MECHANISTIC STUDY OF ACTIVATING REAGENTS IN COPPER ORE BENEFICIATION PROCESSES

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Abstract. This paper presents a mechanistic study of activating reagents used in copper ore beneficiation processes. The research focuses on the interaction between activating ions and the surface of copper sulfide minerals, collector adsorption behavior, and changes in surface charge and electrokinetic properties during flotation. Experimental results demonstrate that activating reagents promote the formation of active sites on mineral surfaces, thereby enhancing collector attachment and improving copper recovery. It is shown that the dosage of activating reagents has a significant influence on flotation performance, with optimal concentration ranges providing maximum beneficiation efficiency. The findings provide a scientific basis for optimizing reagent regimes, improving flotation efficiency, and reducing reagent consumption in copper ore beneficiation operations.

Keywords: Copper ore beneficiation; Flotation; Activating reagents; Mineral surface mechanism; Collector adsorption; Surface charge; Electrokinetic properties; Sulfide minerals

Аннотация. В статье проведено комплексное исследование механизма действия активирующих реагентов в процессах обогащения медных руд. Основное внимание уделено изучению взаимодействия активирующих ионов с поверхностью сульфидных минералов, адсорбции коллекторов и изменению поверхностных и электрохимических свойств минералов в процессе флотации. Экспериментальные результаты показали, что активирующие реагенты способствуют формированию активных центров на поверхности минералов меди, что повышает эффективность адсорбции коллекторов и улучшает извлечение меди. Установлено, что концентрация активирующих реагентов существенно влияет на показатели флотационного обогащения, при этом существуют оптимальные диапазоны их применения. Полученные результаты могут быть использованы для повышения технологической эффективности флотации и снижения расхода реагентов в процессах обогащения медных руд.

Ключевые слова: Обогащение медных руд; Флотация; Активирующие реагенты; Механизм взаимодействия с поверхностью минералов; Адсорбция коллекторов; Поверхностный заряд; Электрокинетические свойства; Сульфидные минералы

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Annotatsiya. Ushbu maqolada mis rudalarini boyitish jarayonlarida qo‘llaniladigan faollashtiruvchi reagentlarning ta’sir mexanizmi kompleks ravishda tadqiq etilgan. Tadqiqot flotatsiya jarayonida faollashtiruvchi ionlar va reagentlarning mineral yuzasi bilan o‘zaro ta’siri, kollektorlarning adsorbsiyasi hamda sirt zaryadi va elektrokinetik xususiyatlarning o‘zgarishini o‘rganishga qaratilgan. Eksperimental tadqiqotlar natijasida faollashtiruvchi reagentlarning sulfidli mis minerallari yuzasida faol markazlar hosil qilishi va natijada kollektorlarning samarali birikishini ta’minlashi aniqlangan. Faollashtiruvchi reagentlar konsentratsiyasining optimal qiymatlari flotatsiya samaradorligi va mis ajralish darajasiga sezilarli ta’sir ko‘rsatishi ko‘rsatib berilgan. Olingan natijalar mis rudalarini flotatsion boyitish jarayonlarini optimallashtirish va reagentlar sarfini kamaytirish uchun ilmiy-amaliy asos bo‘lib xizmat qiladi.

Kalit so‘zlar: Mis rudalarini boyitish; Flotatsiya; Faollashtiruvchi reagentlar; Mineral yuzasi mexanizmi; Kollektor adsorbsiyasi; Sirt zaryadi; Elektrokinetik xususiyatlar; Sulfidli minerallar

INTRODUCTION

Copper remains one of the most strategically important metals in modern industry due to its extensive use in electrical engineering, renewable energy systems, electronics, and construction. As high-grade copper deposits are gradually depleted, the processing of low-grade, complex, and finely disseminated copper ores has become increasingly important. In this context, flotation continues to be the primary beneficiation method for copper ores; however, its efficiency is strongly dependent on reagent schemes and surface chemical interactions.

Activating reagents play a critical role in flotation by modifying the physicochemical properties of mineral surfaces and enhancing their affinity for collectors. In copper ore beneficiation, activators such as copper sulfate, lead nitrate, and metal ions are commonly used to promote the flotation of sulfide minerals, particularly in ores containing oxidized surfaces, complex mineral associations, or secondary copper minerals. Despite their widespread industrial application, the fundamental mechanisms governing the action of activating reagents remain insufficiently understood, especially under varying mineralogical and chemical conditions.

The effectiveness of activating reagents is closely related to their ability to alter surface charge, promote collector adsorption, and induce the formation of chemically active sites on mineral surfaces. These processes are influenced by multiple factors, including reagent dosage, pulp pH, mineral composition, surface oxidation state, and the presence of competing ions in the flotation system.

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Improper selection or dosing of activators may lead to excessive reagent consumption, reduced selectivity, or unstable flotation performance.

Recent advances in surface chemistry, electrokinetic measurements, and spectroscopic techniques have enabled a more detailed investigation of reagent–mineral interactions at the micro- and nanoscale. However, there is still a need for systematic studies that link surface chemical mechanisms with flotation performance parameters such as recovery, selectivity, and reagent efficiency.

Therefore, this study aims to investigate the mechanistic role of activating reagents in copper ore beneficiation processes by analyzing their influence on mineral surface properties, collector adsorption behavior, and flotation performance. The results are expected to contribute to the development of optimized reagent regimes, improved process efficiency, and reduced operating costs in copper flotation operations.

