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PHYSICOCHEMICAL STUDY OF SERPENTINITE WASTE AND PHOSPHORIC ACID PRODUCTS

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Abstract. This study investigates the formation of magnesium- and phosphorus-containing compounds suitable for use as fertilizers, based on the reaction of serpentinite waste with phosphoric acid. In this study, the physicochemical interaction between serpentinite waste generated during chrysotile-asbestos processing at the Zhitikara deposit (Kazakhstan) and phosphoric acid was investigated with the aim of obtaining magnesium-phosphate products suitable for agricultural applications. Serpentinite residue containing approximately 42 wt.% MgO was treated with phosphoric acid under different stoichiometric conditions. Thermodynamic calculations were performed to evaluate the feasibility of magnesium phosphate formation and to compare the effectiveness of phosphoric acid with sulfuric, hydrochloric, and nitric acids.

The obtained products were characterized by X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), chemical analysis, and pH measurements. The results demonstrated that phosphoric acid effectively decomposes the serpentinite structure, leading to the formation of hydrated magnesium phosphates. The phases $Mg(H_2PO_4)_2 \cdot 2H_2O$ and $MgHPO_4 \cdot 3H_2O$ were identified as the dominant reaction products, while crystalline magnesium orthophosphate was not detected because of its lower thermodynamic stability. Under a $Mg^{2}{}_{-3}PO_4$ molar ratio of 1:1, the system reached a nearly neutral pH value (~6.9), providing favorable conditions for obtaining fertilizer-grade products. FTIR analysis confirmed the destruction of the original serpentine structure and indicated the presence of amorphous silica in the solid residue. The proposed approach represents a resource-efficient and environmentally sustainable method for valorization of serpentinite waste and offers promising prospects for the production of magnesium- and phosphorus-containing fertilizers from technogenic raw materials.

Keywords: serpentinite waste, phosphoric acid, IR spectroscopy, magnesium phosphates, fertilizers

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СЕРПЕНТИНИТ ҚАЛДЫҚТАРЫНЫҢ ФОСФОР ҚЫШҚЫЛЫМЕН ӘРЕКЕТТЕСУ ӨНІМДЕРІНІҢ ФИЗИКА-ХИМИЯЛЫҚ ЗЕРТТЕЛУІ

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Аннотация. Бұл зерттеуде Жітіқара кен орнындағы хризотил-асбест шикізатын өңдеу барысында түзілетін серпентинит қалдықтарының фосфор қышқылымен физика-химиялық әрекеттесуі зерттеліп, ауыл шаруашылығында қолдануға жарамды магний фосфатты қосылыстарды алу мүмкіндігі қарастырылды. Құрамында шамамен 42 масс.% MgO бар серпентинит қалдықтары фосфор қышқылымен әртүрлі стехиометриялық қатынастарда өңделді. Магний фосфаттарының түзілу мүмкіндігін бағалау және фосфор қышқылының күкірт, тұз және азот қышқылдарымен салыстырғандағы тиімділігін анықтау үшін термодинамикалық есептеулер жүргізілді.

Алынған өнімдер рентгенфазалық талдау (XRD), Фурье түрлендіру инфрақызыл спектроскопиясы (FTIR), химиялық талдау және pH мәнін анықтау әдістерімен зерттелді. Зерттеу нәтижелері фосфор қышқылының серпентинит құрылымын тиімді түрде ыдыратып, гидратталған магний фосфаттарының түзілуіне әкелетінін көрсетті. Негізгі реакция өнімдері ретінде $Mg(H_2PO_4)_2 \cdot 2H_2O$ және $MgHPO_4 \cdot 3H_2O$ фазалары анықталды, ал магний ортофосфаты оның термодинамикалық тұрақтылығының төмен болуына байланысты анықталған жоқ. $Mg^{2}{}_{-3}PO_4$ = 1:1 мольдік қатынасында жүйенің pH мәні бейтарапқа жуық деңгейге (~6,9) жетіп, тыңайтқыштық мақсаттағы өнімдерді алу үшін қолайлы жағдай қалыптастырды. FTIR талдауы бастапқы серпентин құрылымының толық бұзылуын және қатты қалдық құрамында аморфты кремнеземнің болуын растады. Ұсынылған тәсіл серпентинит қалдықтарын кәдеге жаратудың ресурсты үнемдейтін және экологиялық тұрғыдан тұрақты әдісі болып табылады әрі техногендік шикізат негізінде магний және фосфор құрамды тыңайтқыштар өндірудің болашағын ашады.

