

FORMATION OF A POROUS SILICA-RICH MATRIX FROM CHRYSOTILE-ASBESTOS WASTE FOR POTENTIAL APPLICATION IN SILICON REMOVAL FROM PROCESS SOLUTIONS

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Abstract: Silicon-containing species in uranium-bearing process solutions can accumulate on ion-exchange materials, impairing mass transfer and sorption efficiency. Inexpensive porous inorganic materials for preliminary silicon removal are therefore of practical interest. This study aimed to evaluate how thermal, chemical and mechanical post-treatment affects the porous structure of a silica-rich product obtained by hydrochloric acid leaching of chrysotile-asbestos waste, in order to select a promising matrix for sorption studies. Raw material underwent magnetic separation followed by HCl leaching. Five products were examined: material calcined at 650 °C; material calcined at 850 °C (1 h) and modified with 5% NiSO₄ and 10% MoO₄; material calcined at 650 °C for 52 h; leached product before attrition; and the same product after attrition. Textural properties were assessed via low-temperature N₂ adsorption using BET, Langmuir, t-plot and BJH methods. The BET specific surface area of the samples varied from 56.55 to 169.02 m²/g. The most favorable textural characteristics were observed for the leaching product without additional grinding: the specific surface area was 169.02 m²/g, the micropore area was 44.72 m²/g, the t-plot micropore volume was 0.0180 cm³/g, and the average pore diameter was 3.89 nm. After attrition, surface area remained high (165.99 m²/g) while total pore volume increased to 0.1951 cm³/g. Calcination at 650 °C and prolonged 52-h calcination reduced surface area to 106.61 and 91.41 m²/g, respectively; combined 850 °C treatment with Ni–Mo modification gave the lowest value (56.55 m²/g). HCl leaching was the key step forming the porous silica matrix. The unattrited leached product was selected as the most promising matrix for silicon removal from uranium solutions.

Keywords: chrysotile-asbestos waste, hydrochloric acid leaching, amorphous silica, inorganic adsorbent, BET, BJH, porosity, silicon removal, uranium process solutions

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1. Introduction

Chrysotile asbestos production waste is a large-scale man-made magnesium silicate raw material, the recycling of which is of interest from both an environmental and resource-saving perspective [1-3]. The main mineral in this waste is chrysotile, with the composition $\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$, whose structure can be significantly transformed by acid exposure. During acid leaching, magnesium predominantly passes into solution, while the solid residue is enriched with silica and, due to the destruction of the original magnesium silicate structure, acquires a developed porous surface [4-5]. This creates the preconditions for the production of silica-containing materials from chrysotile-asbestos waste, potentially suitable as matrices for sorption and other functional materials.

The functional properties of silica-containing materials are largely determined by their textural characteristics, including specific surface area, total pore volume, micro- to mesopore ratio, and pore size distribution. A well-developed porous structure ensures surface accessibility for interaction with solution components, while the presence of surface silanol groups enables further chemical modification of the silica matrix [6]. In this regard, acid processing of magnesium silicate man-made raw materials is of interest not only as a method for extracting soluble components, but also as an approach to the formation of a porous silica-containing product with potential sorption properties.

One potential application for such materials is the preliminary removal of silicon-containing components from hydrometallurgical process solutions. In particular, in uranium productive solutions, dissolved and colloidal forms of silicon can accumulate in the pore space and on the surface of ion-exchange materials, impairing mass transfer and reducing the efficiency of uranium sorption extraction [7,8]. Therefore, the development of inexpensive porous materials for preliminary silicon reduction before the main ion-exchange stage is of practical interest [9,10]. At this stage, however, the primary task is to obtain and texturally evaluate a suitable porous matrix, while its effectiveness directly in the silicon removal process requires separate experimental study.

For Kazakhstan, this area is of additional importance due to the presence of man-made waste from chrysotile asbestos production. Work on processing waste from the Zhitikarinskoye deposit demonstrated the possibility of combining magnetic separation and acid leaching to produce silica-containing products with a developed surface area [11]. However, the production of a silica-containing product alone does not determine its suitability as a matrix for a functional material, as subsequent thermal, chemical, and mechanical processing steps can significantly alter the resulting pore structure. The impact of such processing on the specific surface area, pore volume, and pore size distribution of products from the acid processing of chrysotile asbestos waste requires separate assessment.

