

IRSTI 61.31.57

A.K. Kalymbet¹ – main author, | ©
Sh.N. Kubekova², V.I. Kapralova³



¹Master of Engineering and Technology, Senior Lecturer,

²Candidate of Technical Sciences, Associate Professor,

³Doctor of Technical Sciences, Associate Professor

ORCID

¹<https://orcid.org/0000-0003-2513-1181> ²<https://orcid.org/0000-0001-8665-9970>

³<https://orcid.org/0000-0003-1565-0818>



¹Satbayev University,



Almaty, Kazakhstan



¹a.kalymbet@satbayev.university

<https://doi.org/10.55956/DBHH4781>

COMPARATIVE STUDY OF A SILICOPHOSPHATE SORBENT BASED ON ENRICHMENT WASTES FROM THE AKBAKAY DEPOSIT AND BENTONITE IN THE SORPTION OF COPPER IONS FROM AQUEOUS SOLUTIONS

Abstract. This work presents a comparative evaluation of a modified silicophosphate sorbent, synthesized from gold ore processing wastes of the Akbakay deposit via treatment with 20% orthophosphoric acid and subsequent calcination at 600°C, against natural and thermally treated bentonite. Key performance indicators, including solubility, mechanical strength, and equilibrium sorption capacity for copper ions, were determined. The Akbakay-derived silicophosphate sorbent exhibited exceptionally low aqueous solubility (1.22%), in stark contrast to natural bentonite, which actively disperses to form a stable colloidal emulsion. The modified sorbent demonstrated significantly superior Cu²⁺ removal efficiency across the entire investigated concentration range. While the high colloidal and solubility of bentonite constrain its utility in water treatment applications, the silicophosphate sorbent maintains its structural integrity and operational performance. This comparative analysis confirms the practical advantage of the modified sorbent derived from Akbakay technogenic waste for implementation in wastewater purification systems.

Keywords: silicophosphate sorbent, processing wastes, bentonite, copper cation, sorption, solubility, mechanical strength, heavy metals, water treatment.



Kalymbet A.K., Kubekova Sh.N., Kapralova V.I. Comparative study of a silicophosphate sorbent based on enrichment wastes from the Akbakay deposit and bentonite in the sorption of copper ions from aqueous solutions //Mechanics and Technology / Scientific journal. – 2026. – No.1(91). – P.427-432. <https://doi.org/10.55956/DBHH4781>

Introduction. Industrial wastewater streams frequently contain toxic heavy metal ions, such as copper, which pose significant environmental and health risks and necessitate efficient remediation strategies [1-3]. Natural aluminosilicate minerals, particularly bentonite clays, have been extensively employed as adsorbents for this purpose, leveraging their abundance, low cost, and inherent cation exchange capacity [4,5]. However, their application, especially in dynamic filtration systems, is severely hampered by intrinsic drawbacks, including high

dispersibility, a propensity for emulsion formation, and partial solubility in aqueous media [6,7].

The development of chemically stabilized sorbents from mineral and technogenic raw materials represents a promising avenue. Silicophosphate materials, in particular, offer enhanced chemical durability, resulting in low solubility and high stability in water [8]. This study presents a direct comparative assessment of a novel silicophosphate sorbent against conventional bentonite. The comparison is fundamentally justified by the compositional similarity of the matrices; both materials are predominantly silicate-based, with silica (SiO₂) constituting 50-60% of their mass. The novelty of this research lies in a comprehensive evaluation of a sorbent modified from Akbakay gold mining waste (using 20% H₃PO₄ and calcination at 600°C) versus natural and calcined bentonite, focusing on critical physicochemical and sorptive properties relevant to practical application.

Materials and methods. The following materials were investigated:

- A silicophosphate sorbent synthesized from Akbakay deposit processing waste, modified with 20% orthophosphoric acid and calcined at 600°C;
- Natural granular bentonite (conforming to Technical Specifications TU 2164-004-00204493-2009);
- Bentonite calcined at 600°C.

Analysis Methods:

- Solubility and mechanical strength were determined using standard methods [9].

