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INNOVATIVE METHODS FOR PROCESSING COPPER ORES IN KAZAKHSTAN: A COMPREHENSIVE APPROACH TO ENHANCING THE EFFICIENCY OF VALUABLE COMPONENT EXTRACTION

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Abstract. This article presents an innovative approach to processing copper ore from one of the deposits in Kazakhstan, aimed at enhancing the efficiency of copper extraction from materials with a complex mineral composition. The described methodology includes several key stages: comprehensive analysis of the ore's material composition, gravity and flotation beneficiation, as well as hydrometallurgical processes. During the study, the ores underwent preliminary preparation, including crushing and grinding to the required fineness. Experiments on gravity and flotation beneficiation demonstrated that optimizing the parameters of these processes significantly increases the yield of copper concentrate. Additionally, sulfuric acid leaching conducted showed high efficiency in extracting copper from the ground ore. The research results confirm that a comprehensive approach to copper ore processing ensures high efficiency in extracting valuable components and opens up prospects for the sustainable and economically viable utilization of complex copper ores.

Keywords: copper-containing raw materials, ore-beneficiation; gravity; flotation; leaching.

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ҚАЗАҚСТАНДАҒЫ МЫС КЕҢДЕРІН ӨҢДЕУДІҢ ИННОВАЦИЯЛЫҚ ӘДІСТЕРІ: ҚҰНДЫ КОМПОНЕНТТЕРДІ АЛУДЫҢ ТИІМДІЛІГІН АРТТЫРУҒА КЕШЕНДІ КӨЗҚАРАС

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Аннотация. Бұл мақалада Қазақстанның бір кен орнынан алынған мыс рудасын өңдеудің инновациялық тәсілі ұсынылған, ол күрделі минералды құрамдағы материалдардан мыс алу тиімділігін арттыруға бағытталған. Сипатталған әдістеме бірнеше негізгі кезеңдерді қамтиды: руданың материалдық құрамын жан-жақты талдау, гравитациялық және флотациялық байыту, сондай-ақ гидрометаллургиялық процестер. Зерттеу барысында рудалар қажетті ұсақтыққа дейін ұсақтау және майдалау сияқты алдын ала дайындықтан өтті. Гравитациялық және флотациялық байыту бойынша жүргізілген эксперименттер бұл процестердің параметрлерін оңтайландыру мыс концентратын шығымын айтарлықтай арттыратынын көрсетті. Сонымен қатар, күкірт қышқылымен шаймалау ұсақталған рудалардан мыс алудың жоғары тиімділігін көрсетті. Зерттеу нәтижелері мыс рудаларын кешенді өңдеуге жүйелі көзқарас құнды компоненттерді алудың жоғары тиімділігін қамтамасыз ететінін және күрделі мыс рудаларын тұрақты және экономикалық тиімді пайдаланудың келешегін ашатынын растайды.

Түйін сөздер: мыс құрамындағы шикізат, руда байыту, гравитация, флотация; шаймалау.

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ИННОВАЦИОННЫЕ МЕТОДЫ ПЕРЕРАБОТКИ МЕДНЫХ РУД В КАЗАХСТАНЕ: КОМПЛЕКСНЫЙ ПОДХОД К ПОВЫШЕНИЮ ЭФФЕКТИВНОСТИ ИЗВЛЕЧЕНИЯ ЦЕННЫХ КОМПОНЕНТОВ

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Аннотация. В данной статье представлен инновационный подход к переработке медной руды одного из месторождений Казахстана, направленный на повышение эффективности извлечения меди из материалов с сложным минеральным составом. Описанная методология включает несколько ключевых этапов: всесторонний анализ вещественного состава руды, гравитационное и флотационное обогащение, а также гидрометаллургические процессы. В ходе исследования руды прошли предварительную подготовку, включая дробление

и измельчение до необходимой тонкости. Эксперименты по гравитационному и флотационному обогащению показали, что оптимизация параметров этих процессов значительно увеличивает выход медного концентрата. Дополнительно, сернокислотное выщелачивание показало высокую эффективность в извлечении меди из измельченной руды. Результаты исследования подтверждают, что комплексный подход к переработке медной руды обеспечивает высокую эффективность извлечения ценных компонентов и открывают перспективы для устойчивого и экономически выгодного использования сложных медных руд.

