, some cyanide ions react with hydrogen ions to produce hydrocyanic acid, which increases the consumption of cyanide. The gold leaching rate should be increased, and the hydrolysis of cyanide should be avoided as much as possible at pH 10.5.

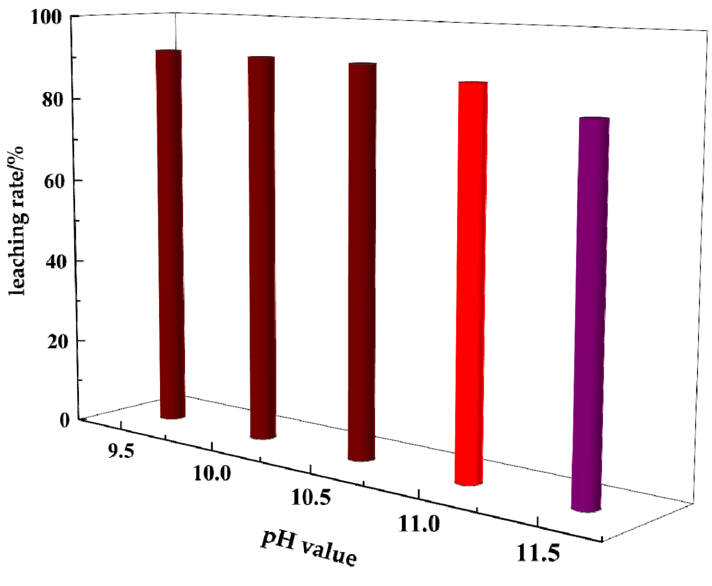

Figure 6. Effect of pH value on the gold leaching rate.

3.5. Effect of Temperature on Gold Dissolution

The temperature of the cyanide leaching system significantly affects gold leaching. The test used 400 g of gold ores with a grinding fineness of −0.074 mm (92.53%), a stirring speed of 1500 r/min, a pulp leaching concentration of 28.57%, a KCN dosage of 4 kg/t, a leaching time of 24 h, and a pH of 10.5. Figure 7 shows the gold leaching effect within 15–35 °C.

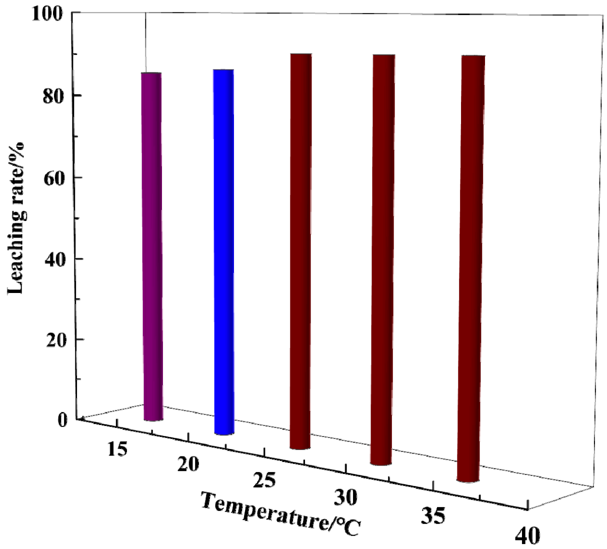

Figure 7. Effect of the temperature on gold leaching rate.

Figure 7 shows that the gold leaching rate gradually increases with temperature. The leaching rate of gold rapidly increases from 85.45% to 90.91% at 15–25 °C because the increased diffusion coefficient and the thinning of the diffusion layer are conducive to gold leaching. The gold leaching rate rises to 91.36%, and the increase significantly slows at 35 °C. The oxygen solubility decreases due to the increased ore pulp temperature. Other metals dissolved in the solution have harmful effects on the hydrolysis of cyanide. Unfavorable factors, such as increases in cyanide dosage, solution evaporation, and energy consumption, increase the cost of mineral processing [33]. Meanwhile, it pollutes the environment and reduces the purity of the leaching solution. Therefore, the leaching temperature was set to 25 °C.

3.6. Effect of Stirring Speed on Gold Dissolution

The interaction between gold and cyanide solution occurs at the solid–liquid interface. Agitation significantly affects the gold leaching efficiency. The test used 400 g of gold ore with a grinding fineness of −0.074 mm and a content of 92.53%, a KCN dosage of 4 kg/t, a pulp leaching concentration of 28.57%, a temperature of 25 °C, a leaching time of 24 h, and a pH of 10.5. The effect of the stirring speed within 1000–2000 r/min on gold leaching was tested (Figure 8).

