DEVELOPMENT OF COMPOSITE CHEMICAL FLOATING REAGENTS AND THEIR APPLICATION IN THE EXTRACTION PROCESS OF NON-FERROUS AND PRECIOUS METALS

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Abstract - This study establishes the scientific foundations for the development and comprehensive investigation of composite chemical flotation reagents – foam-forming agents, formulated from a combination of organic and inorganic components, and intended for effective application in the flotation processes of ores containing nonferrous and noble metals. The importance of this study lies in the need to replace imported flotation reagents widely used in Uzbekistan's metallurgical industry and to improve both the efficiency and environmental safety of flotation processes. As a raw material base, locally available and secondary components were used, including gossypol resin, injection-adhesion fraction of alcohol production, glycerol, ethylene glycol, sodium lauryl sulfate, alkylbenzene, and urea. A comprehensive analytical approach—combining IR spectroscopy, X-ray diffraction, and thermal analysis—was applied to determine the chemical structure and physicochemical properties of the developed reagents. It has been shown that the composite flotation reagents CHF-FS exhibit high foam stability and optimal density, viscosity, and pH values comparable to the standard industrial reagent T-92. Tests conducted on copper–molybdenum ores from the Kalmakyr deposit (Almalyk Mining and Metallurgical Complex JSC) confirmed the efficiency of the developed compositions: copper recovery into the rougher concentrate reached 91.35%, which is nearly equivalent to that achieved with T-92. Among them, the KXF-VS-B3 composition demonstrated the best foaming ability and foam stability. Additional flotation tests showed that gold recovery using KXF-VS-MGS averaged 53.66% compared to 60.9% with T-92, indicating the need for further optimization of reagent composition. The obtained results confirm the scientific and practical significance of organic–inorganic composite frothers as effective and environmentally safe alternatives to imported analogs, enabling cost reduction and supporting the development of the national chemical and metallurgical industry.

Keywords: Flotation, Flotation reagents–frothers, Composite reagents, Organic–inorganic components, Copper recovery, Gold recovery, Flotation efficiency, Foaming properties.

1. Introduction

The metallurgical industry plays a key role in the global economy, providing strategic resources for energy, mechanical engineering, electronics, and other high-tech industries. With the declining quality of mineral raw materials and the depletion of rich deposits, methods for processing low-grade, complex, and difficult-to-process ores are becoming increasingly important, with flotation remaining the most versatile and selective beneficiation method [1–3].

The efficiency of flotation processes is largely determined by the flotation reagents used. Traditional reagents based on alcohols, oils, and simple organic compounds (xanthates, alkyl sulfates, etc.) provide a stable process, but have several limitations: high cost, dependence on imports, limited selectivity, and environmental risks [4-6].

Recent research indicates that the global flotation reagent market is rapidly transforming: approximately 52% of reagents used today are "green" or environmentally friendly formulas, and

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more than 60% of mining companies are implementing sustainable flotation technologies [5].

One of the promising areas is the creation of innovative biopolymers and low-toxicity reagents [6-7]. Thus, the polymer collector Lixomax 6499 (BASF) demonstrated a 40% reduction in toxicity to aquatic organisms compared to traditional xanthates [8, 9]. Other developments, including Florrea Ecoxanthater (KNR) and Aero 7249, have demonstrated high efficiency in the flotation of copper-molybdenum, gold-bearing, and multicomponent ores, ensuring the extraction of precious metals up to 95.9% [8-10]. These data confirm the potential of using composite flotation reagents based on organo-inorganic systems.

In Uzbekistan, which boasts a large metallurgical base (Almalyk Mining and Metallurgical Combine, Navoi Mining and Metallurgical Combine, and others), the problem of import dependence on flotation reagents remains extremely pressing. Currently, enterprises widely use imported foaming agents (T-92, MIBK, and others), while local raw materials and industrial waste could become a source for the creation of effective import-substituting compounds [11-19]. Recent studies have shown that the use of domestic composite flotation reagents (Qualitet series) can increase the extraction of copper, molybdenum, and gold from porphyry copper-gold ores, as well as reduce the consumption of traditional reagents [13-14].