Ключевые слова: медьсодержащее сырьё, обогащение руд, гравитация, флотация, выщелачивание

Introduction

The use of copper, the red metal with remarkable properties, is of paramount importance in the field of clean energy and renewable technologies (2023: 54268). The unique characteristics of copper, such as high electrical conductivity, ductility, efficiency, and recyclability, make it indispensable for various applications in renewable energy systems, including solar and wind technologies (2023: 07.01.04). The significant role of copper in energy storage devices, such as flow batteries, lithium-ion batteries, and sodium batteries, underscores its crucial importance in the production of electric vehicles.

Copper's electrical conductivity is among the highest of all metals, making it an ideal material for the efficient transmission of electricity from renewable sources. Copper's ductility allows for the production of thin wires necessary for complex electrical components in solar panels and wind turbines. Copper's efficiency in energy conversion and its ability to be recycled without losing its properties enhance its environmental sustainability.

The energy storage sector, which ensures balance amidst interruptions in renewable energy sources, also heavily relies on copper. Lithium-ion batteries, widely used in electric vehicles and grid storage, require approximately 44 pounds of copper per megawatt of energy storage (Silpa et al., 2022: 12050545).

Technologies for using renewable energy sources, particularly solar and wind systems, require significantly more copper than traditional fossil fuel-based power generation. For instance, solar systems need approximately 5.5 tons of copper per megawatt of electricity, while 3 MW wind turbines require around 4.7 tons. This is due to the extensive wiring, power transformers, and inverters critical to the functioning of renewable energy systems (Keming and Druffel, 2021: 9519105).

The International Copper Association (ICA) emphasizes that no other metal can match copper's versatility and efficiency in these areas. Copper's exceptional properties make it a cornerstone in the development of clean energy and technologies based on renewable sources. Its indispensable role in solar and wind energy systems, energy storage solutions, and electric vehicle production highlights its significance for transitioning to a sustainable and low-carbon future.

The complete dematerialization of high-grade copper ore and the continuously growing demand necessitate the processing of low-grade resources to sustain industrial growth and development (Zhumashev et al., 2021). Copper deposits worldwide are predominantly of the porphyry type, comprising 50–60% of global copper production. They consist of copper sulfide minerals such as chalcopyrite ($CuFeS_2$), chalcocite (Cu_2S), and bornite (Cu_5FeS_4). About 90% of copper is extracted from sulfide deposits, with chalcopyrite accounting for roughly half of the copper production. Besides sulfide minerals, copper also occurs in oxide forms such as cuprite (Cu_2O), malachite ($CuCO_3 \cdot Cu(OH)_2$), azurite ($2CuCO_3 \cdot Cu(OH)_2$), chrysocolla ($CuSiO_3 \cdot 2H_2O$), and mixed ores containing both oxidized and sulfide minerals.

Copper, a major non-ferrous metal, is present in the Earth's crust at a concentration of 50 parts per million (ppm). In mining operations, the copper content in open-pit mines is around 0.4%, while in underground mines it ranges from 1% to 2%, along with other valuable minerals and gangue materials. The geological distribution and chemical properties of copper require advanced extraction and processing technologies to maximize yield and efficiency (Gerardo et al., 2020: 04255-9).

Kazakhstan produces about 4% of the world's copper volume and 50% of the CIS production (Zhang et al., 2019: 5137852). The country's copper consumption is 8% of total production, with 22% exported to neighboring countries and 70% to distant markets. Kazakhstan ranks high in the global non-ferrous metals market in terms of reserves, mining, and refined copper production: 7th in refined copper production, 9th in copper reserves, and 11th in mining. Copper from Zhezkazgan and Balkhash is registered as a benchmark on the London Metal Exchange (LME). The observed rise in copper prices on the LME underscores the viability and potential for further investment in the copper industry in the Republic of Kazakhstan (Figure 1). The current price on the London Metal Exchange is $9,489.50 per ton (https://www.lme.com/Metals/Non-ferrous/LME-Copper/Summary).