Figure 8 shows that the leaching rate of gold increases linearly with the stirring speed. As the stirring speed increases from 1000 to 2000 r/min, the gold leaching rate increases from 87.14% to 92.86%. This is because the oxygen molecules and CN^- on the gold surface are consumed during the dissolution of gold. The concentration difference between the gold surface and solution occurs, and the oxygen molecules and CN^- diffuse from the solution to the gold surface [34]. AuCN gradually dissolves and diffuses from the gold particle surface to the solution, and gold continues to dissolve. The resistance of the leaching agent to the gold surface of the solution comes from the diffusion layer adjacent to the gold surface. Stirring has the following functions: destroying the saturated solution layer on the gold surface, generating the surface adsorbents of gold cyanide, and accelerating the diffusion speed of CN^-, O_2, AuCN, and $[Au(CN)_2]^-$. Thus, stirring intensity is increased to improve the gold leaching effect, but it causes the wear of equipment and higher energy consumption. The stirring speed is optimal at 1500 r/min.

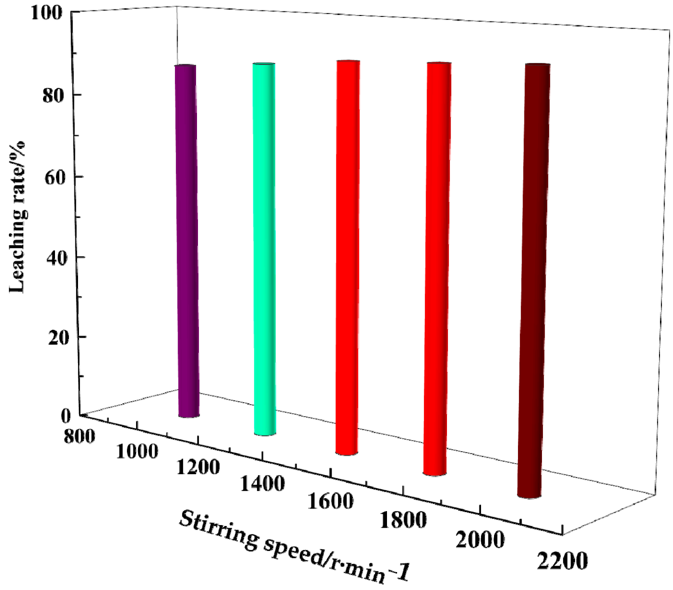

Figure 8. Effect of the stirring speed on the gold leaching rate.

3.7. Effect of Aid-Leaching Agents on Gold Dissolution

Under optimal leaching conditions, the content of −0.074 mm grinding fineness was 92.53%, with a stirring speed of 1500 r/min, a pulp leaching concentration of 28.57%, a pH of 10.5, and a conventional KCN leaching dosage of 4 kg/t. The aid-leaching agent amount was 0.6 kg/t, and the KCN amount was 2 kg/t under the leaching-aid condition. Figure 2 shows the cyanide leaching process, and Figure 9 shows the results of examining the effect of leaching time on the gold leaching effect with the aid-leaching agents.

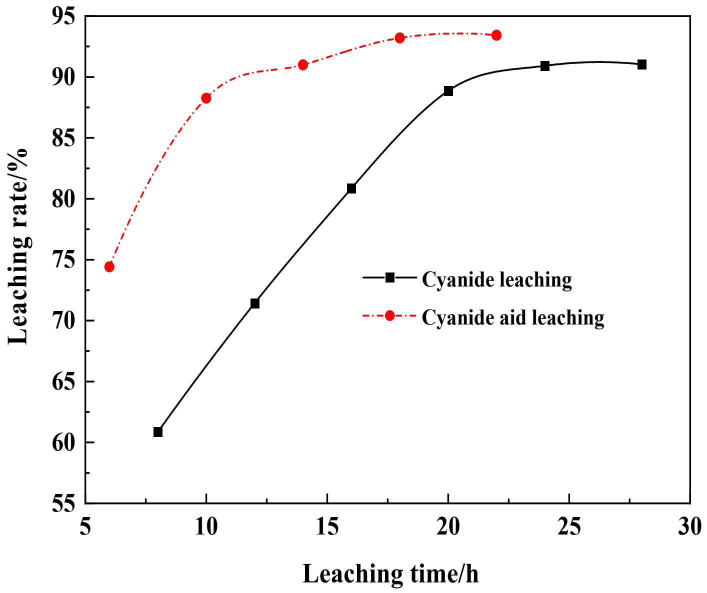

Figure 9. Effect of leaching time on gold leaching rate with aid-leaching agents.

