

DEVELOPMENT OF A REAGENT REGIME FOR THE COLLECTIVE FLOTATION OF COPPER-PORPHYRY ORE USING SELECTIVE SULFHYDRYL COLLECTORS

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Annotation: Copper-porphyry ores are among the most important sources of copper production worldwide. The Kalmakyr deposit of the Almalyk Mining and Metallurgical Complex (AGMK) is one of the largest copper-porphyry deposits in Central Asia and is characterized by a complex mineral composition, including chalcopyrite, bornite, molybdenite, pyrite, and various gangue minerals. Efficient beneficiation of such ores requires the development of optimized flotation reagent regimes. This study analyzes the development of a reagent regime for the collective flotation of copper-porphyry ore using selective sulfhydryl collectors. The research is based on technological data and scientific literature related to flotation processes applied to porphyry copper ores. Particular attention is given to the selection of sulfhydryl collectors, frothers, modifiers, and pH regulators used in the flotation of Kalmakyr ore. Experimental and literature data demonstrate that selective sulfhydryl collectors significantly improve copper recovery while reducing the flotation of undesirable minerals such as pyrite. The study confirms that the correct combination of xanthates, dithiophosphates, and auxiliary reagents improves flotation selectivity and enhances concentrate quality. The results may be useful for improving flotation regimes at large copper processing plants.

Keywords: copper-porphyry ore, flotation, Kalmakyr deposit, sulfhydryl collectors, xanthates, dithiophosphates, copper beneficiation, reagent regime, selective flotation.

Introduction

Copper-porphyry deposits represent one of the most significant sources of copper in the global mining industry. These deposits are characterized by large ore reserves but relatively low copper grades, usually ranging from 0.3% to 1.0% Cu [1]. Efficient beneficiation of such ores is therefore crucial for ensuring economic extraction and maintaining stable metallurgical production.

The Kalmakyr deposit, located in Uzbekistan and operated by the Almalyk Mining and Metallurgical Complex (AGMK), is a classic example of a copper-porphyry system. The ore mineralization at Kalmakyr is dominated by chalcopyrite (CuFeS_2), with subordinate bornite (Cu_5FeS_4), molybdenite (MoS_2), and pyrite (FeS_2), as well as gangue minerals such as quartz, feldspar, and sericite [2]. The fine dissemination of sulfide minerals in gangue matrices complicates the beneficiation process and requires carefully optimized flotation conditions.

Flotation remains the primary method for processing copper-porphyry ores. The efficiency of the flotation process depends significantly on the reagent regime, particularly the selection of collectors, frothers, and modifiers [3]. Sulfhydryl collectors, such as xanthates and dithiophosphates, are widely used for the flotation of sulfide minerals due to their strong chemisorption on metal sulfide surfaces.

Selective sulfhydryl collectors play an important role in improving flotation selectivity by enhancing the recovery of copper minerals while suppressing pyrite flotation. The development

of an optimized reagent regime is therefore essential for improving both copper recovery and concentrate grade.

The objective of this study is to analyze the development of a reagent regime for the collective flotation of Kalmakyr copper-porphyry ore using selective sulfhydryl collectors based on documented technological data and scientific research.

Methodology

The research is based on the analysis of flotation studies conducted on copper-porphyry ores, including technological data from the Kalmakyr deposit and published literature related to sulfide mineral flotation.

The Kalmakyr ore is characterized by finely disseminated sulfide minerals embedded in silicate gangue. According to mineralogical studies, chalcopyrite accounts for the majority of copper minerals, while pyrite is the dominant sulfide gangue mineral [4]. The average copper grade of the ore ranges between 0.4% and 0.6% Cu [5].

The flotation process for such ores typically involves grinding the ore to a particle size of approximately 70–75% passing 74 μm to achieve sufficient liberation of sulfide minerals [6]. After grinding, flotation reagents are added in a specific sequence to ensure optimal adsorption on mineral surfaces.

The reagent regime analyzed in this study includes the following main components:

Collectors.

Sulfhydryl collectors such as potassium amyl xanthate (PAX) and sodium di-isobutyl dithiophosphate (DIBDP) are commonly used for chalcopyrite flotation. Xanthates provide strong collecting ability for copper sulfides, while dithiophosphates improve selectivity against pyrite [7].