– **Material Characterization:** The detailed mineralogical and elemental composition of the initial Akbakay processing waste and the derived silicophosphate sorbent, confirming the structural transformation upon phosphoric acid treatment and calcination, was established in our prior study using X-ray diffraction (XRD), scanning electron microscopy (SEM), and other analytical techniques [8].

– **Sorption Experiments:** Batch sorption experiments were conducted to evaluate Cu²⁺ uptake. A 3.0 g sample of each sorbent was mixed with 100 mL of Cu²⁺ solution at varying initial concentrations (1, 10, 20, 30, and 40 mg/L). The suspensions were stirred at 200 rpm for 24 h at room temperature. After filtration (0.45 μm membrane filter), the residual Cu²⁺ concentration was measured using an AA-7000 atomic absorption spectrometer (Shimadzu, Japan). The equilibrium sorption capacity (q_e, mg/g) was calculated using the mass balance equation [10].

Research results. Solubility and Mechanical Strength. According to the results presented in Table 1 natural bentonite undergoes rapid dispersion in water, forming a persistent turbid emulsion. Thermal treatment at 600°C reduces its solubility by approximately 50%, yet fails to resolve the fundamental issue of colloidal stability, consistent with reported behavior of thermally modified clays [11].

Table 1

Physicochemical Properties of the Sorbents

Sample	Solubility, %	Mechanical Strength, %
Silicophosphate sorbent (Akbakay, 600°C, 20% H ₃ PO ₄)	1.22	91.0
Natural bentonite	80.0	83.5
Bentonite calcined at 600°C	42.4	90.0

Equilibrium Sorption of Copper Ions (Cu²⁺). The silicophosphate sorbent exhibited consistently high removal efficiency, markedly surpassing both bentonite variants across the tested concentration spectrum (Table 2). Its performance advantage is particularly pronounced at medium to high initial Cu²⁺ concentrations (10-40 mg/L), where the bentonite samples demonstrate unstable and limited sorption capacity [6,11].

Table 2

Residual Cu²⁺ concentrations and calculated sorption capacities after 24 h equilibrium

C ₀ (mg/L)	Akbakay Silicophosphate Sorbent		Natural Bentonite		Bentonite (600°C)	
	C _e (mg/L)	q _e (mg/g)	C _e (mg/L)	q _e (mg/g)	C _e (mg/L)	q _e (mg/g)
1	0.0357	0.032	0.0099	0.033	0.0141	0.033
10	0.0299	0.332	0.6461	0.312	0.5739	0.314
20	0.0930	0.664	2.2238	0.593	1.1543	0.628
30	0.0606	0.998	2.0226	0.933	1.3982	0.953
40	0.1802	1.327	0.3845	1.320	1.9594	1.268

The comparative efficiency of the investigated sorbents for Cu²⁺ ion removal is visualized in Figure 1. The plot reveals a fundamental difference in material behavior: the silicophosphate sorbent maintains exceptionally low equilibrium concentration values (C_e) across the entire studied range of initial concentrations (C₀ = 1–40 mg/L), whereas for both natural and calcined bentonite, a sharp increase in C_e is observed even at moderate loadings (C₀ > 10 mg/L). This dependence of C_e on C₀ provides clear evidence of the higher and more stable sorption capacity of the modified silicophosphate material.