The aim of the work is to establish the patterns of change in the specific surface area and porous structure of the silica-containing product of hydrochloric acid leaching of chrysotile asbestos waste with various methods of subsequent processing and to justify the choice of the most promising matrix base for the

creation of an inorganic chemisorbent intended for the preliminary removal of silicon compounds from process solutions before the sorption extraction of uranium.

2. Experimental part

The textural characteristics of the samples were determined by low-temperature nitrogen adsorption on an EASY-V3210 analyzer using an N₂–He gas system. The specific surface area was calculated using the Brunauer–Emmett–Teller (BET) method and the Langmuir model. Micropore and external surface area were estimated using the t-Plot method; mesopore size distribution, cumulative pore area, and pore volume were estimated using the Barrett–Joyner–Halenda (BJH) method using the adsorption and desorption isotherms.

The feedstock used was man-made waste from chrysotile asbestos production, with a particle size of – 1.0 to + 0.25 mm. The feedstock was subjected to dry magnetic separation to produce magnetic (17.5–18.0%) and non-magnetic (82.0–82.5%) fractions. The composition of the non-magnetic fraction sent for subsequent leaching was, wt. %: MgO – 39,0–41,3; SiO₂ – 33,4–36,5; CaO – 0,5–1,4; Fe₂O₃ – 2,7; Fe₃O₄ – 4,9. The non-magnetic fraction was leached with an HCl solution with a concentration of 0.45 mol/l at a solid-to-liquid ratio (S:L) = 1:5, a temperature of 75 °C and a duration of 3 hours from the moment the operating temperature was reached. The resulting solid residue was washed with water at an S:L ratio of 1:2, then filtered and dried. The content of the silica component in the resulting product reached 78–80 wt. %. The scheme of preliminary magnetic separation of the source material is shown in Figure 1.

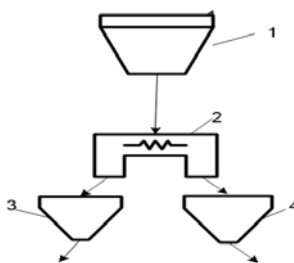


Figure 1 – Hardware diagram of magnetic separation of chrysotile-asbestos waste: 1 – feedstock bin; 2 – magnetic separator; 3 – non-magnetic fraction; 4 – magnetic fraction.

Magnetic separation separated the original chrysotile asbestos waste into magnetic and non-magnetic fractions. The magnetic fraction was separated from the main process stream, while the non-magnetic fraction, enriched in magnesium silicate, was sent for hydrochloric acid leaching, followed by the production of a silica-containing product. To evaluate the influence of subsequent thermal, chemical and mechanical treatment on its porous structure, five samples were prepared, the conditions for obtaining which are given in Table 1.

Table 1 – Conditions for obtaining the test samples

№	Sample	Treatment conditions of the product after leaching
1	Sand 1	Calcination at 650 °C
2	Sand 2	Calcination at 850 °C for 1 h and modification with 5% NiSO ₄ and 10% MoO ₄
3	Sand 3	Calcination at 650 °C for 52 h
4	Sand 4	Product before the abrasion operation
5	Sand 5	Product after the abrasion operation

3. Results and Discussion

Hydrochloric acid leaching was accompanied not only by changes in the chemical composition but also by a significant restructuring of the original magnesium silicate structure. X-ray diffraction (XRD) analysis was performed using a Rigaku MiniFlex 600 diffractometer (Rigaku Corporation, Tokyo, Japan) with Cu K α radiation ($\lambda = 1.5406 \text{ \AA}$), operated at 40 kV and 15 mA. The diffraction patterns were recorded over a 2θ range of $5\text{--}80^\circ$ with a step size of 0.02° and a scanning rate of $[\text{specify}]^\circ/\text{min}$.

The X-ray diffraction pattern of the product after leaching showed a decrease in the intensity of the characteristic diffraction peaks and diffuse scattering in the 2θ range of approximately $15\text{--}35^\circ$, indicating the formation of a disordered, predominantly amorphous silica-containing component.