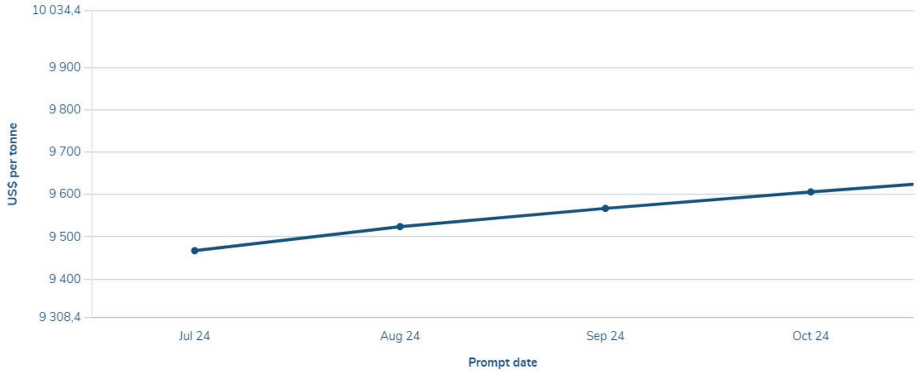


Figure 1 - Dynamics of Copper Prices in US Dollars (USD) per Ton for 2024

In Kazakhstan, the main copper deposits are copper sandstones, copper porphyry, and pyrite-polymetallic types. In 2017, copper ore extraction amounted to nearly 78.5 million tons, of which 26 million tons were mined in the Karaganda region, 28.5 million tons in the Pavlodar region, and 18.3 million tons in the East Kazakhstan region. A total of 10.5 million tons of copper concentrate and 408,435 tons of refined copper were produced. According to UBS Global Research, global demand for refined copper is increasing, reaching 24.4 million tons in 2017. The global population growth and urbanization demand significant investments in infrastructure, for which copper remains a primary raw material. The rising copper prices on the London Metal Exchange highlight the viability of investments in the development of the copper industry in Kazakhstan.

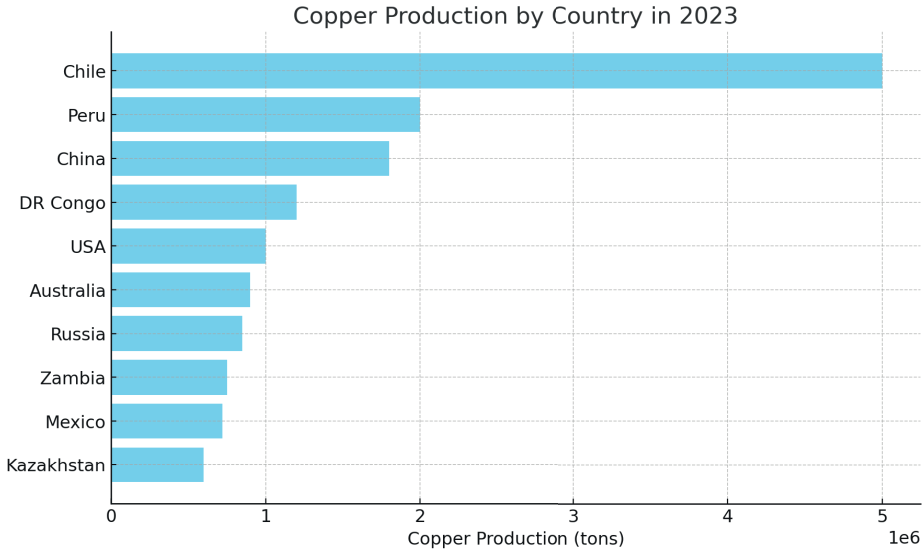


Figure 2 – Copper Production by Country in 2023

The main balance reserves of copper are concentrated in Eastern and Central Kazakhstan, predominantly in low-grade copper porphyry deposits (Chepushtanova et al., 2023: 11–19). Additional reserves include pyrite-polymetallic deposits in the eastern part of the republic (Artemyevskoye, Kosmurun, Akbastau, etc.). In the Karaganda region, the Kenshocky deposit in the Shetsky district and the Nurkazgan copper porphyry deposit with high-grade ores in Central Kazakhstan have been prepared for exploitation. In Southern Kazakhstan, the Shatyrkol copper deposit, and in the Zhezkazgan mining region, one of the largest deposits, Zhaman-Aibat, are notable. Copper porphyry deposits such as Aktogay, Aidarli, Koksay, and Bozshakol also possess significant potential (Koizhanova et al., 2023: 54; Nyamdelger et al., 2023: 26).