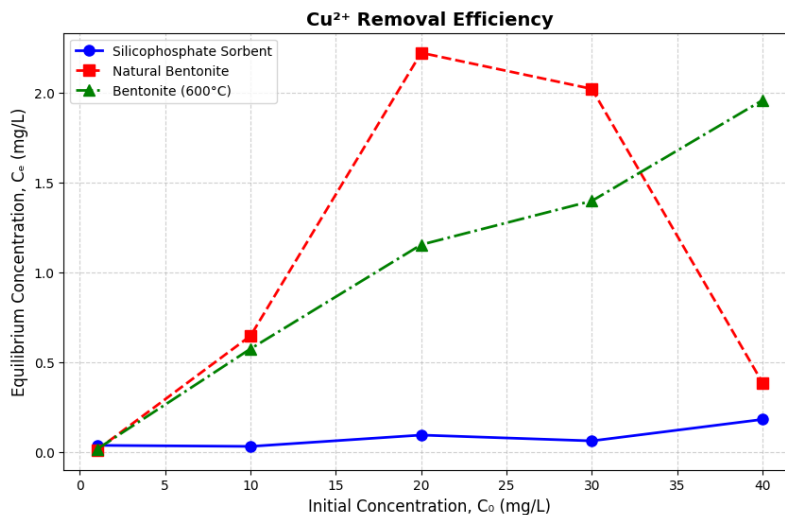


Fig. 1. Equilibrium Cu²⁺ concentration (C_e) vs. initial concentration (C₀) for various sorbents

Discussion. The experimental data underscore the superior operational profile of the modified silicophosphate sorbent derived from Akbakay waste. Its minimal solubility (1.22%) and high mechanical robustness (91%) are attributable

to the formation of a consolidated, cross-linked silicate-phosphate network during acid modification and high-temperature treatment, a synthesis pathway supported by prior research [8]. Conversely, bentonite, even after calcination, retains substantial hydrophilic character, leading to dispersion, mass loss via solubilization, and consequently, increased fouling potential in filtration systems [6,12].

The sorbent's high and stable affinity for Cu^{2+} ions, evident from the consistently low residual concentrations ($C_e < 0.2 \text{ mg/L}$) across all loadings, can be attributed to its developed surface area and the presence of accessible, high-affinity binding sites, primarily protonated phosphate ($\equiv\text{P}-\text{OH}$) and possibly silicate ($\equiv\text{Si}-\text{OH}$) groups. These sites facilitate efficient ion exchange and inner-sphere complexation with Cu^{2+} . In contrast, the sorption behavior of both bentonite samples is non-linear and less effective. Natural bentonite shows a sharp decline in efficiency at moderate concentrations (10-20 mg/L), suggesting rapid saturation of its limited exchange sites. While calcination enhances the mechanical strength of bentonite by dehydroxylation, it does not introduce new sorptive functional groups and may partially collapse the layered montmorillonite structure [11], resulting in only a marginal improvement in copper uptake compared to its natural counterpart.

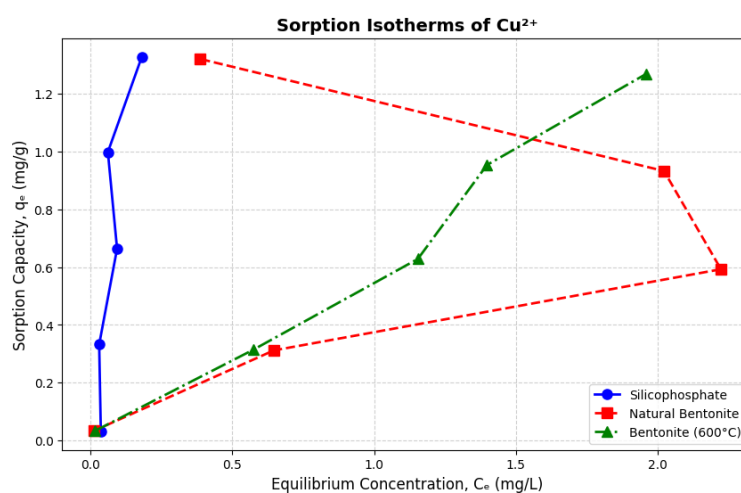


Fig. 2. Experimental sorption isotherms of Cu^{2+}

The sorption isotherms presented in Fig. 2, depicting the uptake (q_e) as a function of equilibrium concentration (C_e), provide a qualitative assessment of the sorbents' affinity for copper ions. The curve for the silicophosphate sorbent is positioned significantly higher and exhibits a steeper initial slope, indicating its high capacity and efficiency at low concentrations. The isotherms for the bentonite samples are more gradual and lie below, revealing a lower number of accessible active sites and weaker binding of Cu^{2+} , which is consistent with the data shown in Table 2.