Кілттік сөздер: серпентинит қалдықтары, фосфор қышқылы, ИҚ-спектроскопия, магний фосфаттары, тыңайтқыштар

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ФИЗИКО-ХИМИЧЕСКОЕ ИССЛЕДОВАНИЕ ПРОДУКТОВ ВЗАИМОДЕЙСТВИЯ СЕРПЕНТИНИТОВЫХ ОТХОДОВ И ФОСФОРНОЙ КИСЛОТЫ

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Аннотация. В настоящем исследовании изучено физико-химическое взаимодействие серпентинитовых отходов, образующихся при переработке хризотил-асбестового сырья Житикаринского месторождения Казахстана, с фосфорной кислотой с целью получения магнийфосфатных соединений, пригодных для применения в сельском хозяйстве. Серпентинитовый остаток, содержащий около 42 мас. % MgO, обрабатывали фосфорной кислотой при различных стехиометрических соотношениях. Для оценки возможности образования фосфатов магния и сравнения эффективности фосфорной кислоты с серной, соляной и азотной кислотами были выполнены термодинамические расчёты. Полученные продукты исследованы методами рентгенофазового анализа (XRD), инфракрасной спектроскопии с преобразованием Фурье (FTIR), химического анализа и измерения pH. Результаты показали, что фосфорная кислота эффективно разрушает структуру серпентинита, способствуя образованию гидратированных фосфатов магния. В качестве основных продуктов реакции идентифицированы фазы $Mg(H_2PO_4)_2\cdot 2H_2O$ и $MgHPO_4\cdot 3H_2O$, тогда как кристаллический ортофосфат магния не обнаружен вследствие его более низкой термодинамической устойчивости в исследуемых условиях. При мольном соотношении $Mg^{2}-_{4}^{3-}$ = 1:1 система достигала практически нейтрального значения pH (~6,9), что создаёт благоприятные условия для получения продуктов удобрительного назначения. Данные FTIR-анализа подтвердили разрушение исходной структуры серпентина и наличие аморфного кремнезёма в твёрдом остатке. Предложенный подход представляет собой ресурсоэффективный и экологически устойчивый способ утилизации серпентинитовых отходов и открывает перспективы получения магний- и фосфорсодержащих удобрений на основе техногенного сырья.

Ключевые слова: серпентинитовые отходы, фосфорная кислота, ИК-спектроскопия, фосфаты магния, удобрения

Introduction. Magnesium compounds and magnesium-containing materials are an integral part of modern chemical production. However, there are currently no industrial enterprises in Kazakhstan that produce magnesium-based compounds and fertilizers of industrial significance. Moreover, the country's fertilizer production remains narrowly focused on nitrogen-phosphate and calcium-phosphate fertilizers. At the same time, there is a growing demand for complex fertilizers containing not only phosphorus, but also magnesium, nitrogen, calcium, sulfur, and trace elements. This trend encourages the use of phosphate-containing minerals and industrial by-products to maintain the nutrient balance in soils. Such an approach contributes to the diversification of the raw material base and expansion of the range of mineral fertilizers. In this context, serpentinites are increasingly being considered as alternatives to dolomite. This interest is partly due to the absence of high-quality dolomite deposits in Kazakhstan, which has traditionally served as the main raw material for magnesium production.

Serpentinites are considered promising raw materials due to their high magnesium oxide (MgO) content (35–45 wt.%), which is approximately 3–4% higher than that of dolomite.