The modern copper mining sector faces several fundamental challenges. The depletion of high-grade deposits forces the transition to the development of ores with lower copper content, increasing processing volumes and, consequently, the costs of mining and beneficiation. Additionally, the need to develop deep-seated mines further escalates expenses. The technical complexities of processing such ores require the use of more advanced and costly technologies, leading to higher production costs for copper. This process is also associated with the necessity of impurity removal, requiring additional processing stages.

The primary objective of this research is to analyze the technological parameters and patterns that determine the efficient processing of copper ore from one of the deposits in Kazakhstan. Particular attention is given to studying the material composition of the ore, conducting comprehensive mineralogical and chemical analyses, and developing and optimizing beneficiation methods such as gravity and flotation. The research aims to obtain new data on the structural changes in copper ores during processing and to develop effective technological solutions for extracting valuable components, thereby enhancing the profitability and environmental sustainability of the copper ore processing process.

Object of study

The research object is copper ore from one of the deposits in Kazakhstan, located in the Karaganda region. The aim of this study is to develop an efficient technology for processing copper ore that contains both oxidized and sulfide copper minerals, as well as other associated components. The primary focus is on studying the material composition of the ore, conducting mineralogical and chemical analyses, and optimizing beneficiation and leaching methods to enhance the copper extraction rate.

The experimental part includes comprehensive laboratory studies such as X-ray fluorescence and X-ray phase analyses, gravity and flotation beneficiation, as well as sulfuric acid leaching. Various technological samples representing different parts of the deposit were selected for analysis: rocks with high malachite content, quartz-sulfide ores, and skarn types.

Experimental Section

Before initiating the research on processing copper ore from one of the deposits in Kazakhstan, the main parameters for gravity and flotation beneficiation, as well as sulfuric acid leaching, were established. A three-inch Knelson KC-MD 3 centrifugal concentrator with continuous discharge was used for gravity beneficiation, under conditions including a cone diameter of 7.5 cm, a water flow rate of 3.5 l/min, a pressure of 25 kPa, and a gravitational acceleration of 60 G.

Sample preparation involved grinding the ores to a fineness of 98% passing -0.071 mm. The samples prepared for the studies were subjected to X-ray fluorescence and X-ray phase analysis to determine their material composition. The loading of ore material samples into the concentrator was performed in averaged mass ratios.

For flotation beneficiation, a laboratory flotation machine of the “Mekhanobr” type with a chamber volume of 3.0 liters was used. Flotation was carried out at a pulp solid particles ratio of 33% in two stages, yielding primary and control concentrates, as well as final tailings. The reagent regime included butyl xanthate and frother C7 at pH 9.0

For sulfuric acid leaching, a sample ground to 80% passing -0.071 mm was used. Leaching was carried out with a 2.5% sulfuric acid solution at a solid-to-liquid ratio of 1:4 for 8 hours. The elemental composition of the initial ore from one of the deposits in Kazakhstan, presented in Table 1, was determined using fluorescence analysis, which allows for the detection of element spectra from oxygen to uranium.