In this regard, the development of a new generation of composite flotation reagents-frothers based on local and secondary resources in Uzbekistan is of scientific, technological, and strategic importance. This study aims to establish a scientific basis for the synthesis of these reagents and analyze their effectiveness in the flotation of copper-molybdenum ores.

2. Research Methodology

A wide range of organic and inorganic compounds were used in the study, including glycerin, ethylene glycol, isoamyl alcohol (IAA), alkylbenzene, sodium lauryl sulfate, oleic acid, urea, castor oil, industrial oil (I-20A), sodium hydroxide, and calcium oxide. Copper-molybdenum ore from the Almalyk Mining and Metallurgical Plant, as well as secondary raw materials from the processing of alcohol and oil and fat production, were used as mineral raw materials.

The study was carried out using a complex of modern physicochemical methods, including infrared spectroscopy, X-ray diffraction analysis (XRD), differential thermal analysis (DTA), atomic absorption spectroscopy (AAS), inductively coupled plasma mass spectrometry (ICP-MS), as well as a flotation machine of the FML12 type (247 FL) and other generally accepted analytical techniques.

Copper-molybdenum ore samples from the Kalmakyr deposit, collected at the copper processing plant of JSC Almalyk MMC, were used as study objects. The chemical composition of the ores was determined using atomic absorption spectroscopy (AAS) and inductively coupled plasma optical emission spectrometry (ICP-OES). The mineralogical composition of the samples was studied using X-ray diffraction (XRD) analysis and optical microscopy.

Before flotation testing, the ore was crushed and ground in a laboratory ball mill. Grind size control was performed using sieve analysis; the grinding degree was 70% (0.071 mm).

Flotation experiments were conducted in a laboratory mechanical flotation machine with a 3.0-liter chamber volume. The solids content of the pulp was maintained at 25-45%. Distilled water was used in all experiments to eliminate the influence of foreign impurities. The pulp pH was adjusted using calcium oxide (CaO) and maintained in the pH range of 10.5-11.0 for the flotation of gold and polymetallic sulfide ores.

During the experimental studies, the test reagents were introduced into the flotation machine chamber in their natural form by dropwise dosing in accordance with GOST 14180-80. The pilot tests were carried out in open and closed cycles under the following experimental conditions: copper-molybdenum ore grinding - 21 min (the content of -0.071 mm classes reached 70%); frother consumption - 45 g/t; pH adjustment to 10.5–11.0 using CaO; rough flotation - 5 min (xanthate consumption - 17 g/t); control flotation - 7 min (xanthate consumption - 7 g/t).

Flotation machines come in various designs, but their primary purpose is to ensure stable suspension of ore particles in the pulp and to supply air, which is dispersed by an impeller. The air concentration in the pulp reaches up to 25%, with the maximum bubble diameter not exceeding 2 mm. During flotation, the solid phase (25–45%) of the ore, crushed to the required fineness and diluted with water, is treated with appropriate reagents that enhance the difference in hydrophilicity between the extracted minerals and those subject to depression. The prepared suspension is then sent to the flotation chamber, where the components are selectively separated based on their wettability. When a hydrophobic particle contacts an air bubble, it adheres, while hydrophilic minerals are not retained by the bubbles. Due to their lower density compared to the pulp, the air bubbles, to which the metal particles adhere, rise at a speed of up to 8 cm/s, forming a crude concentrate of non-ferrous and precious metals.

The process flow diagram for determining the flotation capacity of the developed reagents is shown in Figure 1.

