

Upcycling Chrysotile Asbestos Waste into High-Performance Wollastonite Chemisorbents for Demetallization and Desulfurization of Heavy Oil Residues

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Received: August 20, 2026
Peer-reviewed: September 10, 2026
Accepted: October 21, 2026

ABSTRACT

The disposal of chrysotile asbestos waste poses significant environmental hazards, while heavy oil residues demand costly pretreatment to remove toxic metals and sulfur. This study presents a circular economy approach to convert acid-leached chrysotile asbestos waste into a functional chemisorbent for the simultaneous demetallization and desulfurization of heavy petroleum residues. Following hydrochloric acid leaching, the asbestos waste transformed into an amorphous, highly reactive silica-rich material. Through high-temperature synthesis (1100 - 1280 °C) with calcium and sodium carbonates, a wollastonite (CaSiO₃) and calcium silicate-based chemisorbent was produced. Comprehensive characterization using XRD, FTIR, TG-DTA, BET, and EPR confirmed that the synthesized material exhibits a remarkably high specific surface area (280 - 315 m²/g), substantial pore volume (1.213 cm³/g), and abundant active paramagnetic centers - far exceeding those of commercial zeolite. When tested in the thermal adsorption treatment of vacuum tar (380 - 410 °C), the chemisorbent achieved removal efficiencies of 40 - 55% for vanadium (V), nickel (Ni), and iron (Fe), along with significant sulfur reduction. These results demonstrate a viable pathway for transforming hazardous asbestos waste into a value-added adsorbent, enabling cleaner heavy oil processing and reducing both industrial waste and refinery operating costs.

Keywords: wollastonite, chrysotile asbestos waste, heavy oil residue, demetallization, desulfurization, chemical adsorption, circular economy, vanadium recovery.

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Introduction

The global refining industry is increasingly processing heavier crude oils and petroleum residues due to the depletion of conventional light oil reserves and the growing demand for transportation fuels [[1], [2], [3]. Heavy crude oils, vacuum residues, and bituminous feedstocks are characterized by elevated concentrations of sulfur, nitrogen, asphaltenes, resins, and metal-containing compounds, which significantly complicate downstream refining processes [[1], [4]].

Among the most problematic contaminants in heavy petroleum feedstocks are vanadium and nickel. These metals are mainly associated with porphyrin and non-porphyrin complexes concentrated in resin–asphaltene fractions and are responsible for catalyst poisoning, equipment corrosion, increased coke formation, and deterioration of fuel quality [[2], [4], [5], [6]]. Recent studies have shown that the concentrations of vanadium and nickel in some heavy oils and residues may exceed their concentrations in low-grade mineral ores, making petroleum residues a potential secondary source of strategic metals [[2], [5]].

Hydrodemetallization and hydrodesulfurization remain the dominant industrial technologies for the removal of sulfur and metals from heavy petroleum fractions [[1], [7], [8]]. However, these processes require high hydrogen consumption, elevated operating pressures, expensive catalyst systems, and significant capital investments [[7], [8], [9]]. Furthermore, catalyst deactivation caused by metal deposition remains a major challenge for processing heavy feed-stocks [[8], [10]].

Consequently, increasing attention has been focused on alternative demetallization technologies including solvent deasphalting, adsorption, oxidative treatment, extraction, membrane separation, microwave-assisted processing, and thermoadsorptive upgrading [[1], [11], [12], [13], [14]]. Among these methods, adsorption-based approaches have attracted considerable interest due to their operational simplicity, lower energy requirements, environmental compatibility, and potential integration into existing refinery schemes [[14], [15], [16], [17]].

Recent investigations demonstrated that zeolites, mesoporous silicates, aluminosilicates, activated carbons, metal oxides, and hybrid porous materials exhibit promising performance for the removal of metal-containing compounds and sulfur species from heavy petroleum streams [[17], [18], [19], [20]]. The adsorption efficiency strongly depends on the pore structure, surface chemistry,

concentration of active sites, and specific surface area of the adsorbent [[18], [19], [20], [21]].

Attention has been paid to the development of low-cost adsorbents produced from industrial and mining waste. The valorization of waste materials into functional adsorbents not only reduces production costs but also contributes to circular economy principles and sustainable waste management [[21], [22], [23], [24]]. In this regard, chrysotile-asbestos waste represents a promising secondary raw material due to its abundance and high content of silicon and magnesium compounds [[24], [25], [26]].

Several studies have demonstrated that acid treatment of chrysotile asbestos causes extensive leaching of magnesium ions and transformation of the crystalline fibrous structure into highly reactive amorphous silica-rich materials [[26], [27]]. Such transformations increase the specific surface area, porosity, and concentration of surface-active centers, making the treated material suitable for the synthesis of adsorbents, catalyst supports, and ceramic materials [[27], [28], [29]].

Recent advances in asbestos waste recycling have shown that thermally and chemically modified chrysotile can be converted into wollastonite-, calcium silicate-, and zeolite-type materials possessing high adsorption capacities and excellent thermal stability [[23], [29]]. These materials have demonstrated significant potential in environmental remediation, wastewater treatment, catalytic applications, and adsorption-based purification processes [[11], [29]].

Despite the growing interest in waste-derived adsorbents, limited information is available regarding the utilization of acid-leached chrysotile-asbestos waste for the preparation of chemisorbents intended for demetallization and desulfurization of heavy petroleum residues. Therefore, the objective of the present study was to synthesize a wollastonite-containing chemisorbent from chrysotile-asbestos waste after acid leaching, investigate its physicochemical properties using XRD, FTIR, TG-DTA, EPR, and BET analyses, and evaluate its performance in the thermoadsorptive removal of vanadium, nickel, iron, and sulfur compounds from heavy oil residues.

Experimental part

Materials:

- Asbestos waste following HCl leaching, supplied by Kostanay Minerals JSC (Kazakhstan); (Table 1). The particle size of the material is -2.0 ± 1.0 mm.

