Optimization of cyanidation process for gold-bearing ores from Central Kazakhstan

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The possibility of processing of 1.09 g/t gold content ore from Central Kazakhstan by cyanidation on activated carbon has been studied. The results of studies on ore phase composition are presented: the total amount of cyanidable gold in the sample is 80.59%; the share of refractory gold not recoverable by direct cyanidation is 19.41% of the total mass of metal; the total share of free gold with clean surface at ore size of 95% grade –0.071 mm is 36.78%. Based on the results of Preg Robbing Adsorption Kinetics test, the preg robbing property of ore is established. It was found that during the ore cyanidation process, the dissolved gold has a reverse deposition effect on the ore. It is shown that when the contact time of ore with solution is increased up to 60 min, the gold allocation to ore components increases from 23 to 50%.
Experiments on cyanidation of ore on activated carbon in CIP and CIL modes in a bottle-type agitator at sodium cyanide flow rates of 0.5 kg/t, 0.75 kg/t and 1.25 kg/t were carried out. Norit RO 3515 activated carbon was used as a sorbent. In all experiments CaO was added to the leaching solution at the rate of 1.2 kg/t. The acidity of the solution was maintained at pH = 11.5. On the basis of comparative test results in CIP and CIL modes the superiority of ore cyanidation in CIL mode is shown. The optimal parameters of ore cyanidation in CIL mode were established: duration = 12 hours; NaCN consumption = 0.5 kg/t; acidity pH = 11; oxygen concentration in the solution 11.5 mg/l. Gold recovery in solution was more than 77%.

Key words: ore, pregrobbing, gold, kinetics, recovery, allocation, cyanidation, CIP mode, CIL mode.

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Introduction

The ability of cyanide to form stable complexes with gold [1] has ensured its widespread use as the main leaching agent for the extraction of gold from ores. Currently, cyanide leaching of gold remains the dominant gold production process due to its technical simplicity. However, the use of cyanide is increasingly raising environmental, health and safety concerns [2, 3].

Despite the fact that in the world practice of gold production there are many different methods of gold recovery such as: flotation [4, 5], hydrometallurgy [6, 7], roasting [8, 9], or a combination of these technologies [10], traditional cyanidation remains the most widely used method due to its economic efficiency. In addition, many alternative leaching methods pose an equal risk to the environment.

The most developed and the only method introduced in the industry as an alternative to cyanidation is thiosulphate leaching, which is characterized by low toxicity and high efficiency in processing pre-mined gold ore [11]. Despite the advantages, this method has several disadvantages, which include: complexity of the process, high consumption of reagents, sensitivity to pH and redox regimes, complexity of process control, etc. [12]. Alternatives to cyanide leaching also include methods based on the use of thiourea, thiocyanate and halides. Despite the positive results of laboratory studies on gold recovery, almost all of these alternative substitutes for cyanide have limitations that prevent their widespread use in the gold mining industry [13].

Overall trends show that the normalized environmental costs of gold production by cyanidation are increasing, both in terms of energy, water and cyanide consumption and greenhouse gas emissions. Ore grade, or the amount of gold contained in a ton of mined rock, determines the potential profitability of gold ore mining, as well as potential costs. When compared to the total energy, water and cyanide consumption ratios required to produce a kilogram of gold ore, it is evident that the normalized environmental costs of gold will increase significantly in the near future, considering the decline in ore quality.

From a technological and environmental point of view, accumulated cyanidation tailings and ores containing refractory minerals and carbonaceous substances, the presence of which causes "inhibition" of the kinetic characteristics of leaching and reduced gold recovery, are

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of particular relevance. Processing of these materials by cyanidation entails high cyanide consumption and increased costs [12, 14, 15].

A characteristic feature of the tailings is that they contain significant gold and cyanide content. Extraction of gold from them is complicated by the fact that during cyanidation of ore on the surface of cyanidation tailings films are formed, which have a restraining effect on the rate of gold leaching during flotation. The presence of cyanide compounds in cyanidation tailings significantly affects the flotation of gold-bearing pyrite and released gold. In addition, fine cyanidation tailings adversely affect the flotation process.