Thermogravimetric analysis performed using a Q-1500D derivatograph (Paulik–Paulik–Erdey system, Hungary) revealed successive stages of water removal at 110, 140, and 170 °C. The total loss of hydration water over the temperature range of $40\text{--}310^\circ\text{C}$ was 8.45%. The presence of various forms of bound water and OH groups was consistent with the structural heterogeneity of the surface after acid treatment.

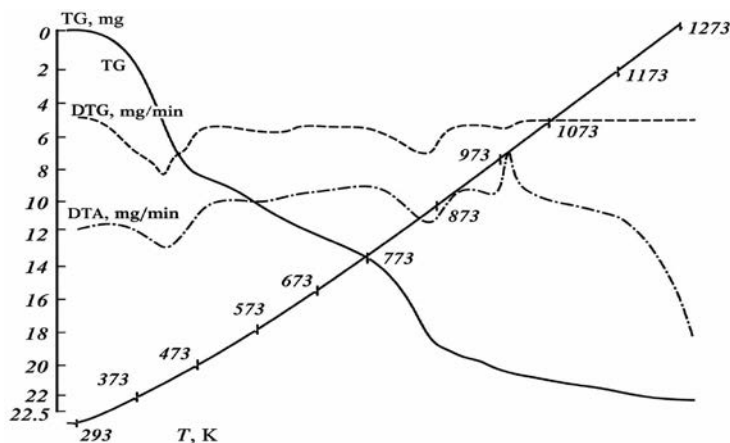


Figure 2 – Thermogravimetric curves of the residue after leaching.

To confirm the extent of structural disordering, X-ray phase analysis was performed on the leached product, comparing peak positions and intensities with the initial crystalline phase (Figure 3).

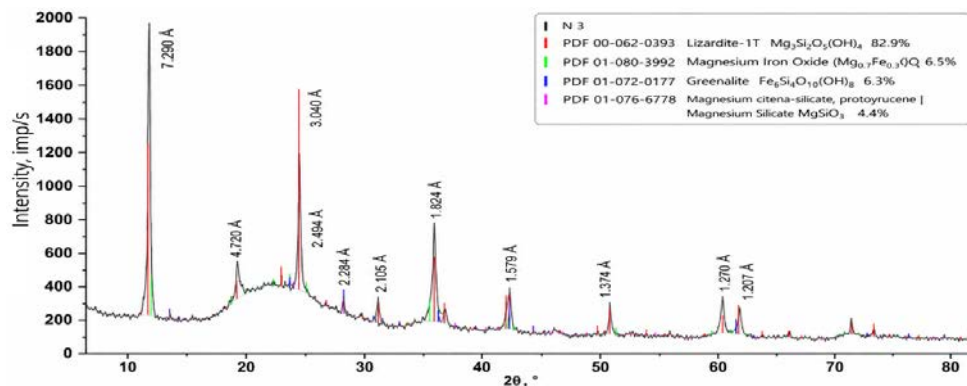


Figure 3 – X-ray diffraction pattern of the residue after leaching.

FTIR spectroscopy was additionally used to characterize surface functional groups and confirm the presence of OH groups and silica-containing fragments consistent with the acid-leached structure (Figure 4).

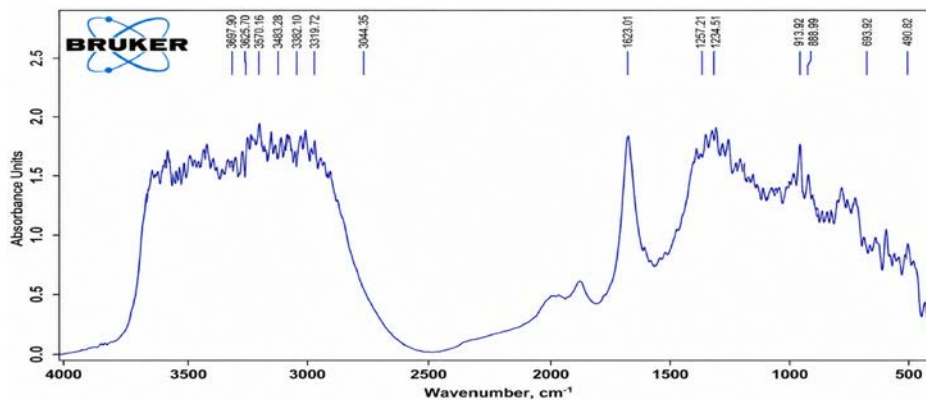


Figure 4 – IR spectrum of the product after leaching.