Figure 9 shows that the gold leaching rate gradually increases with leaching time, and the aid-leaching agents improve the leaching effect of gold ores. The leaching rate is 60.86% with conventional cyanide leaching for 8 h. The leaching rate is 74.42% with the additive for 6 h. The gold leaching rate gradually increases with leaching time, but the leaching efficiency slows down. The leaching rate of gold is 91% after aid leaching for 14 h, which is close to the conventional gold leaching rate after 28 h. The gold leaching rate is 93.20% after aid leaching for 18 h, which is 2.29% higher than that of conventional leaching for 24 h. Therefore, the aid-leaching agents of gold can increase the reaction speed and gold leaching rate of cyanide leaching and reduce the cyanide by half.

4. Discussion

In the cyanidation leaching system of oxidized gold ores, the solution is rich in condensed $SiOH_2^+$, condensed SiOH, and condensed SiO^- as well as gold and its complexes, surfactant ions, peroxides, oxygen molecules, and cyanide ions.

Quartz and silicate minerals undergo chemical or mechanochemical reactions during wet treatment to form silica compounds in active semi-crystalline or amorphous phases, such as alkali metal (aluminum) silicates, short-chain silicates, and polymerized silicon [35]. Quartz and silicate minerals generate part of the silica components in the grinding process of gold ores, with strong activity and adsorbing gold and its complex in the solution. Han et al. [36] used electrochemical tests, showing that a finer size of quartz particles means a faster dissolving speed of cyanide leaching of gold and a higher adsorption rate of the gold solution on quartz. The adsorption mechanism of AuCN and $[Au(CN)_2]^-$ to quartz is explained using density functional theory.

The main components of the aid-leaching agents are trisodium citrate, sodium dodecyl sulfate, and magnesium peroxide in the system of the cyanide leaching of gold system. Trisodium citrate in aid-leaching agents can ionize the COO^- functional group in the solution. It can be adsorbed on the surface of quartz and silicate minerals containing $\equiv SiOH_2^+$, $\equiv$SiOH, and $\equiv SiO^-$. The gold leaching rate is improved, reducing the interaction between silicate minerals and gold complexes. Magnesium peroxide in aid-leaching agents can improve the oxidation potential of the solution, accelerating the oxidation of dissolved gold.

Oxygen is used as a leaching reactant to increase the dissolved oxygen content and accelerate the cyanide leaching efficiency of gold. Dodecyl sulfate is used to wrap the quartz and other silicon-containing minerals, which inhibits the adsorption of gangue minerals into gold complexes. Moreover, it avoids the "prog-robbing gold" effect of silicon-containing minerals on gold ores. The contact area between gold and cyanogen ions is increased to reduce the cyanide consumption and increase the gold leaching rate.

5. Conclusions

(1) The gold grade of the oxidized gold deposit in Guangxi Province was 1.32 g/t, and the main gangue minerals were quartz, feldspar, talc, and magnesite. Furthermore, the gold mainly occurred in quartz gangues.

(2) The gold leaching rate was 90.91% under the optimal conditions for the following conventional leaching process: steel forging was used as a grinding medium, a −0.074 mm grinding fineness content of 92.53%, a stirring speed of 1500 r/min, a pulp leaching concentration of 28.57%, pH 10.5, an ore pulp temperature of 25 °C, a leaching time of 24 h, and a potassium cyanide dosage of 4 kg/t.

(3) The new aid-leaching agents (0.6 kg/t) were adopted, and the potassium cyanide dosage was 2 kg/t. The gold leaching rate was 88.25%, with other conditions unchanged after aid leaching for 10 h. This is close to the conventional leaching rate of 88.86% for 20 h. The gold leaching rate was 93.20% after aid-leaching for 18 h, and the amount of potassium cyanide used was reduced by 50%. Meanwhile, the cyanide leaching time of gold was significantly shortened.

(4) The aid-leaching agents could restore the surface activity of passivated gold particles and inhibit the adsorption of gangue minerals to gold and its complexes. Therefore, the gold leaching efficiency and rate were improved.

6. Patents

Dai, S.J.; Han, J.H.; Su, X.; Yi, S.; Li, P.C. A kind of aid-leaching agent for cyanide leaching of gold ore and its action method [P]. 201911390239.3.