The cyanidation process is widely used for gold production in Kazakhstan. One of the modern gold recovery plants (GRP), located in Central Kazakhstan, processes gold-bearing ore with a gold content of 1—1.5 g/t. Despite the steady development of the plant, in cases of changes in ore composition, there are noticeable deviations from the planned technological regimes. Thus, in cases when the plant works "off the wheels" (production volumes do not have time to cover the daily demand of the plant), when processing ores that contain carbonaceous substances, a sharp decrease in gold recovery is observed. In this case, the process control at the plant is carried out by controlling the concentration of gold in the liquid phase using a rapid analysis using the atomic adsorption method. Operational control of the process is based on control of cyanide concentration in all vats, including the last sorption vat. Equalization of gold dissolution kinetics in all vats of cyanidation and sorption, in case of a sharp decrease in gold recovery, is carried out by increasing the cyanide concentration in the first leaching vat. To intensify the sorption process, more fresh charcoal is added to the vats to quickly adsorb dissolved gold on it, and to ensure a more complete dissolution reaction of gold in the cyanide solution. This practice has resulted in a significant increase in cyanide consumption (4 times), compared to conventional cyanide consumption. Involvement of carbonaceous gold-bearing ores, which have the ability to adsorb gold cyanide from leaching solutions (preg-robbing), is the reason for the decrease in gold recoveries [16].

The practice of the plant operation shows that the issues of gold extraction from ores containing high content of carbonaceous substances remain open to date and require additional research. The importance of studying this issue is amplified by the fact that there are only a limited number of studies in the scientific literature devoted to the study of gold recovery based on specific ore properties. In addition, the known studies did not achieve high gold recovery from such ores.

The purpose of this work is to establish the relationship between the ability to absorb gold cyanide by the carbonaceous substance of the ore and the pregrobbing behavior of the parent ore, as well as the study of the distribution of gold between the products of ore leaching by cyanidation, aimed at optimizing the process of cyanidation of ores from Central Kazakhstan, containing carbonaceous substances.

Materials and methods of research

A sample of ore from a gold-bearing deposit of Central Kazakhstan with a gold content of 1.09 g/t, 80% class size –75 microns was used as an object of the study.

Control of gold content in leach products was carried out by atomic absorption and assay methods of analysis.

Studies of the form of gold, the nature of its relationship with ore and rock-forming minerals, as well as the assessment of free gold in the ore sample were carried out by the amalgamation method. Amalgamation was carried out in a stage-by-stage manner, reducing the coarseness of the material from the original (–2 mm) to 95% grade –0.071 mm.

Preg Robbing Adsorption test experiments to study the kinetics of adsorption of gold cyanide complexes on the surface of carbonaceous substances were carried out by cyanide leaching of ore in a bottle-type agitator. The total duration of the process amounted to 2 hours. During the experiments every 15 minutes the change of gold concentration in the solution was controlled by taking intermediate samples of solutions. According to the results of the experiments, the distribution of gold in the leaching products was calculated.

Laboratory studies on ore leaching were conducted in two sorption modes – CIP and CIL. In each mode, the sodium cyanide flow rate was set at three levels: 0.5 kg/t, 0.75 kg/t, and 1.25 kg/t. The entire NaCN flow rate was applied at the beginning of each test. Norit RO 3515 grade activated carbon was used as sorbent. In all experiments, CaO was injected into the leaching solution at a flow rate of 1.2 kg/t. The acidity of the solution was maintained at pH = 11.5.

NaCN concentration, dissolved oxygen and pulp acidity (pH) were monitored during the tests. Cyanidation products were analyzed by atomic absorption (solution) and assay (cake) techniques.

For the purpose of reproducibility and obtaining accurate results, each experiment performed in two sorption modes at each reagent flow rate was repeated 4 times under identical leaching conditions.

The parameters of ore sample leaching in the CIP mode, where the cyanidation stage precedes sorption, and in the CIL mode, where the leaching and sorption processes are combined, are summarized in **Table 1.**

Test experiments in CIP and CIL modes were carried out on a laboratory bottle agitator, the general view of which is shown in **Fig. 1.**

Results and discussion

Study of the initial ore phase composition

The results of the initial ore sample phase analysis are presented in **Table 2**.

From the results of ore phase analysis it can be seen that the proportion of free gold at the initial size of –2 mm is

5.37%. When reducing the material size to 60% of –0.071 mm grade, the free gold content increases by 21.21%. Increasing the grinding fineness to 95% of –0.071 mm grade allows an additional 10.20% of gold to be released. The total part of free gold with a clean surface at ore size of 95% –0.071 mm is 36.78%. 43.81% of metal was found in the form of open aggregates with ore and rock-forming minerals (cyanidable).