Table 1 – Chemical composition of corporation after leaching

Component	Content, % by mass
Silicon oxide	90.0
Magnesium oxide	6.5
Iron oxide	2.5
Other impurities	1.0

- CaCO_3 : (moisture content not exceeding 1.0%; a chemically pure product with a high calcium carbonate content—the mass fraction of calcium and magnesium carbonates, calculated as CaCO_3 , is 99–99.9%. Calcium carbonate is free of impurities. The mass fraction of the residue insoluble in hydrochloric acid is 0.22%, and the mass fraction of water-soluble substances is 0.014%)

- Sodium carbonate, grade “XH” (sodium carbonate in the calcined product, not less than 99.8%; water-insoluble substances, not more than 0.02%)

- Liquid glass, 10%

Experimental Methodology

The chelating agents were prepared with the addition of sodium carbonate. Sugar molasses (0.5% of the total mass) and sodium lignosulfonate (2.0%) were used as a binder and plasticizer, respectively; these do not affect the composition of the final product at high temperatures. To do this, the components listed in Table 2 were mixed, then co-ground to a particle size of at least 100 μm . Next, plastic molding was performed. The resulting molded materials were subjected to a two-stage firing at 1,100°C for 60 minutes and 1,280°C, with a holding time of 60 minutes.

Table 2 – Composition of the active component for preparing the catalyst by impregnation

Compound Name	Formula	Content, % by mass
Serpentine after leaching	SiO_2	55.0
Calcium carbonate	CaCO_3	40.0
Baking soda	Na_2CO_3	5.0
Total		100.0

Analytical Methods and Equipment Used in the Study

To identify the mineral phases, structural characteristics, and chemical makeup of the synthetic chemisorbent produced with various

activating additives, the following analytical techniques and equipment were employed:

- X-ray diffraction (XRD) - performed on a BRUKER D8 ADVANCE diffractometer.
- X-ray fluorescence (XRF) - conducted using a Venus 200 wavelength-dispersive spectrometer (PANalytical B.V., Netherlands).
- Chemical composition analysis - carried out with an Optima 2000 DV inductively coupled plasma optical emission spectrometer (PerkinElmer, USA).
- Elemental and phase distribution mapping was performed on a JXA-8230 electron probe microanalyzer (JEOL, Japan).
- Thermal analysis was carried out with a STA 449 F3 Jupiter simultaneous thermal analyzer, and the resulting data were processed using NETZSCH Proteus software.
- Sample activity studies were performed using a JES-FA 200 electron paramagnetic resonance (EPR) spectrometer (JEOL, Japan), in conjunction with a thermal analyzer, a Raman spectrometer, a scanning electron microscope (SEM), and an X-ray phase analyzer. (Instrument models are specified as above.)

Analytical Methods

X-ray diffraction patterns were recorded using a BRUKER D8 ADVANCE instrument. A PANalytical Venus 200 wavelength-dispersive spectrometer (Netherlands) was employed for X-ray fluorescence analysis. Chemical composition of the samples was determined using an Optima 2000 DV inductively coupled plasma optical emission spectrometer (PerkinElmer, USA). Elemental and phase distribution mapping was conducted with a JXA-8230 electron probe microanalyzer (JEOL, Japan). Thermal analysis was carried out on a STA 449 F3 Jupiter simultaneous thermal analyzer, and the acquired data were processed using NETZSCH Proteus software.

Results and Discussion

Characterization of the corporation after leaching, used as the base material

X-ray diffraction analysis of asbestos waste (AW) after leaching

X-ray diffraction (XRD) was used to obtain information on the structure and phase composition, and to determine the qualitative and semi-quantitative composition of the samples, the texture of the material, and the crystallite sizes (coherent scattering regions) of the polycrystalline sample.

After leaching asbestos waste with hydrochloric acid, a reconstruction of the crystalline components occurs, which is reflected in the shape of the X-ray diffraction pattern (Figure 1). First and foremost, the disappearance of distinct diffraction peaks in the X-ray diffraction pattern should be noted. A diffuse scattering peak is observed in the Bragg angle range from 15 to 35 degrees. It is worth noting the low-intensity diffraction peaks, which are interpreted primarily as SiO_2 (Table 3). Crystalline silica is absent in the leaching residues; it is replaced by amorphous silica, which affects the porosity of the structure.

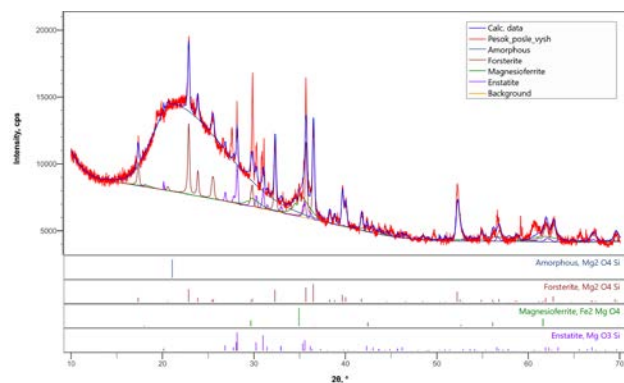


Figure 1 – XRD pattern obtained to determine the phase composition

Table 3 – Phase composition of the sample, determined by XRD

Component		Chemical formula	Mass fraction, %
A	Amorphous	$\text{Mg}_2\text{O}_4\text{Si}$	37.9
B	Forsterite	$\text{Mg}_2\text{O}_4\text{Si}$	42.0
C	Magnesioferrite	Fe_2MgO_4	10.7
D	Enstatite	MgO_3Si	9.4

Interpretation of the FTIR Absorption Spectrum

The absorption spectrum presented in Figure 2 displays multiple bands above 3000 cm^{-1} . The band at 3400 cm^{-1} is assigned to water present in the bulk phase, including film water and water trapped within inclusions. The feature at 3304 cm^{-1} arises from the absorption of water molecules influenced by the crystal's surface field. This field slightly elongates the charge separation within the water molecular dipoles relative to their average distance in the bulk phase, thereby reducing bond stiffness and vibrational frequency.