Table 1 – Results of X-ray Fluorescence Analysis of Ore Samples from One of the Deposits in Kazakhstan

Element	Content, %	Element	Content, %	Element	Content, %	Element	Content, %
O	45.782	P	0.412	Mn	0.157	Mo	0.008
F	0.261	S	0.269	Fe	3.417	Ag	0.034
Mg	0.807	Cl	0.125	Cu	5.626	Ba	0.082
Al	3.113	K	0.722	Zn	0.541	Pb	8.557
Si	21.491	Ca	0.726	As	0.033		
Ti	0.116	Cr	0.025	Sr	0.012		

X-ray phase analysis determined the primary composition of the rock-forming components. The measurements were conducted using a D8 Advance (Bruker) apparatus, α-Cu, with a tube voltage of 40 kV and a current of 40 mA. The processing of the obtained diffractogram data and calculation of interplanar distances were performed using EVA software. Sample interpretation and phase identification were conducted using the Search/match program with the PDF-2 powder diffraction database. The results of the X-ray phase analysis are presented in Figure 3 and Table 2.

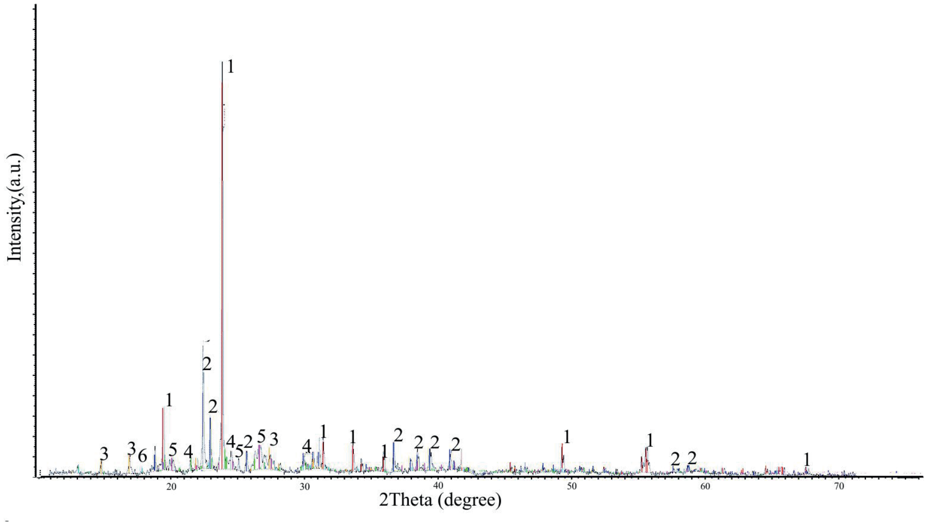
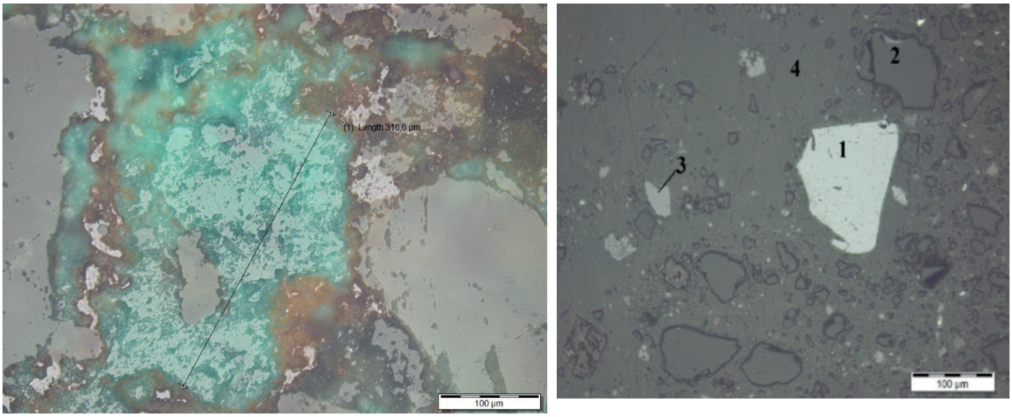


Figure 3 – Diffractogram of the Sample from One of the Deposits in Kazakhstan

Table 2 – Results of X-ray Phase Analysis of the Initial Sample from One of the Deposits in Kazakhstan

№	**Compound Name**	**Formula**	**Content. rel. %**
1	Quartz	SiO_2	63.3%
2	Cerussite	$PbCO_3$	19.3%
3	Malachite	$CH2Cu_2O_5$	6.2%
4	Orthoclase	KSi_3AlO_8	4.9%
5	Lead Phosphate	$Pb_3(PO_4)_2$	4.8%
6	Clinochlore	$Al\text{-}Fe\text{-}SiO_2\text{-}OH$	1.5%