The total amount of cyanidizable gold in the sample is 80.59%. The share of refractory gold, which is not recoverable by direct cyanidation, accounts for 19.41% of the total metal mass. The main reason for the refractoriness of ore to the cyanide process is the association of gold with sulfides, which amounted to 14.35%. The gold content in acid-soluble films is at 1.38%. In quartz and other minerals insoluble in aqua regia the gold content is 3.68%.

In general, the results of phase analysis show the possibility of using the ore as a promising raw material for gold extraction by known methods: gravity, flotation and cyanidation. However, the presence of carbonaceous substances and refractory forms of gold in the ore may cause possible difficulties in extracting gold from the ore during processing. For ores of Central Kazakhstan containing refractory forms of gold, the establishment of the relationship between the ability to absorb gold cyanide by the carbonaceous matter of the ore and the preg-robbing behavior of the parent ore is of great importance. Studies of the kinetics of the interaction between ore and cyanide may provide an opportunity to determine the distribution of gold between the ore leach products and outline the ways to optimize the process towards higher gold recovery. This is of fundamental importance for Kazakhstan GRP, both technologically and in terms of the environmental component of the process.

Table 1
Parameters of agitation leaching of ore samples

Parameter	Unit	CIP mode	CIL mode
Material coarseness	μm	–75 (80%)	
Sodium cyanide consumption	kg/t	0.5; 0.75; 1.25	
Lime consumption	kg/t	1.2	
Slurry density during cyanidation	% of solid	40	
Type of sorbent	–	Activated carbon Norit RO 3515	
Coal concentration in the slurry at the sorption cyanidation stage	g/l	40	15
Duration of the pre-cyanidation stage	hours	12	–
Duration of sorption cyanidation stage	hours	2	12
Total leaching time	hours	14	12

Fig. 1. Laboratory bottle agitator (*photo provided by the authors*)

Table 2
Results of the initial ore sample phase analysis

Gold form	Gold distribution, %
Free, with clean surface at coarseness –2 mm	5.37
Free, with a clean surface at a coarseness of 60% grade –0.071 mm	21.21
Free, with clean surface at 95% grade coarseness –0.071 mm	10.20
Total free gold with a clean surface:	**36.78**
In the form of open aggregates with ore and rock-forming minerals ("cyanidable")	43.81
Total in cyanidable form:	**80.59**
In acid-soluble minerals and films	1.38
In sulfides	14.35
In the minerals and quartz insoluble in aqua regia	3.68
Total:	**100.00**

Preg Robbing Adsorption Kinetics Tests results

The necessity of test experiments is caused by the fact that changes in the material and phase composition of the ore can lead to pregrobbing, in which the cyanide complex of gold ($Au(CN)_2$) can adsorb on the ore and be removed from the solution with it. The main ore constituents that cause pregrobbing are the carbonaceous matter and sulphides.

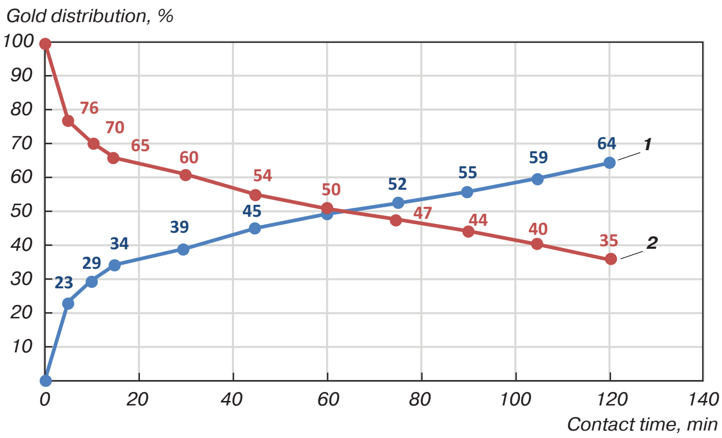
Preg Robbing Adsorption Kinetics tests were performed to evaluate the sorption activity of the ore. The essence of the tests was as follows. Pre-dried ore sample in the amount of 400 g was loaded into a container and brought into contact with sodium cyanide solution. Ore grinding tonnage of 80% grade –71 microns corresponded to the tonnage of ore used in the technological process of ore leaching at the GRP.

For the test, a standard solution saturated with gold up to 3 mg/L was prepared with a total volume of 600 ml. Leaching was carried out on a bottle agitator (**Fig. 1**) under constant stirring for a given time. To study the kinetic regularities, control samples of 30 ml of solutions were taken every 15, 30, 45, 60, 75, 90, 105, 120 minutes, in which the gold content was determined by the atomic absorption analysis method. Each sample of solution taken after a certain time interval was subjected to filtration. The resulting filtrate was analyzed for its gold content.