The results showed a significant dependence of textural characteristics on the type of post-treatment applied (Table 2). The specific surface area of BET varied from 56.55 to 169.02 m²/g across the five samples studied.

Table 2 – Main textural characteristics of the studied samples

Sample	Specific surface area BET, m ² /g	Specific surface area of Langmuir, m ² /g	Micropore area, m ² /g	Outer surface, m ² /g	Total pore volume, sm ³ /g	Micropore volume t-Plot, sm ³ /g	Average pore size, nm
1 650 °C	106,61	168,39	4,74	101,87	0,1179	0,00151	4,42
2 850 °C + Ni–Mo	56,55	73,72	5,30	51,25	0,1211	0,00185	8,57
3* 650 °C, 52 h	91,41	135,29	—	—	0,1556	0	6,81
4* before abrasion	169,02	214,27	44,72	124,31	0,1644	0,01802	3,89
5 after abrasion	165,99	192,77	42,31	123,68	0,1951	0,01779	4,70
<i>Note – BET is the Brunauer–Emmett–Teller specific surface area; t-Plot is the method for assessing the microporous and external surface area Sample 4 (highlighted) was selected as the most promising matrix; t-Plot micro/outer surface values for Sample 3 were not determined.</i>							

The maximum surface area was determined for Sample 4 (product after leaching, before the attrition operation): $S_{\text{BET}} = 169.02 \text{ m}^2/\text{g}$, micropore area = $44.72 \text{ m}^2/\text{g}$, external surface area = $124.31 \text{ m}^2/\text{g}$, total pore volume = $0.1644 \text{ cm}^3/\text{g}$, and average pore size = 3.89 nm – identifying it as the most promising matrix among all samples tested (Table 3).

Table 3 – Comparative interpretation of textural characteristics

Sample	S_{BET} , m ² /g	Key features	Interpretation
4 – before abrasion	169,02	Maximum BET-surface area and micropore area	The most promising matrix
5 – after abrasion	165,99	Maximum total pore volume $0,1951 \text{ sm}^3/\text{g}$	Abrasion increases pore volume
1 – 650 °C	106,61	Surface reduction after firing	Heat treatment reduces the available surface
3 – 650 °C, 52 h	91,41	Average pore size $6,81 \text{ nm}$	Long firing further reduces S_{BET}
2 – 850 °C + Ni–Mo	56,55	Smallest S_{BET} ; pore size $8,57 \text{ nm}$	Cumulative treatment produces the coarsest pore structure

Firing at 650 °C (sample 1) was accompanied by a decrease in S_{BET} to $106.61 \text{ m}^2/\text{g}$ and micropore area to $4.74 \text{ m}^2/\text{g}$. With prolonged exposure at 650 °C for 52 hours (sample 3), the specific surface area further decreased to $91.41 \text{ m}^2/\text{g}$, and the average pore size increased to 6.81 nm . This indicated a decrease in

accessible surface area with increasing thermal exposure. The lowest value of $S_{\text{BET}} = 56.55 \text{ m}^2/\text{g}$ was obtained for sample 2, which was fired at 850°C for 1 h and subsequently modified with NiSO_4 and MoO_4 compounds. The average pore size of this material was 8.57 nm . Since the processing temperature and surface chemical composition were changed simultaneously for this sample, the available data characterize the combined effect of these factors and do not allow a separate assessment of the contribution of each of them. Mechanical abrasion altered the pore space differently. After abrasion, S_{BET} decreased only from 169.02 to $165.99 \text{ m}^2/\text{g}$, while the total pore volume increased from 0.1644 to $0.1951 \text{ cm}^3/\text{g}$, and the average pore size increased from 3.89 to 4.70 nm . Consequently, mechanical action primarily affected the volumetric and size characteristics of the pores without further development of the specific surface area.