The absorption at 3478 cm^{-1} in the sample is indicative of molecular water. The bending vibrations of H_2O within the mineral crystals appear in the higher-frequency region (1620 cm^{-1}),

reflecting the presence of stronger hydrogen bonds binding the water molecules.

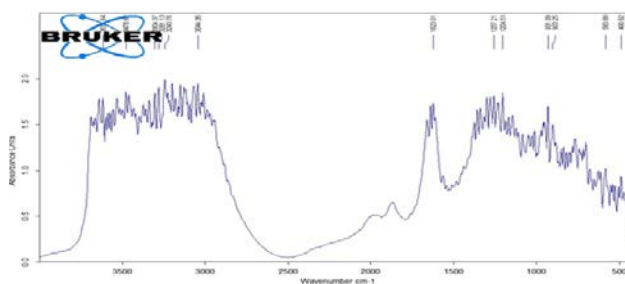


Figure 2 – FTIR spectroscopy of serpentine after leaching

The absorption band for nearly free OH groups is observed around 3600 cm^{-1} , while the band for water appears near 3450 cm^{-1} . Absorption corresponding to short $\text{O}-\text{H}\cdots\text{O}$ hydrogen bonds is found at approximately 3300 cm^{-1} , and the band at 1620 cm^{-1} is attributed to OH bending vibrations.

Overall, the crystalline structure of the original asbestos material is predominantly transformed into an ionic state, which governs the physicochemical properties of the leaching residue.

Thermal Analysis of Temperature Profiles for Synthetic Chemisorbent Production

To analyze the decomposition products of calcium carbonate and secondary calcium silicates, the prepared mixture was heated to 1000 °C and held at that temperature for one hour. This thermal treatment was followed by differential thermal analysis (DTA) and thermogravimetric analysis (TGA) using a Q-1000D derivatograph. The following results were obtained.

During dynamic heating of the sample from 20 to 1000 °C , several thermal events appeared on the DTA curve. Three endothermic peaks—observed at 140 , 600 , and 820 °C —result from the release of water, hydroxyl groups, and carbon dioxide, respectively, into the atmosphere. An exothermic peak at 725 °C arises from the decomposition of the hydrosilicate structure, which releases thermal energy into the system (Figure 3).

The shape of the DTA curve between 350 and 730 °C closely resembles that of the differential decomposition curve of serpentine. However, the curve morphology and the configurations of the DTG and TG traces indicate low-intensity dehydration of this sample component, along with only a weak similarity to the thermal peak trajectories of classic serpentine. Therefore, the structure of the presumed mineral is highly defective and does not fully meet the crystallochemical criteria of standard serpentine. The content of this phase in the sample

is determined by the amount of constitutional water (OH) it contains, which corresponds to the sum of the weight losses $\Delta m_{3/2} + \Delta m_4 = 1.05\% + 2.5\%$ (i.e., half of Δm_3 plus the whole of Δm_4), as shown in Table 4. Based on the stoichiometric formula of serpentine, the proportion of this mineral in the sample is calculated to be 24.6%.

Another component identified in the test sample is calcite. This carbonate is detected through a significant release of carbon dioxide at high temperature, producing a sharp weight loss step on the TG curve. On the DTG curve, the evolution of carbon dioxide forms a pronounced peak at 800 °C, indicating a high dissociation rate. Consequently, the decomposition of calcite generates an intense endothermic peak at 820 °C on the DTA curve, reflecting a substantial outflow of thermal energy from the sample. The presented nature of the thermal decomposition of CaCO_3 is characteristic of well-crystallized calcites.

Based on the amount of CO_2 released into the atmosphere (1.05% + 22.5%), Table 5, and considering the stoichiometric formula of this carbonate, its content in the sample is 53.5%.

It should be noted that the water released from the sample in the 20-200°C range, amounting to 3.3%, is not part of the composition of “serpentine” and calcite. Therefore, it must be classified as mechanically bound water, which is considered impurity.

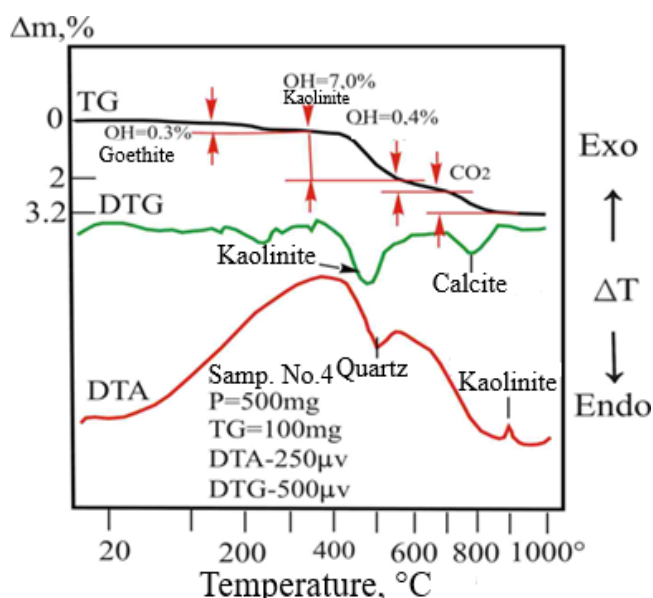


Figure 3 – Derivative plot of sample No. 1

Table 4 – Thermogravimetric data for sample No. 1 in the range of 20-1000°C

Weight loss curve	Weight loss, %	Volatile components of the heated sample	Decomposition stages, °C
Δm_1	3.3	H_2O	20-200
Δm_2	0.7	OH	200-350
Δm_3	2.1	$\text{OH} + \text{CO}_2$	350-560
Δm_4	2.5	OH	560-640
Δm_5	20.0	CO_2	640-1000
$\Sigma \Delta m_{1000^\circ\text{C}}$	28.6	$\text{H}_2\text{O}, \text{OH}, \text{CO}_2$	20-1000

An analysis of the stages listed above shows that at a temperature of 500 °C, the two-calcium silicate Ca_2SiO_4 is formed, while at temperatures above 850 °C, the three-calcium silicate $\text{Ca}_3\text{Si}_2\text{O}_7$ is formed and the formation of wollastonite CaSiO_3 begins. Based on the product composition, Based on the findings, it can be inferred that Ca_2SiO_4 and $\text{Ca}_3\text{Si}_2\text{O}_7$ represent unstable intermediate phases. The thermograms indicate that wollastonite starts to form only after the complete synthesis of tricalcium silicate, which occurs at temperatures exceeding 900 °C.