Author Contributions: J.H.: Conceived, designed, performed the experiments, data curation, writing—original draft. S.D.: Contributed reagents, materials, analysis tools and investigation. J.D.: Validation, writing—review. S.Q.: Materials, analysis tools. Y.Z.: Materials, analysis tools. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by grants from the National Natural Science Foundation of China (grant No. 51574146).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: Author Shandong Que was employed by the company Guangxi Senhe High Technology Co., Ltd. Author Yugao Zhou was employed by the company Guangxi Nandan Nanfang Metal Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Habashi, F. Gold—An historical introduction. In *Gold Ore Processing*; Project Development and Operations; Elsevier: Amsterdam, The Netherlands, 2016; pp. 1–20. [CrossRef]
2. Deschênes, G. Advances in the cyanidation of gold. *Adv. Gold Ore Process.* **2005**, *15*, 479–500. [CrossRef]
3. Yang, Y.B.; Li, Q.; Jiang, T.; Jin, Y.S. Cyanide leaching of gold ores by heavy metal ions. *Chin. J. Nonferrous Met.* **2005**, *15*, 1283–1288. [CrossRef]
4. Elsner, L. Über das Verhallen verschiedener Metalle in einer wässrigen Lösung von Cyankalium. *J. Prakt. Chem.* **1846**, *37*, 441–446. [CrossRef]
5. Bodländer, G. Die Chemie des Cyanidverfahrens. *Z. Angew. Chem.* **1896**, *9*, 583–587. [CrossRef]
6. Kameda, M. Fundamental Studies on Dissolution of Gold in Cyanide Solutions. II: On Equations of Reactions and Effects of Cyanide Strength and Other Variables on Dissolution Rate. Ph.D. Thesis, Tohoku University, Miyagi, Japan, 1949; pp. 223–230.
7. Monhemius, A.J. Recent applications of peroxygen reagents in hydrometallurgy. *Miner. Process. Extr. Metall. Rev.* **1992**, *8*, 35–46. [CrossRef]
8. Bas, A.D.; Safizadeh, F.; Zhang, W.; Ghali, E.; Choi, Y. Active and passive behaviors of gold in cyanide solutions. *Trans. Nonferrous Met. Soc. China* **2015**, *25*, 3442–3453. [CrossRef]
9. Donato, D.B.; Nichols, O.; Possingham, H.; Moore, M.; Ricci, P.F.; Noller, B.N. A critical review of the effects of gold cyanide-bearing tailings solutions on wildlife. *Environ. Int.* **2007**, *33*, 974–984. [CrossRef] [PubMed]
10. Azizi, A.; Ghaedrahmati, R. Optimizing and evaluating the operational factors affecting the cyanide leaching circuit of the Aghdareh gold processing plant using a CCD model. *Proc. R. Soc. A Math. Phys. Eng. Sci.* **2015**, *471*, 20150681. [CrossRef]
11. Bas, A.D.; Zhang, W.; Ghali, E.; Choi, Y. A study of the electrochemical dissolution and passivation phenomenon of roasted gold ore in cyanide solutions. *Hydrometallurgy* **2015**, *158*, 1–9. [CrossRef]
12. Jiang, T.; Zhang, Y.Z.; Yang, Y.B.; Huang, Z.C. Influence of copper minerals on cyanide leaching of gold. *J. Cent. South Univ. Technol.* **2001**, *8*, 24–28. [CrossRef]
13. Senanayake, G. A review of effects of silver, lead, sulfide and carbonaceous matter on gold cyanidation and mechanistic interpretation. *Hydrometallurgy* **2008**, *90*, 46–73. [CrossRef]
14. Dai, X.; Breuer, P.L. Leaching and electrochemistry of gold, silver, and gold-silver alloys in cyanide solutions: Effect of oxidant and lead (II) ions. *Hydrometallurgy* **2013**, *133*, 139–148. [CrossRef]
15. Robins, R.G.; Jayaweera, L.D. Arsenic in gold processing. *Miner. Process. Extr. Metall. Rev.* **1992**, *9*, 255–271. [CrossRef]
16. Karimi, P.; Abdollahi, H.; Amini, A.; Noaparast, M.; Shafaei, S.Z.; Habashi, F. Cyanidation of gold ores containing copper, silver, lead, arsenic and antimony. *Int. J. Miner. Process.* **2010**, *95*, 68–77. [CrossRef]
17. Zhong, Q.; Yang, Y.; Chen, L.; Li, Q.; Xu, B.; Jiang, T. Intensification Behavior of Mercury Ions on Gold Cyanide Leaching. *Metals* **2018**, *8*, 80. [CrossRef]
18. Jeffrey, M.I.; Breuer, P.L. The cyanide leaching of gold in solutions containing sulfide. *Miner. Eng.* **2000**, *13*, 1097–1106. [CrossRef]
19. Li, X.; Zhang, Q.; Xie, J.; Shen, Z. $[Au(CN)_2]^-$ Adsorption on a Graphite (0001) Surface: A First Principles Study. *Minerals* **2018**, *8*, 425. [CrossRef]
20. Choma, J.; Dziura, A.; Jamioła, D.; Nyga, P.; Jaroniec, M. Preparation and properties of silica–gold core–shell particles. *Colloids Surf. A Physicochem. Eng. Asp.* **2011**, *373*, 167–171. [CrossRef]
21. Mohammadnejad, S.; Provis, J.L.; van Deventer, J.S.J. Computational modelling of interactions between gold complexes and silicates. *Comput. Theor. Chem.* **2017**, *1101*, 113–121. [CrossRef]