Accordingly, research into the utilization of serpentinites for the production of magnesium compounds or magnesium-based fertilizers is of considerable scientific and practical interest, particularly in the field of agriculture. The advantages of using serpentinites include:

• their abundant natural occurrence, particularly in countries with developed mining sectors;

• their association with nickel, chromite, and chrysotile-asbestos deposits, which reduces the need for additional mining;

• the ability to repurpose mining waste, thereby contributing to environmental sustainability;

• and the potential to develop complex fertilizers due to their high magnesium content-especially when combined with phosphorus, nitrogen, or sulfur compounds.

• serpentinites can be crushed into powder form and used to improve soil acidity levels, owing to the simplicity and low cost of the preparation technologies.

Additional advantages include the low cost of serpentinite extraction and the possibility of establishing fertilizer production facilities in serpentinite-rich regions, which would significantly reduce logistics and transportation expenses, among other benefits.

Serpentinite is a magnesium-rich silicate mineral that is widely distributed in nature but is often underutilized as a raw material in the mining industry. Traditional acid treatment methods using H_2SO_4 or HCl have been sufficiently studied (Maslennikova, 2007; Teir et al., 2007; Aueshov et al., 2017), however, phosphoric acid (H_3PO_4), acting both as a reagent and a source of phosphorus for fertilizers, has been studied to a lesser extent (Pirimov et.al., 2023; Federockova et al., 2014; Yamada and Nagai 1970). H_3PO_4 is considered promising in agriculture due to its dual function and can be used for the production of magnesium phosphates - compounds important for agriculture - as well as amorphous silica applicable in industry (Viera et al., 2022; Liu et al., 2023; Knyazev et al., 2021; Nakamura et al., 1956).

One of the largest serpentinite deposits in Kazakhstan is located in Zhitikara, Kostanay region. As a result of long-term processing of chrysotile-asbestos raw materials at this site, a vast amount of serpentinite waste—estimated at approximately 300 million tons—has accumulated. This waste represents a valuable technogenic raw material for the production of magnesium-based products and fertilizers. The magnesium content in the waste reaches up to 43.0 wt.% MgO. Despite this potential, the possibilities of utilizing this material for magnesium extraction remain underexplored to date.

Today, agrochemical science increasingly emphasizes the importance of using magnesium- and silicon-containing fertilizers, placing them on par with conventional nitrogen (N), phosphorus (P), and potassium (K) fertilizers. Magnesium is an essential nutrient for plants, as it not only enhances crop yield but also improves the nutritional quality of agricultural products. Currently, fertilizers containing both Mg and NPK are mainly produced as simple mechanical blends of different fertilizers, commonly referred to as compound fertilizer mixtures. These mixed formulations are typically more expensive than conventional fertilizers and are produced in limited quantities.

An analysis of studies on this topic (Auyeshov et al., 2024; Yeskibayeva et al., 2024; Katyshev et al., 2014) shows that the majority of research efforts related to the processing of serpentinites and serpentinite waste have focused on acid leaching for magnesium extraction. In most cases, sulfuric and hydrochloric acids have been employed for material decomposition, while the use of nitric acid has been less common. The proposed technologies generally differ in the type of acid used, the degree of raw material pulverization, the operating conditions of the processes, and the methods used for purification of the magnesium-containing solutions. The possibility of producing magnesium- and phosphorus-containing fertilizers through the treatment of serpentinites or serpentinite waste with phosphoric acid has been demonstrated in several works (Arynov et al., Patent KZ 2017).

Accordingly, the objective of this study was to investigate the interaction between serpentinite waste from the Zhitikara deposit and phosphoric acid, with particular emphasis on the phase state of the resulting reaction products.