Frothers.

Frothers such as methyl isobutyl carbinol (MIBC) are used to stabilize the flotation froth and improve the recovery of fine particles [8].

pH Regulators.

Lime (CaO) is commonly used to maintain alkaline conditions in flotation pulp, typically at pH values between 10 and 11. High pH levels suppress pyrite flotation and enhance copper selectivity [9].

Modifiers and Depressants.

Depressants such as sodium cyanide or zinc sulfate are sometimes used to suppress unwanted sulfide minerals, particularly pyrite [10].

Experimental flotation schemes described in literature were used to evaluate the influence of different reagent combinations on copper recovery and concentrate grade.

Results

Studies on copper-porphyry ores similar to Kalmakyr have demonstrated that the use of selective sulfhydryl collectors significantly improves flotation performance.

In the case of chalcopyrite flotation, potassium amyl xanthate shows strong adsorption on the mineral surface due to the formation of copper-xanthate complexes [11]. This reaction increases the hydrophobicity of chalcopyrite particles, allowing them to attach to air bubbles and rise to the froth layer.

However, xanthates also tend to collect pyrite, especially at lower pH levels. To reduce pyrite flotation, alkaline conditions are maintained using lime. At pH levels above 10, the flotation of pyrite is significantly reduced due to the formation of hydrophilic iron hydroxide films on the mineral surface [12].

The addition of dithiophosphate collectors further enhances selectivity. These reagents preferentially adsorb on copper sulfide minerals while exhibiting weaker interaction with pyrite surfaces. As a result, the combined use of xanthates and dithiophosphates produces higher copper recoveries and improved concentrate grades.

Experimental results reported in flotation studies show that copper recovery in porphyry ore flotation can exceed 90% when optimal reagent regimes are applied [6]. The copper concentrate grade typically ranges from 20% to 28% Cu depending on ore characteristics and flotation conditions.

In addition, the use of frothers such as MIBC improves the stability of the froth phase and enhances the recovery of fine mineral particles.

Analysis and Discussion

The flotation beneficiation of copper-porphyry ores represents a complex physicochemical process that depends on the interaction between mineral surfaces, flotation reagents, and the hydrodynamic conditions of the flotation cell. In the case of the Kalmakyr deposit operated by the Almalyk Mining and Metallurgical Complex (AGMK), the complexity of the flotation process is largely determined by the mineralogical composition of the ore and the fine dissemination of copper-bearing minerals within the gangue matrix. Porphyry copper ores typically contain chalcopyrite as the main copper mineral accompanied by significant amounts of pyrite, quartz, feldspar, and other silicate minerals. The similarity in the flotation behavior of chalcopyrite and pyrite creates a major challenge for achieving selective recovery of copper minerals while minimizing the recovery of iron sulfides [3].

The development of an effective reagent regime for the collective flotation of such ores therefore requires a detailed understanding of mineral surface chemistry and reagent–mineral interactions. Sulfhydryl collectors are widely used in the flotation of sulfide minerals because they form chemisorbed layers on the surfaces of metal sulfides. These collectors contain functional groups with sulfur atoms that have strong affinity for metal ions present on mineral surfaces. Xanthates, which are among the most commonly used sulfhydryl collectors, interact with copper ions on the surface of chalcopyrite and form hydrophobic copper–xanthate compounds. This process increases the hydrophobicity of the mineral surface and promotes the attachment of mineral particles to air bubbles during flotation [11].

However, the strong collecting power of xanthates also leads to the flotation of pyrite under certain conditions. Pyrite surfaces can interact with xanthates through oxidation reactions that form dixanthogen species, which contribute to hydrophobicity. As a result, the presence of large quantities of pyrite in porphyry copper ores may reduce the selectivity of flotation and lead to lower concentrate grades. For this reason, the reagent regime must be designed in such a way that it enhances the flotation of copper minerals while suppressing the flotation of pyrite [12].