To preserve the original experimental data and visually compare the adsorption pattern, Figure 8 shows the initial N_2 adsorption-desorption isotherms from the EASY-V3210 analyzer reports for all five samples. The highest adsorption capacity was observed for samples 4 and 5, consistent with their maximum specific surface area values.

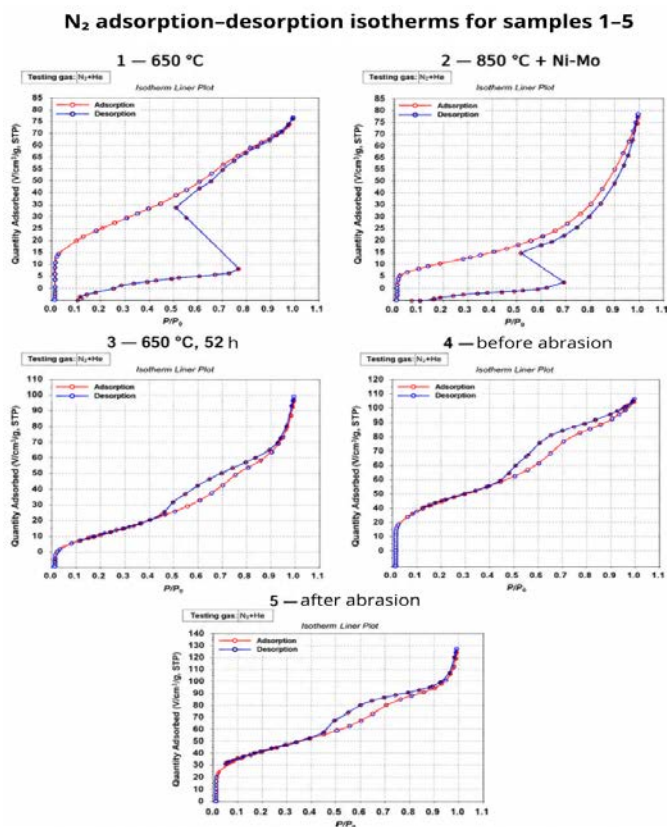


Figure 8 – N_2 adsorption-desorption isotherms for samples 1-5.

The pore size distribution calculated using the BJH method confirmed a significant change in the mesoporous component during thermal and mechanical treatment. For the thermally treated materials, the characteristic pore sizes shifted toward larger values, while sample 4 combined the maximum specific surface area with a smaller average pore size. The pore size distribution calculated by the BJH method for samples 1-5 is shown in Figure 9.

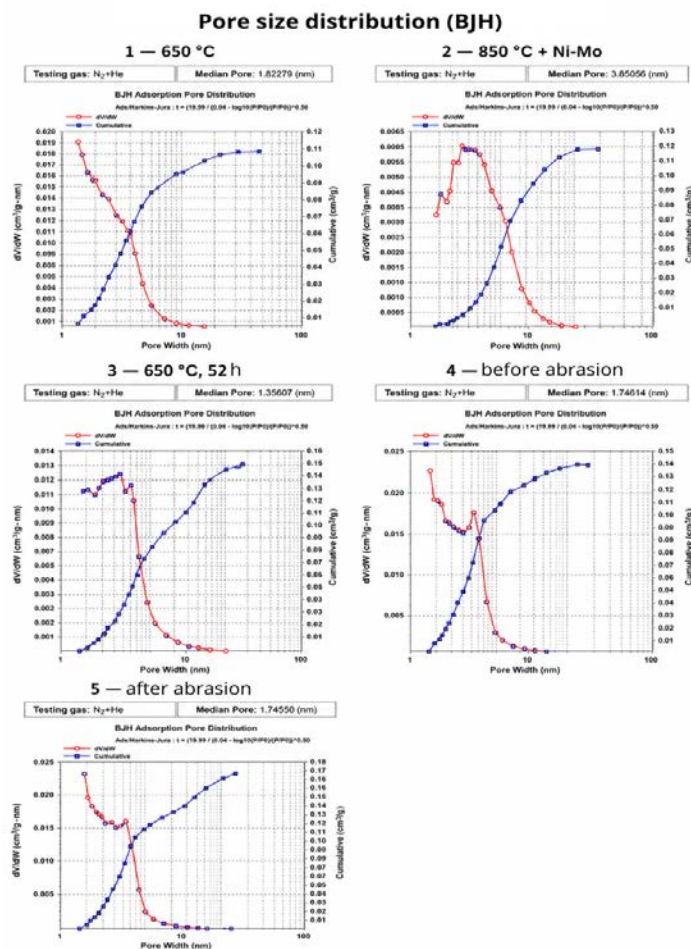


Figure 9 – Pore size distribution by the BJH method for samples 1–5.