Conclusion. A novel silicophosphate sorbent, synthesized from Akbakay processing waste via phosphoric acid modification (20% H_3PO_4) and calcination (600°C), has been developed. It exhibits exceptional operational characteristics: ultra-low aqueous solubility (1.22%), high mechanical strength (91%), and stability of granule morphology in water.

Natural and thermally treated bentonites are characterized by significant dispersibility and solubility in water (42-80%), representing critical limitations for their deployment in continuous-flow treatment processes.

The modified silicophosphate sorbent demonstrates significantly greater efficacy in removing Cu^{2+} ions from aqueous solution across the concentration range of 1-40 mg/L compared to both bentonite samples. It maintains residual Cu^{2+} levels below 0.2 mg/L, whereas the bentonites exhibit a sharp increase in C_e , exceeding 1-2 mg/L, at medium loadings.

The synergistic combination of low solubility, physical integrity, mechanical strength, and superior, consistent sorption performance validates the practical viability and promise of this silicophosphate sorbent, derived from technogenic waste, for the treatment of heavy metal-contaminated wastewater.

References

1. Carolin C.F., et al. Efficient techniques for the removal of toxic heavy metals from aquatic environment: A review // Journal of Environmental Chemical Engineering. – 2017. – Vol. 5. – No. 3. – P. 2782-2799.
2. Alloway B.J. Heavy metals in soils: trace metals and metalloids in soils and their bioavailability. – Vol. 22. – Springer Science & Business Media, 2013.
3. Barakat M.A. New trends in removing heavy metals from industrial wastewater // Arabian Journal of Chemistry. – 2011. – Vol. 4. – No. 4. – P. 361-377.
4. Adepoju O.T., Oladipo O.S., Afolabi O.M. Bentonite clay as an alternative adsorbent for removal of heavy metals in wastewater // FUOYE Journal of Engineering and Technology. – 2023. – Vol. 8. – No. 3. – P. 1033.
5. Wang S., Peng Y. Natural zeolites as effective adsorbents in water and wastewater treatment // Chemical Engineering Journal. – 2010. – Vol. 156. – No. 1. – P. 11-24.
6. Bhattacharyya K.G., Gupta S.S. Adsorption of a few heavy metals on natural and modified kaolinite and montmorillonite: a review // Advances in Colloid and Interface Science. – 2008. – Vol. 140. – No. 2. – P. 114-131.
7. Wingenfelder U., Hansen C., Furrer G., Schulin R. Removal of heavy metals from mine waters by natural zeolites // Environmental Science & Technology. – 2005. – Vol. 39. – No. 12. – P. 4606-4613.
8. Kalymbet A., Kubekova S., Kapralova V., Lavrova S. From Gold Mining Waste to Functional Sorbents: Structural and Compositional Insights into Copper Adsorption Efficiency // ES Materials and Manufacturing. – 2025. – Vol. 30. – P. 1777.
9. Standard Methods for the Examination of Water and Wastewater. – 23rd ed. – APHA, AWWA, WEF, 2017.
10. Foo K.Y., Hameed B.H. Insights into the modeling of adsorption isotherm systems // Chemical Engineering Journal. – 2010. – Vol. 156. – No. 1. – P. 2-10.
11. Boukerroui A. Copper(II) ions removal from aqueous solution using bentonite treated with ammonium chloride // American Journal of Physical Chemistry. – 2012. – Vol. 1. – No. 1. – P. 1.
12. Liu P., Zhang L. Adsorption of dyes from aqueous solutions or suspensions with clay nano-adsorbents // Separation and Purification Technology. – 2007. – Vol. 58. – No. 1. – P. 32-39.

This research is funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. BR21881939).