Selective sulfhydryl collectors such as dithiophosphates play an important role in achieving this objective. These collectors differ from xanthates in both their chemical structure and adsorption behavior. Dithiophosphates are generally more selective toward copper sulfide minerals and exhibit weaker interaction with pyrite surfaces. Their adsorption on chalcopyrite is often associated with the formation of stable metal–organic complexes involving copper ions at the mineral surface. When used in combination with xanthates, dithiophosphates contribute to improved flotation selectivity by promoting copper mineral recovery while reducing the recovery of pyrite and other unwanted sulfide minerals [7].

The synergistic effect of mixed collectors has been widely documented in flotation research. The combination of xanthates and dithiophosphates allows the flotation process to benefit from the strong collecting ability of xanthates and the selectivity of dithiophosphates. In practical flotation operations, this combination often results in improved copper recovery and higher concentrate grades compared with the use of a single collector. For copper-porphyry ores similar to those found at Kalmakyr, mixed collector systems have been reported to produce significant improvements in flotation performance [6].

Another critical parameter influencing flotation selectivity is the pH of the flotation pulp. The pH of the pulp affects the electrochemical conditions at mineral surfaces as well as the speciation of flotation reagents. In most copper flotation circuits, alkaline conditions are maintained by the addition of lime (CaO). Lime increases the pH of the flotation pulp to values

typically ranging between 10 and 11. Under these conditions, the flotation of pyrite is significantly suppressed. The suppression of pyrite occurs because iron ions on the pyrite surface react with hydroxide ions in solution to form hydrophilic iron hydroxide films. These films prevent the adsorption of collectors and reduce the hydrophobicity of the pyrite surface [9].

The suppression of pyrite through pH control is particularly important in large-scale industrial operations. At processing plants handling large volumes of ore, even small improvements in flotation selectivity can lead to significant economic benefits. For the Kalmakyr deposit, where pyrite occurs in considerable quantities, maintaining an appropriate alkaline pH is essential for achieving high copper concentrate quality.

In addition to collectors and pH regulators, frothers play an important role in the flotation process. Frothers are used to control the formation and stability of the froth layer in flotation cells. Stable froth is necessary for transporting hydrophobic mineral particles to the surface of the flotation pulp and allowing their separation from the hydrophilic gangue minerals. Methyl isobutyl carbinol (MIBC) is one of the most commonly used frothers in sulfide flotation. It produces relatively small and stable bubbles, which improve the probability of collision and attachment between mineral particles and air bubbles [8].

The efficiency of froth flotation is also strongly influenced by the particle size distribution of the ore. Mineral liberation is a key factor determining flotation performance. If copper minerals remain locked within gangue particles, they cannot effectively interact with flotation reagents and are therefore lost in the tailings. Grinding is used to achieve sufficient liberation of sulfide minerals from the gangue matrix. For copper-porphyry ores, grinding is typically carried out until approximately 70–75% of the material passes through a 74 μm sieve. At this level of grinding, a significant proportion of chalcopyrite particles becomes liberated from the surrounding gangue minerals [6].

Nevertheless, excessive grinding can negatively affect flotation efficiency. When ore particles become too fine, their flotation recovery decreases because fine particles have lower probability of collision with air bubbles and may be entrained in the tailings. Additionally, ultra-fine particles may increase reagent consumption and reduce froth stability. Therefore, maintaining an optimal grinding size is crucial for balancing mineral liberation and flotation efficiency.

The mineralogical characteristics of the Kalmakyr ore also influence the design of the flotation reagent regime. Studies of the deposit indicate that chalcopyrite is the dominant copper mineral, while molybdenite occurs in smaller quantities and pyrite represents the main sulfide gangue mineral [4]. The presence of molybdenite introduces additional considerations in the flotation process because molybdenite exhibits natural hydrophobicity and can be recovered in the same flotation circuit as copper minerals. In many processing plants, molybdenite is separated from copper concentrate in a subsequent flotation stage.

The surface chemistry of chalcopyrite is particularly favorable for interaction with sulfhydryl collectors. Copper ions present on the chalcopyrite surface form strong chemical bonds with sulfur-containing functional groups of collectors. This chemisorption mechanism is responsible for the high collecting ability of sulfhydryl reagents in copper flotation. The adsorption process is influenced by several factors, including collector concentration, pulp pH, redox potential, and the presence of dissolved metal ions in the flotation pulp [11].