According to the specific surface area of BET, the samples were arranged in the following sequence: 4 (169.02) > 5 (165.99) > 1 (106.61) > 3 (91.41) > 2 (56.55 m^2/g). Thus, the most developed surface was formed immediately after hydrochloric acid leaching and was preserved until additional thermal treatment. The obtained result is consistent with the literature data on the formation of

porous amorphized silica during acid destruction of chrysotile and serpentinite matrices [9–11].

Based on a combination of textural parameters, sample 4 was selected as the most promising matrix for further development of an inorganic chemisorbent. However, BET/BJH characteristics alone do not directly demonstrate high silicon sorption capacity; a final assessment must be made based on the results of individual sorption experiments to determine the degree of silicon removal and sorption capacity.

4. Conclusion

Hydrochloric acid leaching of chrysotile asbestos waste produced a silica-rich porous matrix containing 78–80 wt.% SiO_2 . The leached product obtained before attrition exhibited the most favorable textural properties, with a BET specific surface area of $169.02 \text{ m}^2/\text{g}$, a micropore area of $44.72 \text{ m}^2/\text{g}$, a total pore volume of $0.1644 \text{ cm}^3/\text{g}$, and an average pore diameter of 3.89 nm. These results demonstrate that acid leaching is the key stage responsible for magnesium removal and the development of the porous structure.

Subsequent processing affected the pore structure differently. Heat treatment at 650°C , particularly prolonged annealing, reduced the accessible surface area, indicating partial densification or restructuring of the porous matrix. The combination of calcination at 850°C and Ni–Mo modification produced the lowest BET specific surface area of $56.55 \text{ m}^2/\text{g}$. In contrast, mechanical attrition had little effect on the BET surface area but increased the total pore volume to $0.1951 \text{ cm}^3/\text{g}$, suggesting enlargement or improved accessibility of the pore system.

Overall, the leached product obtained before attrition provided the best balance of silica content, specific surface area, and pore characteristics. It was therefore selected as the most promising matrix for further investigation of the preliminary removal of silicon-containing species from process solutions prior to the sorption recovery of uranium. Future studies should evaluate its removal efficiency, selectivity, regeneration behavior, and performance under conditions representative of industrial process solutions.

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ТЕХНОЛОГИЯЛЫҚ ЕРІТІНДІЛЕРДЕН КРЕМНИЙДІ ЖОЮДА ӘЛЕУЕТТІ ҚОЛДАНУ
ҮШІН ХРИЗОТИЛ-АСБЕСТ ҚАЛДЫҚТАРЫНАН КЕУЕКТІ КРЕМНЕЗЕМҚҰРАМДЫ
МАТРИЦА ҚАЛЫПТАСТЫРУ