.**Materials and methods.** The object of this study was serpentinite waste generated at the chrysotile-asbestos beneficiation plant of "Kostanay Minerals" JSC, located at the Zhitikara deposit. The average chemical composition of the waste (wt.%): MgO – 42.0; SiO_2 – 41.0; Fe_2O_3 – 4.0; Al_2O_3 – 0.45; CaO – 0.1; Cr_2O_3 – 0.16. Phosphoric acid of analytical grade (85%) was used in the experiments.

X-ray phase analysis (XRD) was performed using a DRON-3 diffractometer with a Cu Kα radiation source and a nickel filter, in powder mode. Diffracted maxima were recorded using an ionization chamber at a goniometer speed of 2° per minute. Qualitative analysis of the obtained diffractograms was carried out using the WinXPOW software (ICDD PDF-2 database).

Infrared (IR) spectra (FTIR) were recorded on a "Shimadzu IR Prestige-21c" spectrophotometer in the range of 400–4000 cm^{-1}, equipped with proprietary software and a spectral library from Pike Technologies (Miracle accessory). For analysis, the sample was dried at 105 °C, ground into a powder, and pressed firmly onto a diamond crystal. The spectrum was recorded in the range of 4000–400 cm^{-1}.

The acidity (pH) of the chemical system was measured using a laboratory ionometer model И-160.

The Gibbs free energy ($\Delta G^0_{(rxn)}$) under standard conditions was calculated based on thermodynamic data ($\Delta H^0_{(rxn)}$ and $\Delta S^0_{(rxn)}$) using the incremental method developed by B.K. Kasenov and M.K. Aldabergenov (Kasenov et al., 1994). Assessment of the standard thermodynamic function ΔS^0 for various hydrated magnesium phosphate compounds based on the contributions of ions and structural fragments.

The experimental interaction between serpentinite waste and phosphoric acid was carried out using 50% H_3PO_4 solution. According to the stoichiometric ratios defined in reactions 1–3 (Table 1), the following quantities of phosphoric acid were used per 1.0 g of serpentinite: 2.13 g for reaction 1, 1.065 g for reaction 2, and 0.71 g for reaction 3. The reaction was performed in a temperature-controlled reactor flask equipped with a reflux condenser and a propeller stirrer. Prior to the reaction, 2.5 g of serpentinite waste was loaded into the reactor, and the corresponding calculated amount of phosphoric acid was added during stirring.

The interaction was conducted at a controlled temperature for 1 hour. Upon completion, the resulting slurry was first air-dried and then further dried in an oven at 95–100°C. The obtained reaction products were identified using X-ray diffraction (XRD) and Fourier-transform infrared (FTIR) spectroscopy.

Results and Discussion. *Thermodynamic Assessment.* The complex ternary phase diagram of the $MgO–P_2O_5–H_2O$ system illustrates the equilibrium states of various phases depending on temperature and the concentrations of the components in the system. Based on this diagram, it is possible to predict the formation of different hydrated magnesium phosphate salts depending on the Mg^{2-}, PO_4^{3-}, and H_2O ratios. Possible compounds include: $MgHPO_4 \cdot 3H_2O+Mg(H_2PO_4)_2$; $MgHPO_4$ $3H_2O+Mg(H_2PO_4)_2 \cdot 2H_2O$; $MgHPO_4 \cdot 2H_2O+$ $Mg(H_2PO_4)_2$ (Sierra et al., 2018). The formation of specific compounds is influenced by the acidity of the medium and the molar ratios of the components. The ratio of Mg^{2-} to PO_4^{3-} concentrations determine which type of phosphate is likely to dominate in the system. Accordingly, thermodynamic calculations were performed to evaluate the interactions between serpentinite (as the main component of the waste) and phosphoric acid at different molar ratios (1–3), as well as, for comparison, with sulfuric, hydrochloric, and nitric acids (4–6). The results of standard Gibbs free energy ($\Delta G^0_{(rxn)}$ = f(T)) calculations are presented in Table 1.

Table 1. Standard Gibbs free energy values ($\Delta G^0_{(rxn)}$) for the interaction of serpentinite with various acids.