22. Kondos, P.D.; Deschênes, G.; Morrison, R.M. Process optimization studies in gold cyanidation. *Hydrometallurgy* **1995**, *39*, 235–250. [CrossRef]
23. Yang, W.; Deng, Z.; Dong, P. Study on the Intensification Cyanide Leaching of High Arsenic Bearing Gold Concentrate. *Nonferrous Met. Eng.* **2018**, *8*, 83–86.
24. Oraby, E.A.; Eksteen, J.J.; Tanda, B.C. Gold and copper leaching from gold-copper ores and concentrates using a synergistic lixiviant mixture of glycine and cyanide. *Hydrometallurgy* **2017**, *169*, 339–345. [CrossRef]
25. Eksteen, J.J.; Oraby, E.A. The leaching and adsorption of gold using low concentration amino acids and hydrogen peroxide: Effect of catalytic ions, sulphide minerals and amino acid type. *Miner. Eng.* **2015**, *70*, 36–42. [CrossRef]
26. Raphulu, M.C.; Scurrell, M.S. Cyanide leaching of gold catalysts. *Catal. Commun.* **2015**, *67*, 87–89. [CrossRef]
27. Guzman, L.; Chimenos, J.M.; Fernandez, M.A.; Segarra, M.; Espiell, F. Gold cyanidation with potassium persulfate in the presence of a thallium (I) salt. *Hydrometallurgy* **2000**, *54*, 185–193. [CrossRef]
28. Tang, Y.; Yin, W.; Huang, S.; Xue, J.; Zuo, W. Enhancement of gold agitation leaching by HPGR comminution via microstructural modification of gold ore particles. *Miner. Eng.* **2020**, *159*, 106639. [CrossRef]
29. Acar, S. Process development metallurgical studies for gold cyanidation process, Miner. *Metall. Process.* **2016**, *33*, 161–171. [CrossRef]
30. Han, J.H.; Dai, S.J.; Zhang, Z.J.; Li, J.H. Study on grinding effects while steel forging as grinding medium. *Min. Process. Equip.* **2017**, *3*, 38–41. [CrossRef]
31. Lin, Y.; Hu, X.; Zi, F.; Chen, Y.; Chen, S.; Li, X.; Li, J.; Jiang, Y.; Zhang, Y. Rapid gold cyanidation from a sulfur-high and arsenic-high micro-fine concentrate via facile two-stage roasting pre-treatment. *Miner. Eng.* **2022**, *190*, 107938. [CrossRef]
32. Evdokimov, S.I.; Golikov, N.S.; Pryalukhin, A.F. Studying Flotation of Gold Microdispersions with Carrier Minerals and Pulp Aeration with a Steam–Air Mixture. *Minerals* **2024**, *14*, 108. [CrossRef]
33. Chen, X.; Ren, Y.; Qu, G.; Wang, Z.; Yang, Y.; Ning, P. A review of environmental functional materials for cyanide removal by adsorption and catalysis. *Inorg. Chem. Commun.* **2023**, *157*, 111298. [CrossRef]
34. Manzila, A.N.; Moyo, T.; Petersen, J. A Study on the Applicability of Agitated Cyanide Leaching and Thiosulphate Leaching for Gold Extraction in Artisanal and Small-Scale Gold Mining. *Minerals* **2005**, *2022*, 1291. [CrossRef]
35. Dove, P.M.; Han, N.; De Yoreo, J.J. Mechanisms of classical crystal growth theory explain quartz and silicate dissolution behavior. *Proc. Natl. Acad. Sci. USA* **2005**, *102*, 15357–15362. [CrossRef] [PubMed]
36. Han, J.H.; Li, X.A.; Dai, S.J. Electrochemical Influence of Quartz on Cyanide Leaching of Gold. *Chem. Phys. Lett.* **2020**, *739*, 136997. [CrossRef]