3.3 Characterization of the synthesized chelating agents

X-ray diffraction and X-ray analysis of the samples

To verify the reliability of the results, X-ray phase analyses were performed on the samples. The X-ray diffraction analysis was conducted using an automated DRON-3 diffractometer with $\text{CuK}\alpha$ radiation and a β -filter. Conditions for recording diffractograms: $U = 35 \text{ kV}$; $I = 20 \text{ mA}$; θ - 2θ scan; detector 2 deg/min. A semi-quantitative X-ray phase analysis was carried out on the diffractograms of powdered specimens using the equal-weighting method together with artificial mixtures, allowing the quantitative proportions of crystalline phases to be established. The interpretation of the diffractograms relied on data from the ICDD library, specifically the Powder Diffraction File (PDF) Release 2022, processed with HighScorePlus software, from which the concentrations of the major phases were derived. Potential impurities—whose identification remains inconclusive due to either their low abundance, the presence of only one or two diffraction peaks, or poor crystallinity—are presented in Table 5 and Figure 4.

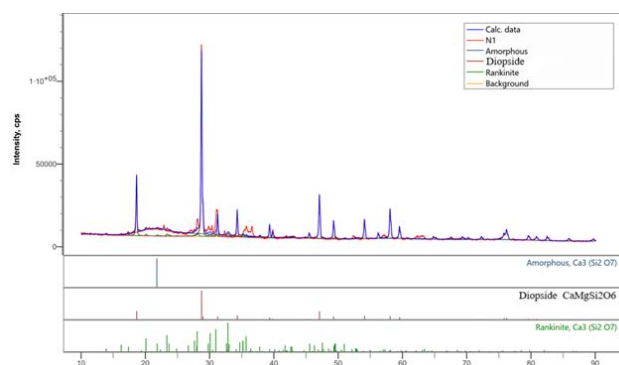


Figure 4 – Diffractogram of the synthesized wollastonite

Table 5 – Results of the semi-quantitative analysis of crystalline phases

Component		Chemical formula	Mass fraction, %
A	Amorphous	$\text{Ca}_3(\text{Si}_2\text{O}_7)$	23.9
B	Calcium Molybdate	$\text{Ca}(\text{MgO}_4)$	52.3
C	Rankinite	$\text{Ca}_3(\text{Si}_2\text{O}_7)$	23.8

The X-ray diffraction data confirm that high-temperature synthesis yields a well-defined synthetic material containing 80-85% of the main mineral, wollastonite ($\text{Ca}(\text{SiO}_3)$). In contrast, the incorporation of molybdenum oxychloride and nickel sulfate as activators facilitates the formation of new mineral phases—namely powellite and libenbergitte—which are fully synthesized from unbound calcium and silicon compounds. The presence of these phases does not negatively affect the physicochemical properties of the resulting material; rather, it enhances the development of a porous structure due to their low density and high specific surface area. The resulting product also contains 7% free amorphous silica in the form of cristobalite.

Comparison of Several Chemisorbents Based on Their Adsorption Properties

EPR Analysis

To determine and compare the activity of the above materials, they were studied using Electron Paramagnetic Resonance (EPR).

The response of magnetic moments to an external magnetic field is governed by several types of interactions involving unpaired electrons, including interactions between the electrons themselves and with their local environment. The key interactions are spin-spin coupling, spin-orbit coupling, hyperfine interactions between unpaired

electrons and their host nuclei, and interactions with the electrostatic field generated by neighboring ions at the site of the unpaired electron.

Measurement parameters: Frequency = 9.445 GHz; center field (F_c) = 340 mT; sweep width = 7.50 mT; modulation frequency = 100 kHz; modulation amplitude = 0.6 mT. EPR spectra were recorded at ambient temperature using a JES-FA 200 spectrometer (Jeol, Japan), with a Mn^{2+} standard in MgO as a reference.

Both the original samples and those subjected to hydrogen plasma treatment for 30 minutes were examined (Figure 5).

A low-intensity EPR signal was detected in sample 1 (raw asbestos waste). Particles with an uncompensated charge could have formed as a result of crushing and grinding serpentinite ores. The samples under study contain a large number of chemical elements that exhibit high magnetic activity: cobalt, chromium, manganese, sodium, potassium, titanium, etc (Figure 6).

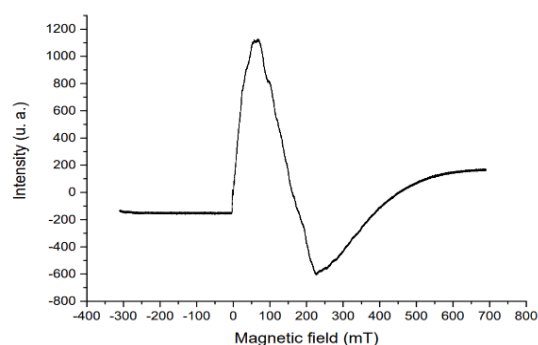


Figure 5 – Raw asbestos waste

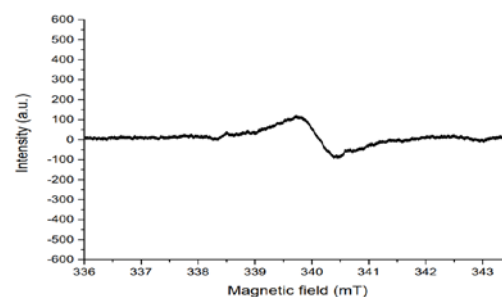


Figure 6 – corporation after leaching

The second sample (asbestos waste after leaching) has a symmetrical spectrum, indicating a uniform distribution of paramagnetic centers in the sample.