Reaction No.	Reaction	ΔG^0_{298}, kJ/mol
1	$3MgO \cdot 2SiO_2 \cdot 2H_2O+6H_3PO_4= 3Mg(H_2PO_4)_2 \cdot 2H_2O+2SiO_2+3H_2O$	-535.8
2	$3MgO \cdot 2SiO_2 \cdot 2H_2O+3H_3PO_4= 3MgHPO_4 \cdot 3H_2O+2SiO_2+2H_2O$	-724.4
3	$3MgO \cdot 2SiO_2 \cdot 2H_2O+2H_3PO_4= Mg_3(PO_4)_2 \cdot 2H_2O+2SiO_2+5H_2O$	-141.6
4	$3MgO \cdot 2SiO_2 \cdot 2H_2O+6HCl= 3MgCl_2+2SiO_2+5H_2O$	-5.7
5	$3MgO \cdot 2SiO_2 \cdot 2H_2O+3H_2SO_4= 3MgSO_4+2SiO_2+5H_2O$	-25.1
6	$3MgO \cdot 2SiO_2 \cdot 2H_2O+6HNO_3= 3Mg(NO_3)_2+2SiO_2+5H_2O$	-11.4

The standard Gibbs free energy (ΔG^0_{298}) values for the reactions between serpentinite ($3MgO \cdot 2SiO_2 \cdot H_2O$) and phosphoric acid, according to reaction equations 1–3, are –535.8, –724.8, and –141.6 kJ/mol, respectively. These values indicate that the reactions are thermodynamically favourable and likely to proceed under standard conditions. Furthermore, compared to sulfuric, hydrochloric, and nitric acids, phosphoric acid exhibits a significantly higher potential to decompose serpentinite.

Based on the thermodynamic likelihood of formation, the stability order of magnesium phosphates is as follows: magnesium hydrogen phosphate trihydrate > magnesium dihydrogen phosphate dihydrate > magnesium orthophosphate. This suggests that the formation of $MgHPO_4 \cdot 3H_2O$ is the most thermodynamically favourable.

The results of the chemical analysis of the reaction products and the pH of the medium under the experimental conditions corresponding to reactions P-1, P-2, and P-3 (Table 1) are presented in Table 2.

Table 2. Chemical composition of the solid products and equilibrium pH values resulting from the "Serpentinite – H_3PO_4" interactions.

Rxn No.	Sample	H_3PO_4 (g), Stoich.	pH	MgO (wt.%)	SiO_2 (wt.%)	Fe_2O_3 (wt.%)	Al_2O_3 (wt.%)	CaO (wt.%)	Cr_2O_3 (wt.%)	P_2O_5 (wt.%)
–	Initial SR*	–	10.12	44.05	37.77	5.55	0.44	0.10	0.16	–
R-1	SR*	2.13	3.15	13.51	18.80	4.00	0.26	0.30	–	48.44
R-2	SR*	1.07	6.90	19.37	25.03	6.11	0.30	0.31	–	–
R-3	SR*	0.71	8.56	34.67	22.00	6.00	0.29	0.22	–	–
* Note: SR – serpentinite residue (solid waste)										

Based on the initial pH value of 10.12 in the aqueous suspension of the serpentinite residue, it can be concluded that the material exhibits basic properties in a water medium. In the case of R-1, conducted with an excess of phosphoric acid, the low equilibrium pH value (3.15) suggests that a portion of the acid remained unreacted. For the stoichiometric amount used in R-2, the pH of 6.9 indicates that acid-base interactions were nearly complete. In contrast, under the conditions of R-3, the observed pH of 8.56 reflects a deficiency of phosphoric acid in the reaction system.

According to the chemical analysis results of the reaction products, a trend is observed wherein, as the system transitions from the R-1 to R-2 and R-3 stoichiometric ratios, the MgO content in the final products increases. At the same time, the P_2O_5 content varies, which is indicative of the formation of different magnesium phosphate phases depending on the initial stoichiometric ratios applied.