A sample of ore from one of the deposits in Kazakhstan was studied using mineralogical analysis in reflected light with an OLIMPUS-BX 51 microscope. The main mass of the briquettes consists of non-metallic minerals, predominantly quartz. Among the rock-forming minerals, malachite was identified (Figure 4a). Cerussite appears gray in reflected light with low reflectivity, exhibiting strong bireflection and anisotropy. The internal reflections are bright and colorless. Cerussite is observed as irregular segregations with intricate contours, composed of anhedral grains ranging from a few hundredths to 0.05 mm in size (Figure 4b). Iron hydroxides and carbonaceous material are also present.



a
Malachite in Association with Iron Hydroxides

b
Cerussite (1), Quartz (2), Carbonaceous Material (3) in Gangue Mass (4)

Figure 4 – Mineralogical Analysis of the Sample at 400x Magnification

Phase analysis of the initial sample revealed the content of various forms of copper, lead, and other elements. The copper content in free oxidized minerals was 4.394%, in bound oxidized minerals—0.07%, in secondary sulfides—0.32%, and in primary sulfides—0.0095%, resulting in a total of 4.79%. The main copper minerals include malachite, azurite, tenorite, and cuprite, as well as bornite, chalcopyrite, and chalcocite (Table 3).

Table 3 – Phase Analysis of the Initial Sample from One of the Deposits in Kazakhstan

Mass fraction of determined elements, %					
Cu free oxidized mineral	Cu bound oxidized mineral	Cu secondary sulfides	Cu primary sulfides	ΣCu	Cu_{total}
4.394	0.07	0.32	0.0095	4.79	4.79
malachite, azurite, tenorite, cuprite	malachite, azurite, tenorite, cuprite	bornite, chalcopyrite, chalcocite	chalcopyrite, cubanit		

The sample from one of the deposits in Kazakhstan primarily consists of camallite, halite, and sylvite, which together constitute more than 86% of the total composition.

The presence of magnesium oxide, magnesium peroxide, and chlorargyrite is also significant, although their combined content is less than 13% of the total composition. These components indicate a high content of chlorides and magnesium compounds in the sample, which may be important for the further processing and utilization of the mineral raw material.

Discussion of Results

Gravity beneficiation was conducted using ground ore with a fineness of 98% passing -0.071 mm and was performed in a single stage, resulting in two main products – gravity concentrate and tailings. The obtained concentrates and tailings were analyzed for valuable component content after drying, with the concentrate sample also being used in further leaching experiments. The results of the gravity beneficiation are presented in Table 4.

Table 4 – Results of Gravity Beneficiation

Product	Weight, g	Mass yield, %	Cu, %	E Cu, %
Concentrate	77.3	7.7	10.388	13.35
Tails	922.7	92.3	5.65	86.65
Total	1000	100.00	6.02	100.00

The processing resulted in the separation of the initial sample into concentrate and tailings. The concentrate contains a high copper content (10.388%), but its yield is only 7.7% of the total mass. The tailings have a lower copper content (5.65%), but their mass yield is 92.3%, which explains the high proportion of recovered copper (86.65%) in the tailings. The overall processing is effective in extracting copper, although a significant portion of copper remains in the tailings, which may require further processing or optimization to increase copper recovery in the concentrate.

For flotation beneficiation experiments, samples from one of the deposits in Kazakhstan were ground in a ball mill to a fineness of 0.071 mm (90%). The following reagent regimes were used during flotation studies: for primary flotation – pH 9.0, butyl xanthate – 120 g/t, frother C7 – 60 g/t, duration – 10 minutes; for control flotation – pH 9.0, butyl xanthate – 60 g/t, frother C7 – 30 g/t, duration – 5 minutes. All obtained flotation concentrates and tailings were dried for further analysis.

The experimental scheme for determining the optimal grinding fineness of the flotation material is shown in Figure 5. The results of the flotation beneficiation experiments are presented in Table 5.