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Түйіндеме. Уран құрамдас ерітінділердегі кремний құрамдас түрлері ион алмасу материалдарында жиналып, масса алмасу мен сорбция тиімділігін төмендетуі мүмкін. Сондықтан кремнийді алдын ала кетіруге арналған арзан кеуекті бейорганикалық материалдар практикалық қызығушылық тудырады. Бұл зерттеу сорбциялық зерттеулер үшін перспективалы матрицаны таңдау мақсатында хризотил-асбест қалдықтарын тұз қышқылымен сілтілеу арқылы алынған кремнийге бай өнімнің кеуекті құрылымына термиялық, химиялық және механикалық өңдеуден кейінгі әсер етуді бағалауға бағытталған. Шикізат магниттік бөлуден, содан кейін HCl сілтілеуден өтті. Бес үлгі зерттелді: 650 °C-та күйдірілген өнім; 850 °C-та 1 сағ күйдіріліп, 5 % NiSO₄ және 10 % MoO₄ қосылыстарымен модификацияланған өнім; 650 °C-та 52 сағ күйдірілген өнім; үйкеліс операциясына дейінгі және одан кейінгі шаймалау өнімдері. Кеуектілік сипаттамалары азоттың төмен температуралық адсорбциясы, BET, Langmuir, t-Plot және BJH әдістерімен анықталды. Үлгілердің БЭТ әдісі бойынша меншікті бет ауданы 56,55-тен 169,02 м²/г-ға дейін өзгерді. Ең жақсы текстуралық сипаттамалар қосымша ұнтақтауға ұшыратылмаған сілтісіздендіру өнімінде байқалды: меншікті бет ауданы 169,02 м²/г, микрокеуектер ауданы 44,72 м²/г, t-график әдісі бойынша микрокеуектер көлемі 0,0180 см³/г, ал кеуектердің орташа диаметрі 3,89 нм болды. Үйкелістен кейін S_BET 165,99 м²/г деңгейінде сақталып, жалпы кеуек көлемі 0,1951 см³/г дейін артты. 650 °C температурада күйдіру және ұзаққа созылған 52 сағаттық күйдіру бетінің ауданын сәйкесінше 106,61 және 91,41 м²/г-ға дейін азайтты; Ni-Mo модификациясымен 850 °C температурада біріктірілген өңдеу ең төменгі мәнді берді (56,55 м²/г). Дамыған кремнеземді кеуекті матрицаны қалыптастыратын негізгі кезең тұз қышқылымен шаймалау болып табылды. Уран ерітінділерінен кремнийді кетіру үшін ең перспективалы матрица ретінде сілтісіздендіру өнімі таңдалды.

Түйінді сөздер: хризотил-асбест қалдықтары, тұз қышқылымен шаймалау, аморфты кремнезем, бейорганикалық адсорбент, BET, BJH, кеуектілік, кремнийді жою, уран ерітінділері

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ФОРМИРОВАНИЕ ПОРИСТОЙ КРЕМНЕЗЕМСОДЕРЖАЩЕЙ МАТРИЦЫ ИЗ ОТХОДОВ ХРИЗОТИЛ-АСБЕСТА ДЛЯ ПОТЕНЦИАЛЬНОГО ПРИМЕНЕНИЯ ПРИ УДАЛЕНИИ КРЕМНИЯ ИЗ ТЕХНОЛОГИЧЕСКИХ РАСТВОРОВ

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Резюме. Соединения кремния, присутствующие в технологических растворах, содержащих уран, могут накапливаться на ионообменных материалах, ухудшая массообмен и снижая эффективность сорбции. В связи с этим практический интерес представляют недорогие пористые неорганические материалы для предварительного удаления кремния. Целью данной работы было изучение влияния термической, химической и механической постобработки на пористую структуру продукта с высоким содержанием диоксида кремния, полученного путем солянокислотного выщелачивания отходов хризотил-асбеста, с целью выбора перспективной матрицы для сорбционных исследований. Исходное сырье подвергалось магнитной сепарации с последующим

выщелачиванием соляной кислотой. Были исследованы пять образцов: материал, прокаленный при 650 °C; материал, прокаленный при 850 °C (в течение 1 ч) и модифицированный 5% NiSO₄ и 10% MoO₄; материал, прокаленный при 650 °C в течение 52 ч; продукт выщелачивания до измельчения (аттриции); и тот же продукт после измельчения. Текстуальные характеристики оценивали методом низкотемпературной адсорбции азота с использованием моделей БЭТ (БЕТ), Ленгмюра, t-графика и метода Барретта-Джойнера-Халенды (ВЖН). Удельная площадь поверхности образцов по методу БЭТ варьировалась от 56,55 до 169,02 м²/г. Наилучшие текстурные характеристики были установлены для продукта выщелачивания без дополнительного измельчения: удельная площадь поверхности составила 169,02 м²/г, площадь микропор - 44,72 м²/г, объём микропор по методу t-графика - 0,0180 см³/г, а средний диаметр пор - 3,89 нм. После измельчения удельная площадь поверхности осталась высокой (165,99 м²/г), а общий объём пор увеличился до 0,1951 см³/г. Прокаливание при 650 °C и длительное прокаливание (52 ч) привели к снижению удельной площади поверхности до 106,61 и 91,41 м²/г соответственно; комбинированная обработка при 850 °C с модифицированием Ni–Mo дала наименьшее значение (56,55 м²/г). Выщелачивание соляной кислотой стало ключевой стадией формирования пористой кремнеземной матрицы. Продукт выщелачивания, не подвергавшийся измельчению, был выбран в качестве наиболее перспективной матрицы для удаления кремния из урансодержащих растворов.