Received: 03 December 2025

Accepted: 18 February 2026

А.Қ. Қалымбет¹, Ш.Н. Кубекова¹, В.И. Капралова¹

¹Сәтбаев университеті, Алматы, Қазақстан

**СУЛЫ ЕРІТІНДІЛЕРДЕН МЫС ИОНДАРЫН СОРБЦИЯЛАУДА АҚБАҚАЙ КЕНІНЕН
АЛЫНҒАН БАЙЫТУ ҚАЛДЫҚТАРЫ НЕГІЗІНДЕГІ СИЛИКОФОСФАТ СОРБЕНТІН
БЕНТОНИТПЕН САЛЫСТЫРМАЛЫ ЗЕРТТЕУ**

Аңдатпа. Бұл мақалада алтын құрамды Ақбақай кен орнында кенді өңдеуден алынған қалдықтардан 20% ортофосфор қышқылымен өңдеу және кейіннен 600°C температурада күйдіру арқылы синтезделген модификацияланған силикофосфат сорбентін табиғи және жылумен өңделген бентонитпен салыстырғанда салыстырмалы бағалауы берілген. Ерігіштігі, механикалық беріктігі және мыс иондарының тепе-теңдік сорбциялық қабілеті сияқты негізгі көрсеткіштер анықталды. Ақбақай кен орнынан алынған силикофосфат сорбенті суда өте төмен ерігіштігін көрсетті (1,22%), бұл тұрақты коллоидты эмульсия түзу үшін белсенді түрде ыдырап кететін табиғи бентонитке қарағанда күрт қарама-қайшы келеді. Модификацияланған сорбент зерттелген концентрацияның барлық диапазонында Cu^{2+} жою тиімділігін айтарлықтай жоғары көрсетті. Бентониттің жоғары коллоидтылығы мен ерігіштігі оны суды тазартуда қолдануда шектесе, силикофосфат сорбенті өзінің құрылымдық тұтастығын және өнімділік сипаттамаларын сақтайды. Салыстырмалы талдау Ақбақайдың өнеркәсіптік қалдықтарынан алынған модификацияланған сорбентті ағынды суларды тазарту жүйелерінде қолданудың практикалық мүмкіндігін растайды.

Тірек сөздер: силикофосфат сорбенті, өңдеу қалдықтары, бентонит, мыс катионы, сорбция, ерігіштік, механикалық беріктік, ауыр металдар, суды тазарту.

А.Қ. Қалымбет¹, Ш.Н. Кубекова¹, В.И. Капралова¹

¹Сәтбаев Университет, Алматы, Казахстан

**СРАВНИТЕЛЬНОЕ ИССЛЕДОВАНИЕ СИЛИКОФОСФАТНОГО СОРБЕНТА НА ОСНОВЕ
ОТХОДОВ ОБОГАЩЕНИЯ МЕСТОРОЖДЕНИЯ АКБАКАЙ И БЕНТОНИТА ПРИ СОРБЦИИ
ИОНОВ МЕДИ ИЗ ВОДНЫХ РАСТВОРОВ**

Аннотация. В данной работе представлена сравнительная оценка модифицированного силикофосфатного сорбента, синтезированного из отходов переработки золотосодержащей руды месторождения Акбакай путем обработки 20% ортофосфорной кислотой и последующего прокаливания при 600 °С, с природным и термически обработанным бентонитом. Были определены основные показатели эффективности, включая растворимость, механическую прочность и равновесную сорбционную емкость по ионам меди. Силикофосфатный сорбент, полученный из месторождения Акбакай, продемонстрировал исключительно низкую растворимость в воде (1,22%), что резко контрастирует с природным бентонитом, который активно диспергируется с образованием устойчивой коллоидной эмульсии. Модифицированный сорбент продемонстрировал значительно превосходящую эффективность удаления Cu^{2+} во всем исследованном диапазоне концентраций. В то время как высокая коллоидность и растворимость бентонита ограничивают его применение в очистке воды, силикофосфатный сорбент сохраняет свою структурную целостность и эксплуатационные характеристики. Проведенный сравнительный анализ подтверждает практическую целесообразность использования модифицированного сорбента, полученного из техногенных отходов Акбакай, в системах очистки сточных вод.

Ключевые слова: силикофосфатный сорбент, отходы переработки, бентонит, катион меди, сорбция, растворимость, механическая прочность, тяжелые металлы, водоочистка.