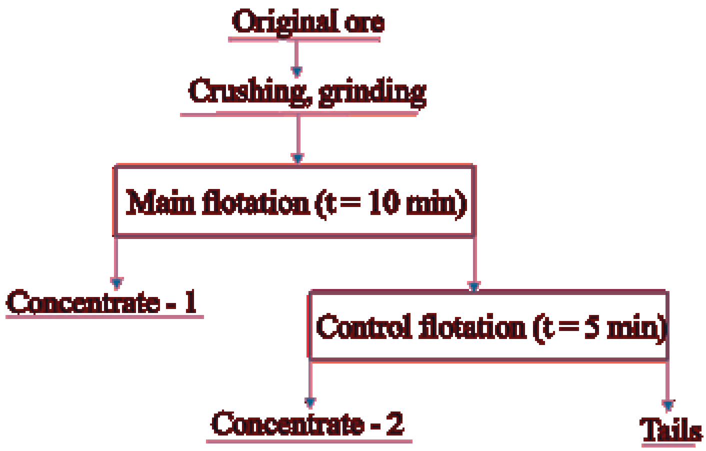


Figure 5 - Flotation scheme

Table 5 – Results of flotation enrichment

Product	Weight, g	Mass yield, %	Cu, %	E Cu, %
Basic concentrate	76.3	7.6	6.034	7.84
Control concentrate	93.5	9.4	6.429	10.24
Tails	830.2	83.0	5.793	81.92
Total	1000	100.00	5.87	100.00

The primary and control concentrates together constitute 17% of the total sample mass but contain relatively high copper concentrations (6.034% and 6.429%, respectively). The tailings, despite their large volume (83% of the total mass), contain less copper (5.793%) but account for the majority of the recovered copper (81.92%).

The overall processing is effective, but a significant portion of copper remains in the tailings, indicating a need for further optimization of the process to increase copper recovery in the concentrate.

For sulfuric acid leaching, an initial sample from one of the deposits in Kazakhstan, containing significant copper concentrations, was used. The filtrate of the productive solution was collected for copper content analysis, which was performed using the atomic absorption method on an AA-7000 instrument (Shimadzu, Tokyo, Japan). The results of the leaching of the sample from one of the deposits in Kazakhstan are presented in Table 6.

Table 6 - Results of sulfuric acid leaching of copper

primary Cu. %	Weight, g	V, L	Cu, g/l	E Cu, %
4.79	100	0.3	12.13	**75.8**

As seen in Table 6, the copper extraction process from the ore demonstrated high efficiency, achieving 75.8% copper recovery, with a copper concentration in the solution of 12.13 g/L.

Conclusion

Thus, a study of the material composition of copper ore from one of the deposits in Kazakhstan was conducted, and samples were collected. The main mass of the ore rock is represented by quartz, albite, and muscovite, while among the copper minerals, malachite, azurite, tenorite, and cuprite dominate. The copper content in the samples ranges from 4.394% in free oxidized minerals to 0.0095% in primary sulfides, totaling 4.79% copper.

The experiments on gravity and flotation beneficiation showed that optimizing the parameters of these processes significantly increases the yield of copper concentrate. Gravity beneficiation was conducted using ground ore with a fineness of 98% passing -0.071 mm on a 3-inch Knelson KC-MD 3 centrifugal concentrator, resulting in two main products – gravity concentrate and tailings. The results of the gravity beneficiation confirm the high efficiency of this method.

Flotation beneficiation experiments were conducted using laboratory flotation machines of the “Mekhanobr” type with butyl xanthate and frother C7 at pH 9.0. The obtained flotation concentrates and tailings were dried and further analyzed, which allowed for the determination of optimal conditions for the flotation beneficiation of copper ore. Sulfuric acid leaching showed high copper extraction efficiency—75.8%, with a copper concentration in the solution of 12.13 g/L.

The study confirmed the feasibility of using a comprehensive approach to processing copper-containing ores from one of the deposits in Kazakhstan. Optimization of beneficiation and leaching parameters ensures high copper extraction efficiency, opening prospects for the sustainable and economically viable utilization of complex copper ores.

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