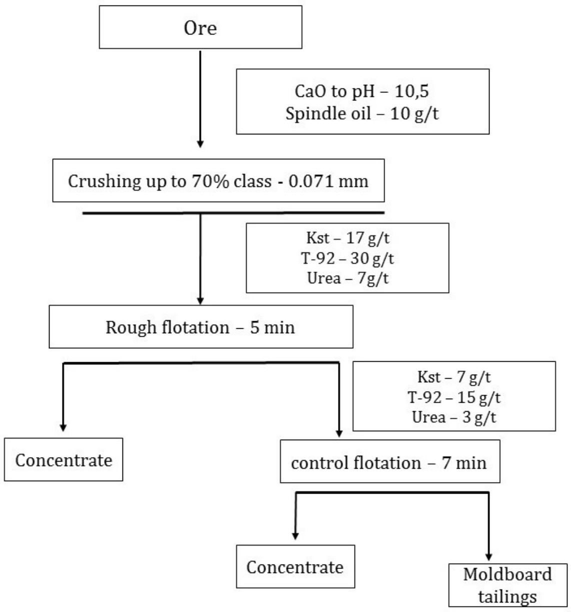


Figure 1: Scheme for conducting laboratory experiments in an open cycle on the ore of the Kalmakyr deposit

Pulp agitation after each reagent addition lasted 1-2 minutes. The total flotation duration per experiment ranged from 10-12 minutes. Air was supplied at a flow rate of 0.8-1.2 l/min. The impeller speed of the flotation machine was maintained at 1200-1500 rpm, ensuring a standard, stable aeration regime. All experiments were conducted at ambient temperature (20-25°C).

The flotation circuit included rougher flotation and scavenger flotation, followed by one or two cleaning operations. Concentrates and tailings from each stage were collected separately, dried, weighed, and sent for chemical analysis. Each experiment was repeated at least three times under identical conditions. Flotation efficiency depends not only on the chemical composition of the medium but also on the technical characteristics of the equipment, which ensures optimal conditions for the interaction of ore particles with reagents.

3. Results and Discussions

In accordance with the above, in the development of domestic composite flotation reagents-foaming agents, the objects of study were gossypol resin, glycerin, ethylene glycol, alkylbenzene, sodium lauryl sulfate, and urea, as well as injection-adhesive fraction (IAF) of alcohol production, and existing industrial flotation reagents.

A study of the properties of the selected ingredients showed that they possess polar chemical bonds, dissolve well in polar solvents, have foaming properties, and meet the basic requirements for flotation reagents. Taking into account their interaction with metals and their impact on extraction efficiency, a model flotation reagent composition was developed.

Research has shown that the developed flotation reagent-foaming agent, provisionally designated KHF-VS, is comparable to the industrial T-92 reagent in terms of foaming properties, foam stability, and mineral extraction efficiency, and meets the basic requirements of the flotation process.

Table 1. Phase composition of the ore

Phase composition				The proportion of Cu in the sum of fractions, %	sulfide, %
Oxidized minerals		Sulfide minerals			
Isolated	Included	Primary	Secondary		
0,01	0,01	0,01	0,39	0,42	95,2

To evaluate the flotation capacity of the model composition of the flotation reagent, a sample of the active copper-molybdenum ore of the Kalmakyr deposit was used, the phase analysis of which is given in Table 1. The table shows that the ore contains a limited amount of non-ferrous and precious metals, the efficient extraction of which requires enrichment.

To evaluate the effectiveness of the developed samples of composite chemical flotation reagents-foaming agents, they were transferred to "Almalyk Mining and Metallurgical Combine" for the purpose of conducting experimental and industrial tests. The test results showed that the model composition did not provide sufficient foam stability and the required level of concentrate extraction, and was inferior in efficiency to the T-92 flotation reagent.

To improve flotation efficiency using the developed composite chemical flotation reagents-frothers, their interaction with minerals comprising non-ferrous metal sulfide ores was studied. Research has shown that hydrophobic properties are imparted to the mineral surface with the participation of sulfide collectors, such as xanthates [20–24]. Adsorption of xanthate anions on the mineral surface leads to the oxidation of sulfur present in the polysulfide ores (1):

$$CuSO_4 + 2C_4H_9OCSSK = (C_4H_9OCSS)_2Cu + K_2SO_4 \quad (1)$$

This ion exchange reaction demonstrates the successful interaction of copper sulfide minerals (Cu^{2+}) with xanthate-based flotation reagents and, during the flotation process, metal ions form stable complex compounds with xanthates to form potassium hydroxide (KOH). These reactions provide hydrophobization of the mineral surface, significantly improving their adhesion to air bubbles during flotation. In other words, xanthates act as effective collectors, allowing for the selective and efficient extraction of rough concentrate of copper, molybdenum, silver, gold, and other precious metals from ores.