Sample 2. The signal is intense, but less so than for Sample 3. After treatment (annealing) in a hydrogen plasma for 30 minutes, the intensity

decreases. Treatment in a hydrogen plasma passivates the uncompensated charge (paramagnetic centers) of the sample (Figure 7).

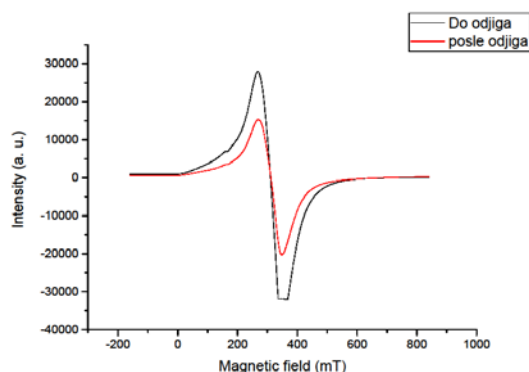


Figure 7 – Synthesized chymadsorbent

The third sample (prepared chemical adsorbent) exhibits a very intense signal. After treatment (annealing) in a hydrogen plasma, the intensity decreases within 30 minutes. Treatment in hydrogen plasma passivates the uncompensated charge

(paramagnetic centers-PMCs) of the sample. Hydrogen particles bind to low-energy uncompensated charges, while stable PMCs remain active (Figure 8).

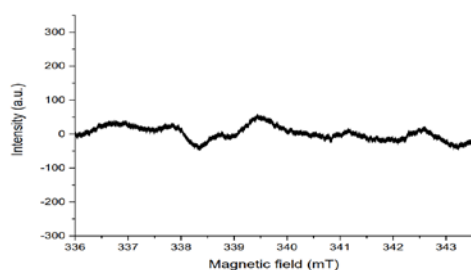


Figure 8 – Commercial Zeolite

An EPR signal is observable in Sample 4 (Commercial Zeolite). The EPR signal shows contributions from several paramagnetic centers. The fourth sample exhibits a symmetrical spectrum, indicating a uniform distribution of paramagnetic centers within the sample.

There may be several reasons for the formation of the EPR signal in these samples: unpaired electrons in the Si-O, Si-O-Ca, or Ca-Ca chains. The high-temperature treatment of the material used in the synthesis process stimulates the formation of particles with an uncompensated charge. The intensity of the EPR signal is also influenced by the grinding process of the substances.

BET Method

Key properties of this material include specific surface area, average pore size, and pore volume. The BET method was utilized to determine the specific surface area and pore size distribution of the porous specimens (Table 6).

To compare the specific surface area, the following samples were tested: the initial asbestos waste material, corporation after the leaching process, pure zeolite, and the chelating adsorbent we produced. The measurements were performed using a SORBTOMETER-M device.

Table 6 — Summary of specific surface area, specific pore volume, and mean pore size for the studied materials

Sample	Specific surface area, m ² /g	Specific pore volume, cm ³	Average pore size
Initial zeolite	8.0-9.0	0.012	1.713
Zeolite after leaching	10.0-13.0	0.137	1.714
Chemical adsorbent obtained	280-315	1.213	1.765
Pure zeolite	90.0-95.0	0.403	1.742

As can be seen from the table, the leaching process increases the specific surface area and specific pore volume of the resulting active component, which will have a positive effect on the properties of the synthetic chemical adsorbent. The average pore size changes only slightly in this process.

Removal of metal impurities from heavy crude oil.

The destructive-adsorptive thermal contact demetallization process involves brief contact between the crude oil and an adsorbent in a two-section reactor heated to temperatures of 300-450 °C. When the feedstock comes into contact with the hot adsorbent, hydrocarbon vapors are produced. These vapors, along with water vapor, are then conveyed to the gas discharge line.

The tar obtained from the delayed coking unit at the Pavlodar Petrochemical Plant LLP is a viscous liquid with low fluidity. It contains up to 0.1 wt.% water and has the following metal concentrations: vanadium—400–600.0 µg/kg; nickel—50–70.0 µg/kg; iron—30–70.0 µg/kg. Its sulfur content ranges from 2.5% to 3.5%, ash content is 0.02 wt.%, the coking index is 18 wt.%, density at 20°C is 1000.0 kg/m³, and the initial boiling point is 380°C.

The study aimed to determine the optimal process parameters—temperature, pressure, and feed flow rate—for the demetallization and desulfurization of heavy petroleum residues. These processes were carried out in the presence of a zeolite-based adsorbent containing wollastonite compounds. Based on the general structure of oil dispersion systems and the reversible conversion between resinous and asphaltene components, it is proposed that during thermal deasphalting and demetallization of crude oil, supramolecular structures (such as metal- and sulfur-containing oil complexes) are broken down and subsequently adsorbed onto the chemical adsorbent.

During the demetallization and desulfurization of the tar feedstock from the Pavlodar Petrochemical Plant's delayed coking unit, various operating conditions were tested using a scaled-up laboratory setup (Table 7):

- Reactor temperature: 300, 320, 340, and 360 °C
- Process duration: 3 hours
- Feed rate: 2–5 L/h
- Volumetric feed rate: 1–3 h⁻¹

To identify the optimal operating conditions, both the feed tar and the resulting treated products were analyzed for metal and sulfur content. Figures 9, 10 and 11 illustrate the relationship between the metal content in the tar and the volumetric feed rate at different temperatures. As shown in Figure 9, under all tested temperatures, the metal content in the feedstock decreases, with a particularly pronounced reduction in vanadium levels. An increase in the volumetric feed rate from 1 to 3 h⁻¹ results in a slight rise in the residual metal content in the tar after processing (Figure 9-11).