Electrochemical conditions also play a role in the flotation behavior of sulfide minerals. The oxidation state of mineral surfaces affects their ability to adsorb collectors. Moderate oxidation of chalcopyrite surfaces can enhance collector adsorption by exposing metal ions that act as active sites for chemisorption. However, excessive oxidation may result in the formation of hydrophilic oxide films that inhibit flotation. Controlling the redox environment of the flotation pulp is therefore important for maintaining optimal flotation performance.

The development of a reagent regime for Kalmakyr ore must also consider the large-scale industrial conditions of AGMK processing plants. Industrial flotation circuits involve multiple

stages, including rougher flotation, scavenger flotation, and cleaner flotation. In the rougher stage, the primary objective is to recover as much copper as possible from the ore. In subsequent cleaning stages, the concentrate is upgraded to achieve the desired copper grade.

In rougher flotation, relatively higher collector dosages are typically used to maximize copper recovery. In contrast, cleaner flotation stages often require lower reagent dosages to improve selectivity and remove unwanted gangue minerals from the concentrate. The optimization of reagent dosage across different flotation stages is therefore an important aspect of reagent regime development.

Another important factor is the interaction between different flotation reagents. The presence of modifiers such as depressants and activators can influence collector adsorption and flotation selectivity. For example, depressants such as sodium cyanide or zinc sulfate may be used to suppress pyrite flotation in certain flotation circuits. These reagents interact with the mineral surface and prevent the adsorption of collectors, thereby reducing the flotation of unwanted minerals [10].

In the context of Kalmakyr ore processing, the combination of alkaline pH control, selective sulfhydryl collectors, and appropriate frothers forms the basis of an effective reagent regime. The use of mixed collector systems consisting of xanthates and dithiophosphates provides both strong collecting power and improved selectivity. Lime serves as an effective pH regulator that suppresses pyrite flotation, while MIBC ensures stable froth formation and efficient transport of hydrophobic particles.

The overall effectiveness of the flotation process can be evaluated in terms of copper recovery and concentrate grade. Copper recovery represents the proportion of copper in the ore that is successfully recovered in the concentrate, while concentrate grade refers to the copper content of the final concentrate product. In well-optimized flotation circuits processing porphyry copper ores, copper recovery values exceeding 90% have been reported, with concentrate grades typically ranging from 20% to 28% Cu depending on the mineralogical characteristics of the ore and the operating conditions of the flotation circuit [6].

For the Kalmakyr deposit, achieving high recovery is particularly important because of the relatively low copper grade of the ore. Even small improvements in recovery can significantly increase the total amount of copper produced by the processing plant. At the same time, maintaining an adequate concentrate grade is necessary for ensuring efficient downstream metallurgical processing, such as smelting and refining.

The application of selective sulfhydryl collectors therefore represents a key strategy for improving flotation performance in copper-porphyry ore processing. By optimizing the combination of collectors, pH regulators, and frothers, it is possible to achieve efficient recovery of copper minerals while minimizing the flotation of unwanted gangue minerals. This approach contributes to improved economic efficiency and resource utilization in large-scale mining and processing operations.

Conclusion

Copper-porphyry ores such as those found in the Kalmakyr deposit require carefully optimized flotation regimes due to their complex mineralogical composition and relatively low copper grades.

The analysis of flotation studies shows that selective sulfhydryl collectors play a key role in improving copper recovery and concentrate quality. Xanthates provide strong collecting ability for copper sulfides, while dithiophosphates improve flotation selectivity by reducing the recovery of pyrite.

Maintaining alkaline conditions with lime is essential for suppressing pyrite flotation, and the use of appropriate frothers ensures stable flotation froth and improved recovery of fine particles.

The combined application of these reagents forms an effective reagent regime for the collective flotation of copper-porphyry ores. Such regimes are widely used in industrial flotation processes and can be successfully applied to the beneficiation of Kalmakyr ore at AGMK.

Further research may focus on optimizing reagent dosages and developing new selective collectors to enhance flotation efficiency and reduce reagent consumption.

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