The developed flotation reagents-frothers ensure selective separation of the material: hydrophobic sulfides adhere to the bubbles, forming a concentrate, while hydrophilic minerals precipitate. Taking into account the identified interaction mechanisms [20-25], Table 2 presents effective formulations of the developed chemical flotation reagents - foaming agents [8-9].

Table 2. Optimal compositions of flotation reagents

№	Organic-inorganic ingredients	KXF-VS-B1	KXF-VS-B2	KXF-VS-B3	KXF-VS-B4	KXF-VS-B5
		Mass part, kg				
1.	Composite powder GS, 10% solution	280	240	424	213	111
2.	Composite polymer adhesive KPK, 10% aqueous solution	260	230	200	150	100
3.	Glycerin, 50% aqueous solution	220	350	120	470	590
4.	Solvent (waste from alcohol production) IAF	200	132,5	102	72	40
5.	Sodium lauryl sulfate	15	20	94	50	94
6.	Alkylbenzene	10	15	50	37,5	60
7.	Caustic soda (NaOH)	15	12,5	10	7,5	5

To study the physicochemical properties of the developed flotation reagents, the dependence of their composition on the density, viscosity, and pH of the solution was studied in comparison with T-92 (Figure 2) [5, 8, 12, 21].

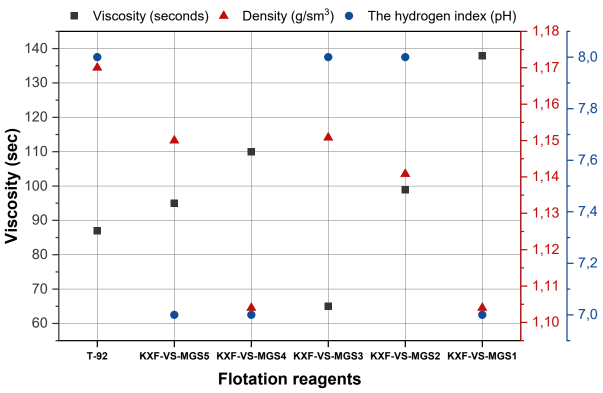


Figure 2: Comparative analysis of the influence of density (red), viscosity (black), and medium pH (blue) on the properties of the developed composite flotation reagents–frothers and the T-92 reagent

From the data presented in Figure 2, it can be seen that the density of composition №3 corresponds to the value of flotation reagent T-92 (Fig. 2, red), the viscosity is lower than T-92 (Fig. 2, black), and the pH value of samples KHF-VS-B2 and KHF-VS-B3 corresponds to the value of T-92 (Fig. 2, blue).

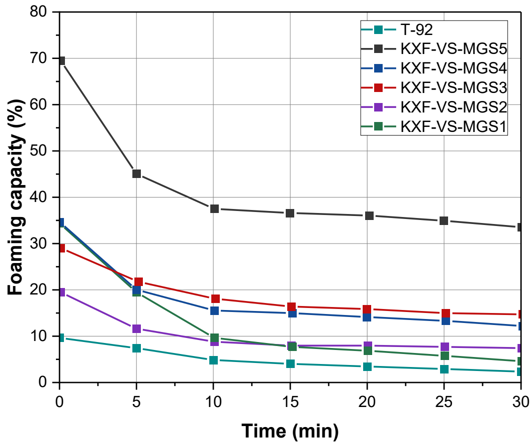
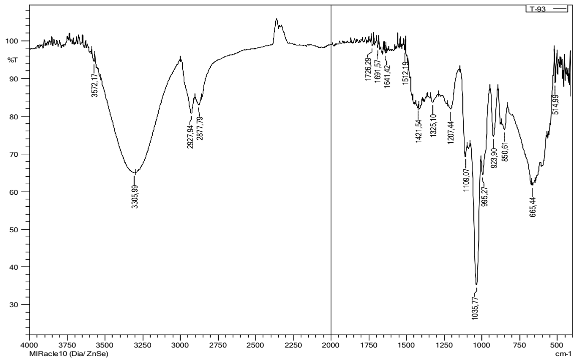