As shown in the table, the optimal temperature range for demetallization of heavy crude oil is 380–410 °C. Under these conditions, the vanadium content in the tar decreases from 50 to 28 µg/kg, the nickel content from 50 to 26 µg/kg, iron from 50 to 12 µg/kg, and sulfur from 2.73% to 2.39%. The maximum metal recovery rate under these conditions is 40–55%.

When the temperature rises above 410 °C, the tar begins to boil and coke, which adversely affects the demetallization process. Therefore, the thermal adsorption process must be conducted at a temperature not exceeding 410–420 °C.

Table 7 - Dependence of metal and sulfur composition in tar on process temperature, comparing values before and after testing

Raw materials and type of adsorbent	T, °C	Content of the elements			
		Ni, µg/kg	Fe, µg/kg	V, µg/kg	S, %
Raw tar	0	237	488	1060	15.4
Modified adsorbent	320	220	413	1012	14.2
	340	180	361	881	13.9
	360	162	309	620	11.6
	380	135	261	540	10.12
	400	126	255	510	9.9

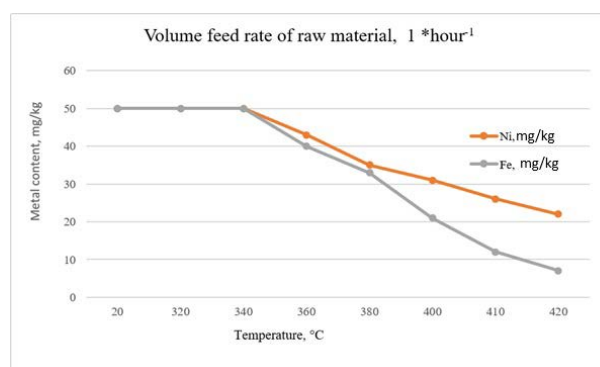


Figure 9 – Degree of nickel and iron removal from tar

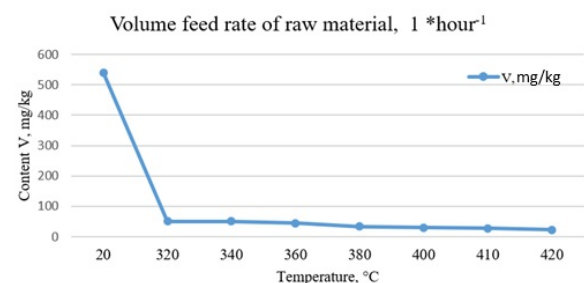


Figure 10 – Degree of vanadium removal from tar

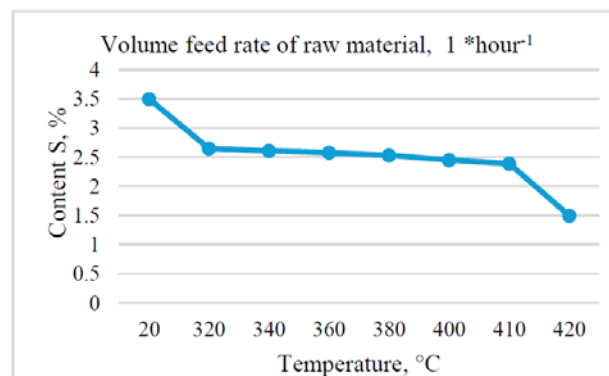


Figure 11 – Degree of sulfur removal from tar

Conclusions

This study successfully demonstrated that chrysotile asbestos waste, after acid leaching, can be upcycled into a highly effective chemisorbent for heavy oil residue upgrading. The acid treatment disrupts the original crystalline fibrous structure, yielding amorphous silica with high reactivity. Subsequent high-temperature synthesis with calcium and sodium carbonates produces a material dominated by wollastonite and calcium silicate phases, which possess a uniquely developed porous architecture.

The synthesized chemisorbent outperforms commercial zeolite, with a specific surface area of 280–315 m²/g and a pore volume of 1.213 cm³/g. EPR spectroscopy further revealed a high density of active paramagnetic centers on its surface, directly correlating with its strong adsorption affinity for metal- and sulfur-containing complexes in heavy oil.

In thermal adsorption tests using vacuum tar from the Pavlodar Petrochemical Plant, the optimal process window was identified at 380–410 °C. Under these conditions, the chemisorbent reduced vanadium, nickel, and iron content by 40–55%, while also lowering sulfur levels. Temperatures exceeding 410 °C led to feedstock coking, limiting process efficiency.

Overall, this work provides a dual benefit: (1) a sustainable solution for hazardous asbestos waste management aligned with circular economy principles, and (2) a low-cost, high-performance chemisorbent that can reduce the metal and sulfur

load in heavy refinery streams, thereby protecting downstream catalysts and lowering operational costs. Future work should focus on pilot-scale validation, adsorbent regeneration cycles, and techno-economic assessment.

Conflicts of interest. On behalf of all authors, the corresponding author states that there is no conflict of interest.

CRedit author statement: **G. Maldybayev:** Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Visualization; **R. Sharipov:** Methodology, Investigation, Data curation, Validation; **R. Urlibay:** Investigation, Formal analysis, Validation; **M. Zhurinov:** Supervision, Project administration, Funding acquisition; **A. Nefedov:** Investigation, Characterization, Data curation; **D. Puzikova:** Investigation, Formal analysis, Visualization; **N.R. Kenzin:** Writing – review & editing, Supervision, Validation.

Acknowledgements. The authors would like to thank the colleagues and staff who contributed to the experimental work and provided technical assistance during the study.

Formatting of funding sources. This research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan under Program No. BR24992812, “Development of materials and technologies for comprehensive corrosion protection of technological equipment in the petrochemical, machine-building, and instrument-making industries.”