The conditions of the Preg Robbing Adsorption Kinetics test and their results are summarized in **Table 3**.

The results of gold distribution between cyanidation products show that dissolved gold, during the process of cyanidation of ore, has the effect of reverse deposition on ore. As can be seen in **Fig. 2**, when the contact time is increased to 60 minutes, the distribution of gold to ore increases from 23% to 50%.

Further increase of contacting time promotes more efficient transfer of gold to ore. Equilibrium distribution of gold between solution and ore is observed at contact time of ore with solution 60 min. The amount of gold transferred to the ore is 0.08 mg (0.89 mg cumulative), which is ~50% of the total amount of gold in the solution.



Fiig. 2. Dependence of gold distribution between leach products on contact time: *1* – gold deposited on ore (cumulative); *2* – residual gold in solution

The obtained results show the properties of ore pregrobbing, which indicates the need for additional research to optimize the process of ore leaching by cyanidation and to ensure maximum recovery of gold in the target product. In order to achieve this goal, comparative test experiments on cyanidation of ore leaching by cyanidation on activated carbon in CIP and CIL modes were carried out in this work.

Laboratory studies of ore leaching under CIP and CIL sorption modes

The results of ore sample cyanidation tests at different sodium cyanide flow rates in the two sorption modes CIP and CIL are presented in **Table 4.**

Comparative analysis of the dependence of gold recovery (average value) on NaCN flow rate (**Fig. 3**) in CIP and CIL modes shows an increase in gold recovery with increasing NaCN flow rate for the two modes studied.

It can be seen that in CIP mode, increasing NaCN consumption from 0.50 to 1.25 kg/t, does not significantly affect the level of gold recovery from ore: gold recovery shows a slight increase from 72.03 to 72.99%, almost remaining at the same level.

Gold recovery in the CIL mode, at the same NaCN flow rate, is higher than in the CIP mode. Moreover, in the CIL mode, the character of the dependence curve is pronounced. The maximum gold recovery from the ore, equal to 77.45%, was achieved at NaCN consumption = 1.25 kg/t. At decrease of NaCN flow rate from 0.75 to 0.50 kg/t a slight (by 1.24% abs.) decrease in gold recovery from the ore sample is observed. The established regularities agree well with the theory of the ore cyanidation process.

The main objective of the carbon-in-leach (CIL) process is to dissolve gold in a cyanide solution in the presence of oxygen. Gold readily dissolves in cyanide solutions in the presence of oxygen. The resulting

Table 3
Preg Robbing Adsorption Kinetics Test results

Contact time, min	Solution volume, ml	Concentration of gold in solution, mg/L	Amount of gold in solution, mg	Amount of gold deposited on ore, mg	Amount of gold deposited on ore (cumulative), mg	Gold distribution, %	
						in solution	on ore (cumulative)
0	600.0	3.00	1.8	0.00	0.00	100.00	–
5	600.0	2.30	1.4	0.42	0.42	76.67	23.33
10	570.0	2.22	1.3	0.11	0.53	70.30	29.70
15	540.0	2.19	1.2	0.08	0.62	65.70	34.30
30	510.0	2.15	1.1	0.09	0.70	60.92	39.08
45	480.0	2.06	1.0	0.11	0.81	54.93	45.07
60	450.0	2.03	0.9	0.08	0.89	50.75	49.25
75	420.0	2.04	0.9	0.06	0.94	47.60	52.40
90	390.0	2.04	0.8	0.06	1.00	44.20	55.80
105	360.0	2.01	0.7	0.07	1.08	40.20	59.80
120	330.0	1.95	0.6	0.08	1.16	35.75	64.25

complex ion (molecule) of gold cyanide is readily adsorbed on activated carbon [17]. In practice, the optimum cyanide concentration is established by monitoring the response to leachable gold losses, determined through daily laboratory leachings and correlated to the cyanide addition rate in the plant [18]. The concentration of dissolved oxygen in the slurry is very important for gold cyanidation. The relationship between cyanide and dissolved oxygen is well described by the Elsner reaction [14]:

$$4Au + 8CN^{-} + O_2 + 2H_2O \rightarrow$$
$$\rightarrow 4Au(CN)_2^{-} + 4OH^{-}.$$

It can be seen from the reaction that the deficiency of dissolved oxygen will cause the reaction to shift to the left, making it difficult to dissolve gold during the cyanidation process. For our case, the level of oxygen concentration in solution equal to 11.5 mg/l is optimal and provides achievement of high recovery of gold in solution. Increasing the oxygen concentration will reduce the amount of suspended solids produced by agitation. This can reduce the effective volume of the leach tank and hence the retention time for coarse solids [13].