Figure 3: Kinetics of foam stability of aqueous solutions of flotation reagents V, mL – foam volume; P, % – foaming ability; U, % – foam stability

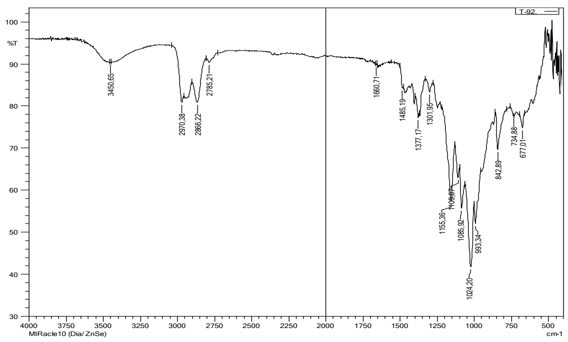
The following are the results of the influence of the developed flotation reagents-foaming agents on foam formation and foam stability in aqueous solutions of copper-molybdenum ore (Figure 3). The presented data showed that the flotation reagent KXF-VS-B3 on a water-alcohol basis has better foaming properties and foam stability compared to the flotation reagent T-92.

The foam that formed with the remaining compositions quickly subsided, and therefore further studies were carried out with a sample of flotation reagent №3.

To assess the quality of the flotation reagent KXF-VS-B3, IR spectroscopic studies were conducted in comparison with the flotation reagent T-92. The results are presented in Figure 4 (a, b).



a)



b)

Figure 4: IR spectral characteristics of the composite flotation reagent–frother KHF-VS-B3 (a) and the standard reagent T-92 (b)

In Figures 4 (a and b), a broad absorption band can be seen at 3305.99 cm^{-1}, which is attributed to the stretching vibrations of the –OH group of alcohols. Additional bands at 1109 cm^{-1}, 1035 cm^{-1}, 1024 cm^{-1}, and 665 cm^{-1} indicate the presence of acetal groups that support foam formation and stability.

The flotation capacity of the developed composite chemical flotation reagent was then studied in open- and closed-loop copper-molybdenum ore beneficiation processes. Open-loop tests were conducted according to the approved process flow chart and ensured duplicate results.

The research compared the effectiveness of the newly developed flotation reagents, KXF-VS-B3, with the Russian equivalent, T-92, currently in use. The experimental program included an assessment of foaming parameters, foam stability, copper yield, and the quality of the resulting concentrate. The test results showed that sample №3 demonstrated the best characteristics: the copper content was 6.74%, the quality was 5.9%, and the degree of copper extraction into concentrate reached 91.35%. For comparison, when using the standard flotation reagent T-92, the copper extraction was 91.49%, with a copper content of 5.71% and a concentrate quality of 7.0 [26-31].

The results show that the flotation capacity of the composite chemical flotation reagent brand KXF-VS-B3 is practically no different from that of the T-92 reagent.

Experiments to evaluate the effectiveness of composite flotation reagents were conducted using KXF-VS-B3 (sample no. 3) and the standard T-92 frother at dosages of 35–55 g/t under the conditions of “Almalyk Mining and Metallurgical Combine” JSC. Closed-loop tests on Kalmakyr copper-molybdenum ores confirmed the ability of KXF-VS-B3 to effectively provide flotation (results are presented in Table 3).

Table 3. Results of experiments on the extraction of copper concentrates in a closed mode using a flotation circuit

Product name	Yield, %	Content, %	Extracted, %	Note
		Copper	Copper	
Concentration	2,07	16,56	87,47	T-92 30 g/t
Final tailings	97,93	0,05	12,53	
Original ore	100,0	0,39	100,0	
Concentration	2,08	16,8	87,69	KXF-VS-B3 30 g/t
Final tailings	97,92	0,05	12,31	
Original ore	100,0	0,40	100,0	

The data presented shows that when using the T-92 flotation reagent, copper concentrate recovery reached 87.47% with a copper content of 16.56% and a product yield of 2.07%.