The flotation behavior of copper minerals is fundamentally governed by surface chemical processes occurring at the mineral–solution interface. Activating reagents modify these surface properties, thereby enhancing the interaction between copper-bearing minerals and flotation collectors. Understanding the surface chemistry underlying activation mechanisms is essential for improving flotation selectivity and efficiency.

Copper sulfide minerals such as chalcopyrite, bornite, and chalcocite often exhibit surface oxidation during grinding and conditioning, leading to the formation of hydrophilic oxide or hydroxide layers. These layers reduce collector adsorption and negatively affect flotation performance. Activating reagents, particularly metal ions (e.g., Cu^{2+}, Pb^{2+}), restore surface reactivity by forming new chemically active sites that promote collector attachment.

The primary activation mechanism involves the adsorption of metal ions onto the mineral surface through ion exchange, surface precipitation, or chemical bonding. For example, Cu^{2+} ions adsorb onto oxidized copper mineral surfaces, increasing surface positive charge and facilitating electrostatic attraction with anionic collectors such as xanthates. This process enhances the formation of metal–collector complexes, which increase surface hydrophobicity.

Another important mechanism is the modification of surface electrokinetic properties. Activation typically shifts the zeta potential toward more positive values, expanding the pH range in which collector adsorption is favorable. This effect is particularly significant in systems containing mixed sulfide–oxide copper minerals, where surface charge heterogeneity can impair flotation selectivity.

Additionally, activating reagents can influence redox reactions at the mineral surface. By promoting controlled surface oxidation or reduction, activators regulate

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the availability of metal ions necessary for stable collector bonding. However, excessive activation may lead to non-selective adsorption and increased gangue flotation, emphasizing the need for optimized reagent dosages.

Table-1.

Surface chemical effects of common activating reagents in copper flotation

Activating reagent	Target mineral surface	Main surface reaction mechanism	Effect on surface chemistry	Impact on flotation performance
Copper sulfate ($CuSO_4$)	Oxidized copper sulfides	Cu^{2+} adsorption and ion exchange	Increases positive surface charge; creates active Cu sites	Enhances collector adsorption and copper recovery
Lead nitrate ($Pb(NO_3)_2$)	Secondary copper minerals	Surface precipitation of Pb compounds	Improves collector bonding and surface hydrophobicity	Improves flotation of difficult-to-float minerals
Sodium sulfide (Na_2S)	Oxide copper minerals	Sulfidization of oxide surfaces	Converts hydrophilic oxides to sulfide-like surfaces	Enables sulfide-type collector flotation
Metal ion mixtures	Complex ores	Competitive adsorption and surface complexation	Adjusts surface charge distribution	Improves selectivity in complex ore systems

The experimental results demonstrate that activating reagents play a decisive role in enhancing the flotation performance of copper-bearing minerals through modification of surface chemical properties. The addition of Cu^{2+} ions as activators significantly improved copper recovery, confirming their effectiveness in promoting collector adsorption and mineral hydrophobicity. The observed increase in recovery with increasing activator dosage up to an optimal level indicates that surface activation is strongly dosage-dependent.

Zeta potential measurements revealed a systematic shift toward less negative and eventually positive values with increasing Cu^{2+} concentration. This shift suggests enhanced electrostatic attraction between the mineral surface and anionic collectors, facilitating stronger adsorption. The correlation between zeta potential evolution and flotation recovery highlights the importance of surface charge

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modification as a primary activation mechanism. However, beyond the optimal activator dosage, the marginal improvement in recovery diminished, likely due to surface saturation or competitive adsorption effects.

The experimental program involved controlled flotation tests using different activator types and concentrations. Surface characterization methods were applied to correlate flotation performance with changes in surface properties.



Fig-1. Experimental workflow for studying activation mechanisms in copper ore flotation

Representative copper ore samples containing sulfide copper minerals were collected, crushed, and ground to a particle size of −74 µm (approximately 70–75% passing). Prior to flotation testing, the samples were homogenized and dried to ensure consistency. Mineralogical composition was determined using X-ray diffraction (XRD) and optical microscopy to identify dominant copper-bearing phases and gangue minerals.

Copper sulfate ($CuSO_4$) was selected as the primary activating reagent due to its widespread industrial application. A xanthate-based collector and a standard frother were used in all tests. The pulp pH was adjusted using lime or sulfuric acid, depending on test conditions.

Conditioning was conducted in stages: first, the activating reagent was added to the pulp and conditioned for a fixed period to allow surface interaction with mineral particles. Subsequently, the collector and frother were introduced. This sequential conditioning ensured that surface activation occurred prior to collector adsorption.

Collector adsorption studies further confirmed that activator ions increase the density of chemically active sites on the mineral surface. The formation of metal–collector complexes, particularly copper–xanthate species, appears to be the dominant mechanism responsible for improved flotation selectivity. Excessive activator addition, however, may lead to non-selective adsorption on gangue minerals, potentially increasing entrainment and reducing concentrate grade.

The combined analysis of flotation performance, zeta potential behavior, and adsorption characteristics indicates that activation is governed by a balance

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between chemical interaction and electrostatic forces. These findings emphasize the necessity of precise control over activator dosage and conditioning parameters to achieve optimal beneficiation efficiency.

Overall, the results confirm that a mechanistic understanding of activating reagent behavior is essential for optimizing flotation reagent schemes, improving copper recovery, and minimizing reagent consumption in industrial beneficiation processes.

The study confirms that activating reagents are crucial for enhancing copper ore flotation performance. Understanding their mechanisms of action allows for rational reagent selection and improved process efficiency in copper beneficiation plants.

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