Cite this article as: Maldybayev GK, Sharipov RK, Urlibay RK, Zhurinov MZh, Nefedov AN, Puzikova DS, Kenzin NR. Upcycling chrysotile asbestos waste into high-performance wollastonite chemisorbents for demetallization and desulfurization of heavy oil residues. Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex Use of Mineral Resources. 2028; 347(4):51-62. <https://doi.org/10.31643/2028/6445.39>

Ауыр мұнай қалдықтарын деметаллдау және күкіртсіздендіру үшін хризотил-асбест қалдықтарын жоғары өнімді волластонит хемосорбенттерін өндіру

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Получение высокоэффективных волластонитовых хемосорбентов из отходов хризотил-асбеста для деметаллизации и десульфуризации тяжёлых нефтяных остатков

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Поступила: 20 августа 2026 Рецензирование: 10 сентября 2026 Принята в печать: 21 октября 2026	АННОТАЦИЯ Утилизация отходов хризотилового асбеста представляет собой значительную экологическую опасность, а остатки тяжелых нефтепродуктов требуют дорогостоящей предварительной обработки для удаления токсичных металлов и серы. В данном исследовании представлен подход, основанный на принципах циркулярной экономики, для преобразования отходов хризотилового асбеста, подвергнутых кислотному выщелачиванию, в функциональный хемосорбент для одновременной демееталлизации и десульфуризации остатков тяжелых нефтепродуктов. После выщелачивания соляной кислотой отходы асбеста превратились в аморфный, высокореактивный материал, богатый кремнеземом. Путем высокотемпературного синтеза (1100 - 1280 °C) с использованием карбонатов кальция и натрия был получен хемосорбент на основе волластонита (CaSiO₃) и силиката кальция. Комплексная характеристика с использованием методов рентгеновской дифракции (XRD), инфракрасной спектроскопии с преобразованием Фурье (FTIR), термогравиметрического анализа с дифференциальным термическим анализом (TG-DTA), метода БЕТ и ЭПР подтвердила, что синтезированный материал обладает исключительно высокой удельной поверхностью (280 - 315 м²/г), значительным объемом пор (1,213 см³/г) и большим количеством активных парамагнитных центров, значительно превосходящих показатели коммерческого цеолита. При тестировании в процессе термической адсорбции вакуумной смолы (380 - 410 °C) хемосорбент достиг эффективности удаления ванадия, никеля и железа на уровне 40 - 55%, а также значительного снижения содержания серы. Эти результаты демонстрируют перспективный путь преобразования опасных асбестовых отходов в ценный адсорбент, что позволит осуществлять более чистую переработку тяжелой нефти и снизить как промышленные отходы, так и эксплуатационные расходы нефтеперерабатывающих заводов.
	Ключевые слова: волластонит, отходы хризотилового асбеста, остатки тяжелой нефти, демееталлизация, десульфуризация, химическая адсорбция, циклическая экономика, извлечение ванадия.
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References

- [1] Nguyen T-H, Nguyen Q-A, Cao ANT, Ernest T, Nguyen TB, Pham PT, Nguyen TMJ. Hydrodemetallization of heavy oil: Recent progress, challenge, and future prospects. *Journal of Petroleum Science and Engineering*. 2022; 216:110762. <https://doi.org/10.1016/j.petrol.2022.110762>
- [2] Vishnyakov AJM. Vanadium and nickel recovery from the products of heavy petroleum feedstock processing: A review. *Metals*. 2023; 13(6):1031. <https://doi.org/10.3390/met13061031>
- [3] Bakkar A, Seleman MME-S, Ahmed MMZ, Harb S, Goren S, Howsawi EJ. Recovery of vanadium and nickel from heavy oil fly ash (HOFA): A critical review. *RSC Advances*. 2023; 13(10):6327-6345. <https://doi.org/10.1039/D3RA00289F>
- [4] Bello SS, Wang C, Zhang M, Gao H, Han Z, Shi L, Su F, Xu G. A review on the reaction mechanism of hydrodesulfurization and hydrodenitrogenation in heavy oil upgrading. *Energy & Fuels*. 2021; 35(14):10998-11016. <https://doi.org/10.1021/acs.energyfuels.1c01015>