When using the KXF-VS-B3 pilot sample under similar conditions, copper concentrate recovery reached 87.67%. The copper content was 16.8%, and the quality was 2.08%.

Thus, the composite flotation reagent KXF-VS-B3 fully meets the requirements of metallurgical enterprises and has the potential to be used in the flotation process of copper-molybdenum ores.

It should also be noted that the composite flotation reagent brand KFH-VS-MGS, created under the same conditions as the currently used standard flotation reagent-foamer T-92, was experimentally tested for the extraction of gold from copper-molybdenum ore during flotation in laboratory and production conditions of Plant of JSC Almalyk MMC. The tests were carried out under the same conditions: grinding time — 21 min, class content – 0,071 mm — 69%; the consumption of foaming agent was 9 g/t; The pH value was adjusted with lime (CaO) to the level 10,5–11,0. The primary flotation was carried out for 5 minutes with a collector feed rate of 17 g/t, and the control flotation was carried out for 7 minutes with a collector dosage of 7 g/t. The results obtained are presented in Table 4.

Table 4. Results of comparative tests on gold recovery using the T-92 flotation reagent and the newly developed KXF-VS reagent

Industrial T-92		developed KXF-VS-MGS	
Au ore content, g/t	Au recovery rate, %	Au ore content, g/t	Au recovery rate, %
0,40	65,00	0,40	50,19
0,38	64,12	0,40	50,51
0,44	53,54	0,40	56,79
0,36	61,67	0,36	60,02
0,42	61,43	0,35	49,91
Average 0,40	60,89	0,37	53,65

According to the table, when flotation was performed using the expensive standard flotation reagent T-92, with a gold content of 0.36–0.42 g/t, gold recovery was 60.89%. When using the composite flotation reagent class KXF-VS-MGS under similar conditions, with a gold content of 0.36–0.40 g/t, recovery was 53.65%.

Considering that using the composite flotation reagent KXF-VS-MGS in the flotation of copper-molybdenum ores results in lower gold recovery than using the flotation reagent T-92, and their cost is the same. Further research in this area is planned to further improve the performance properties and reduce the cost of KXF-VS-MGS. Therefore, the goal was to develop new, more convenient, cost-effective, efficient, and affordable types of flotation reagents belonging to the KXF-VS-MGS class, which became the subject of further research.

Future research will present research on innovative technology for the production of low-cost composite chemical reagents based on organo-inorganic ingredients, including an analysis of their practical application, economic feasibility, and the implementation of the technology in flotation processes for non-ferrous and precious metal ores.

4. Conclusions

The compositions of composite flotation reagents (KXF-VS-B1–B5) were developed and optimized. The results showed that KXF-VS-B3 sample has the best foaming and technological characteristics. It has been shown that in terms of density, viscosity and pH, the reagent KXF-VS-B3 is comparable to the standard industrial reagent T-92.

During flotation of copper-molybdenum ore from the Kalmakyr deposit, copper extraction into rough concentrate using KXF-VS-B3 reaches 91.35%, which is practically the same as the T-92 (91.49%).

In a closed-loop flotation circuit, copper recovery was 87.69% with a copper grade in the concentrate of 16.8%, confirming the reagent's suitability for industrial applications.

For gold recovery, the average recovery was 53.65%, compared to 60.89% for T-92, indicating the need for further optimization of the composition to improve selectivity for precious metals.

The composite reagents are characterized by high foam stability, process stability, and the potential to reduce dependence on imported flotation reagents.

Overall, the developed flotation reagent KHF-VS-B3 is an effective and environmentally friendly alternative to imported frothers for processing copper-molybdenum ores. The obtained results confirm its industrial potential and justify further research aimed at increasing gold recovery rates and optimizing production economics.

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