Ключевые слова: отходы хризотил-асбеста, солянокислотное выщелачивание, аморфный кремнезем, неорганический адсорбент, БЕТ, ВЖН, пористость, удаление кремния, урановые растворы

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References

1. Shokobayev N.M. et al. Rare earth metals sorption recovery from uranium in situ leaching process solutions. *Rare Metals*, 2015, 34. <https://doi.org/10.1007/s12598-014-0237-z>
2. Youssef W.M., Masoud A.M., Elmaadawy M.M. et al. Uranium (VI) sorption from aqueous solution using commercial anion exchange resins: kinetics, isotherm, and thermodynamic investigations. *J. Radioanal. Nucl. Chem.*, 2024, 333, 1975–1989. <https://doi.org/10.1007/s10967-024-09438-1>
3. Sharafutdinov U., Karimov I., Rajabboev I., Yuldashev S., Khamidova M., Khurramova D. Presence and impact of silica and organics in uranium in-situ leaching solutions. *E3S Web Conf.*, 2025, 627, 01011. <https://doi.org/10.1051/e3sconf/202562701011>
4. Kylyshkanov M.K., Kopbaeva M.P., Elemesov T.B., Omirgali A.K., Kenzhetaev Zh.S. Development of Technology for Purifying Ion Exchangers from Silicon Impurities During the Processing of Productive Uranium-Containing Solutions. *Combustion and Plasma Chemistry*, 2025, 23, No. 4, 435–446. [https://doi.org/10.18321/cpc23\(4\)435-446](https://doi.org/10.18321/cpc23(4)435-446)
5. Yavorava V., Scheepers J., Kotze M.H., Auerswald D. Impact of silica on hydrometallurgical and mechanical properties of RIP grade resins for uranium recovery. *J. S. Afr. Inst. Min. Metall.*, 2009, 109, No. 10, 609–619.
6. Zdarta J., Jesionowski T. Silica and Silica-Based Materials for Biotechnology, Polymer Composites, and Environmental Protection. *Materials*, 2022, 15, No. 21, 7703. <https://doi.org/10.3390/ma15217703>
7. Morgan A. Acid leaching studies of chrysotile asbestos from mines in the Coalinga region of California and from Quebec and British Columbia. *Ann. Occup. Hyg.*, 1997, 41, No. 3, 249–268. [https://doi.org/10.1016/S0003-4878\(97\)00001-X](https://doi.org/10.1016/S0003-4878(97)00001-X)

8. Turci F., Tomatis M., Mantegna S. et al. Comparative effect of chrysotile leaching in nitric, sulfuric and oxalic acids at room temperature. *Chem. Geol.*, 2013, 352, 134–142. <https://doi.org/10.1016/j.chemgeo.2013.06.004>
9. Maletaškić J., Stanković N., Daneu N., Babić B., Stojković M., Yoshida K., Matović B. Acid leaching of natural chrysotile asbestos to mesoporous silica fibers. *Phys. Chem. Miner.*, 2018, 45, No. 4, 343–351. <https://doi.org/10.1007/s00269-017-0924-z>
10. Fedoročková, A., Plešingerová, B., Sučík, G., Raschman, P., & Doráková, A. Characteristics of amorphous silica prepared from serpentinite using various acidifying agents. *Int. J. Miner. Process.*, 2014, 130, 42–47. <https://doi.org/10.1016/j.minpro.2014.05.005>
11. Shayakhmetova R.A., Mukhametzhanova A.A., Akbayeva D.N. et al. Magnesium and silicon recovery from chrysotile asbestos waste of the deposit Zhitikara, Kazakhstan. *Sci. Rep.*, 2024, 14, 31866. <https://doi.org/10.1038/s41598-024-83239-0>