- [5] Dembaremba TO, Majodina S, Walmsley RS, Ogunlaja AS, Tshentu ZR. Perspectives on strategies for improving ultra-deep desulfurization of liquid fuels through hydrotreatment: Catalyst improvement and feedstock pre-treatment. *Frontiers in Energy Research*. 2022; 10. <https://doi.org/10.3389/fchem.2022.807225>
- [6] Zhao F, Xu T, Zhu G, Wang K, Xu X, Liu L. A review on the role of hydrogen donors in upgrading heavy oil and bitumen. *Sustainable Energy & Fuels*. 2022; 6(8):1866-1890. <https://doi.org/10.1039/D1SE01969D>
- [7] Pham HH, Kim KH, Go KS, Nho NS, Kim W, Kwon EH, Jung RH, Lim Y-i, Lim SH, Pham DA. Hydrocracking and hydrotreating reaction kinetics of heavy oil in CSTR using a dispersed catalyst. *Journal of Petroleum Science and Engineering*. 2021; 197:107997. <https://doi.org/10.1016/j.petrol.2020.107997>
- [8] Attia M, Farag S, Jaffer SA, Chaouki J. Metal and sulfur removal from petroleum oil using a novel demetallization-desulfurization agent and process. *Journal of Cleaner Production*. 2020; 275:124177. <https://doi.org/10.1016/j.jclepro.2020.124177>
- [9] Ongarbayev YK. Thermoadsorption Demetallization of Heavy Oil Residues. *Eurasian Chemico-Technological Journal*. 2020; 22(4):269-276. <https://doi.org/10.18321/ectj995>
- [10] Iuzmukhametova R, Boldushevskii R, Shmelkova O, Khamzin Y, Minaev A, Nikulshin P. Adsorptive Treatment of Residues on Macroporous Adsorbent for Marine Fuel Production Scheme on Refinery. *Journal of Marine Science and Engineering*. 2023; 11(3):525. <https://doi.org/10.3390/jmse11030525>
- [11] Mironov N, Tazeev D, Milordov D, Yakubova S, Yakubov M. In-depth experimental study on selective acid extraction of petroporphyrins from heavy oil residues. *Fuel*. 2026; 408:137637. <https://doi.org/10.1016/j.fuel.2025.137637>
- [12] Maldybayev G, Shayakhmetova R.A, Baigenzhenov O, Saparbayeva S.R, Sharipov R. Synthesis of Chemical Adsorbent for Purification of Heavy Oil Residue. *International Journal of Technology*. 2024; 15(3):291-319. <https://doi.org/10.14716/ijtech.v15i3.6507>
- [13] Mubark AE, Mohamed BT, Rashad MM. Comparative Study of Synthetic and Bio-Based Adsorbents for Vanadium Recovery: α -Aminophosphonate versus Magnetic Cysteine-Functionalized Chitosan. *Chemistry Select*. 2026; 11(9):e06060. <https://doi.org/10.1002/slct.202506060>
- [14] Popoola LT, Yusuff AS, Adeyi AA, Omotara OO. Adsorptive removal of heavy metals from oil well produced water using *Citrullus lanatus* peel: Characterization and optimization. *South African Journal of Chemical Engineering*. 2022; 39:19-27. <https://doi.org/10.1016/j.sajce.2021.11.001>
- [15] Shi Y, Ye G, Yang C, Tang Y, Peng C, Qian G, Yuan W, Duan X, Zhou X. Pore engineering of hierarchically structured hydrodemetallization catalyst pellets in a fixed bed reactor. *Chemical Engineering Science*. 2019; 202:336-346. <https://doi.org/10.1016/j.ces.2019.03.049>
- [16] Wang H, Wang C, Tao S, Qiu J, Yu Y, Gu M. Biomimetic Preparation of Hybrid Porous Adsorbents for Efficiently Purifying Complex Wastewater. *ACS Sustainable Chemistry & Engineering*. 2016; 4(3):992-998. <https://doi.org/10.1021/acssuschemeng.5b01054>
- [17] Trukhan SN, Chibiryayev AM, Martyanov ON. Vanadyl Porphyrins as a Sulfur Trap in Heavy Oils. *Energy & Fuels*. 2025; 39(10):4719-4727. <https://doi.org/10.1021/acs.energyfuels.4c06358>
- [18] Li W, Bao J, Zeng S, Zheng J, Fang W, Yi X, Yang Q, Lai W. Al₂O₃@SiO₂ supported NiMo catalyst with hierarchical meso-macroporous structure for hydrodemetallization. *Catalysts*. 2025; 15(7):646. <https://doi.org/10.3390/catal15070646>
- [19] Kumari S, Sengupta S. Non-hydrogen processes for simultaneous desulfurization and denitrogenation of light petroleum fuels-an elaborative review. *Environmental Science and Pollution Research*. 2021; 28(44):61873-61907. <https://doi.org/10.1007/s11356-021-15909-9>
- [20] Girotto CP, de Campos SD, de Campos ÉA. Chrysotile asbestos treated with phosphoric acid as an adsorbent for ammonia nitrogen. *Heliyon*. 2020; 6(2):e03397. <https://doi.org/10.1016/j.heliyon.2020.e03397>
- [21] Marian NM, Giorgetti G, Magrini C, Capitani GC, Galimberti L, Cavallo A, Salvini R, Vanneschi C, Viti C. From hazardous asbestos containing wastes (ACW) to new secondary raw material through a new sustainable inertization process: A multimethodological mineralogical study. *Journal of Hazardous Materials*. 2021; 413:125419. <https://doi.org/10.1016/j.jhazmat.2021.125419>
- [22] Maldybayev GK, Shayakhmetova RA, Baigenzhenov O, Saparbayeva SR, Sharipov R. Investigating chrysotile asbestos waste as a potential material for synthetic adsorbents. *Bulletin D. Serikbayev of EKTU*. 2023, 283-293.
- [23] Kim C, Kim Y, Roh Y. Thermal decomposition and phase transformation of chrysotile in asbestos-containing waste. *Minerals*. 2025; 15(4):344. <https://doi.org/10.3390/min15040344>
- [24] Kusiorowski R, Gerle A, Kujawa M, Bloise A. Kinetic Aspects of Chrysotile Asbestos Thermal Decomposition Process. *Minerals*. 2025; 15(6):609. <https://doi.org/10.3390/min15060609>
- [25] Gineika A, Siauciunas R, Baltakys K. Synthesis of wollastonite from AlF₃-rich silica gel and its hardening in the CO₂ atmosphere. *Scientific Reports*. 2019; 9:18063. <https://doi.org/10.1038/s41598-019-54219-6>
- [26] Allah P, Luukkonen T, Kinnunen P, Perumal P. Persulfate-derived porous wollastonite granules for accelerated CO₂ mineralization and suitability for aggregate applications. *Carbon Capture Science & Technology*. 2026; 18:100571. <https://doi.org/10.1016/j.ccst.2026.100571>
- [27] Maiti SK, Prasad MNV, Kumar A. Circular economy approach as management solution for asbestos waste. In: Prasad MNV, editor. *Environmental Materials and Waste*. 2nd ed. Elsevier. 2024, 337-367. <https://doi.org/10.1016/B978-0-443-22069-2.00010-3>
- [28] Dambrauskas T, Baltakys K. Synthesis and properties of catalyst based on semicrystalline calcium silicate hydrate with intercalated Co²⁺, Cu²⁺, and Cr³⁺ ions. *Surfaces and Interfaces*. 2024; 46:104002. <https://doi.org/10.1016/j.surfin.2024.104002>
- [29] Chaturvedi S. Waste-derived nanomaterials as sustainable solution for wastewater remediation. *Discover Chemistry*. 2026; 3:150. <https://doi.org/10.1007/s44371-026-00612-w>