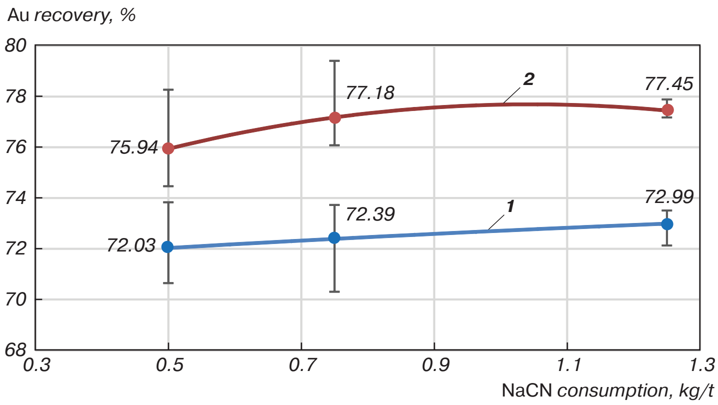


Fig. 3. Dependence of gold recovery on NaCN consumption:w
1 – CIP; *2* – CIL

Thus, the results of the conducted studies show that for the ore of Central Kazakhstan with gold content of 1.09 g/t, the CIL sorption mode is more preferable. When the ore is cyanidized in CIL mode, gold recovery is on average 4.3% higher than in CIP mode. The difference in gold recovery indirectly indicates the presence of low sorption activity of the ore, which was established above as a result of the ore pregrobbing property study.

Table 4
Results of ore sample leaching at different sodium cyanide flow rates in CIP and CIL sorption modes

Test No.	Modes, total process time	NaCN consumption, kg/t	Au content in cake, g/t	Gold recovery, %	pH level	Oxygen concentration, mg/l
1	**CIP – 14 h.** – Leaching – 12 h; – Sorption – 2 h.	0.50	0.297	72.75	11.5	11.3
2			0.310	71.61	11.5	11.0
3			0.319	70.73	11.3	12.6
4			0.294	73.03	11.3	11.4
5		0.75	0.308	71.79	11.6	11.4
6			0.301	72.43	11.5	10.8
7			0.312	71.42	11.3	12.1
8			0.285	73.90	11.3	11.9
9		1.25	0.297	72.75	11.6	10.7
10			0.288	73.62	11.6	10.4
11			0.295	72.98	11.4	10.8
12			0.299	72.61	11.4	10.7
13	**CIL – 12 h.**	0.5	0.261	76.06	11.4	11.3
14			0.250	77.06	11.4	11.1
15			0.282	74.17	11.4	12.9
16			0.257	76.47	11.3	11.9
17		0.75	0.240	78.03	11.5	10.8
18			0.248	77.25	11.5	11.0
19			0.240	77.98	11.3	11.8
20			0.268	75.46	11.5	12.0
21		1.25	0.250	77.11	11.5	11.1
22			0.247	77.39	11.6	11.2
23			0.244	77.66	11.5	11.6
24			0.244	77.66	11.5	12.1

Conclusion

The conceptual possibility of processing the ore from Central Kazakhstan with gold content of 1.09 g/t by cyanidation was shown.

As a result of ore phase composition studies, the total amount of cyanidable gold in the sample was found to be 80.59%. The share of refractory gold not recoverable by direct cyanidation is 19.41% of the total mass of metal. It is shown that the total proportion of free gold with a clean surface at ore size of 95% grade –0.071 mm is 36.78%.

Preg Robbing Adsorption Kinetics test results established the property of ore pregrobbing. It is shown that the equilibrium distribution of gold between the solution and ore is achieved at 60 minutes of contacting the ore with the solution. The amount of gold deposited on the ore is 0.08 mg (0.89 mg cumulative), which is ~50% of the total amount of gold in the solution.

Based on the results of comparative test experiments on cyanidation of ore in CIP and CIL modes it was established that the most preferable mode of cyanidation of the studied ore, providing high gold recovery (77.45%), is the CIL mode. The optimal parameters of ore cyanidation in CIL mode were established: duration = 12 hours; NaCN consumption = 0.5 kg/t; pH = 11; oxygen concentration in the solution 11.5 mg/L.

The results obtained will be used in further studies aimed at increasing gold recovery during ore processing by cyanidation and development of cyanide recirculation technology.

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