X-ray diffraction (XRD) analysis conducted to identify the mineral composition of the products revealed that the characteristic reflection patterns of serpentinite, which constitutes the core of the initial residue, were absent in the products of reactions R-1 and R-2. This indicates complete structural transformation. In the case of reaction R-3, these reflections were only weakly detectable, suggesting incomplete decomposition of the serpentinite structure (see Table 3 and Figures 1 and 2).

Table 3. Diffraction reflection intensities of the reaction products in the ("Serpentinite – H_3PO_4") system.

d/n (Å)	J/J_0 (%)	Identified phase	Chemical formula	Phase name
7.38	100	Serpentine	$Mg[Si_2O_5](OH)_4$	Serpentine
3.66	80	Serpentine	$Mg[Si_2O_5](OH)_4$	Serpentine
2.48	32	Serpentine	$Mg[Si_2O_5](OH)_4$	Serpentine
1.53	20	Serpentine	$Mg[Si_2O_5](OH)_4$	Serpentine
3.14	100	Dihydrated magnesium dihydrogen phosphate	$Mg(H_2PO_4)_2 \cdot 2H_2O$	Dihydrated magnesium dihydrogen phosphate

3.37	80	Dihydrated magnesium dihydrogen phosphate	$Mg(H_2PO_4)_2 \cdot 2H_2O$	Dihydrated magnesium dihydrogen phosphate
2.33	70	Dihydrated magnesium dihydrogen phosphate	$Mg(H_2PO_4)_2 \cdot 2H_2O$	Dihydrated magnesium dihydrogen phosphate
3.45	100	Tris-hydrated magnesium hydrogen phosphate	$MgHPO_4 \cdot 3H_2O$	Tris-hydrated magnesium hydrogen phosphate
3.05	80	Tris-hydrated magnesium hydrogen phosphate	$MgHPO_4 \cdot 3H_2O$	Tris-hydrated magnesium hydrogen phosphate
5.90	40	Tris-hydrated magnesium hydrogen phosphate	$MgHPO_4 \cdot 3H_2O$	Tris-hydrated magnesium hydrogen phosphate
3.41	100	Magnesium hypophosphite	$Mg(H_2PO_2)_2$	Magnesium hypophosphite
4.01	65	Magnesium hypophosphite	$Mg(H_2PO_2)_2$	Magnesium hypophosphite
5.00	63	Magnesium hypophosphite	$Mg(H_2PO_2)_2$	Magnesium hypophosphite
3.47	100	Iron orthophosphate	$FePO_4$	Iron orthophosphate
3.02	40	Iron orthophosphate	$FePO_4$	Iron orthophosphate
4.39	23	Iron orthophosphate	$FePO_4$	Iron orthophosphate
4.62	100	Iron metasilicate	$FeSiO_3$	Iron metasilicate
2.91	90	Iron metasilicate	$FeSiO_3$	Iron metasilicate
6.48	70	Iron metasilicate	$FeSiO_3$	Iron metasilicate

In the first two cases (P-1 and P-2), it was established that within the first hour of interaction, the serpentinite structure is completely destroyed under the action of phosphoric acid. In the case of P-3, an insufficient amount of phosphoric acid is present in the system, resulting in incomplete destruction of the serpentinite structure. Figures 1 and 2 present the X-ray diffraction analysis results of the reaction products for variants P-1 and P-2. According to the WinXPOW program (ICDD PDF-2), diffraction reflections corresponding to magnesium phosphate salts with various degrees of hydration were detected (Table 3). Specifically, the observed d/n values were:

d/n = 3.14, 3.37, and 2.33 corresponding to magnesium dihydrogen phosphate dihydrate; d/n = 3.45, 3.05, and 5.90 corresponding to magnesium hydrogen phosphate trihydrate; d/n = 3.41, 4.01, and 5.00 corresponding to magnesium hypophosphite; d/n = 3.47, 3.02, and 4.39 attributed to iron orthophosphate; d/n = 4.62, 2.91, and 6.48 associated with iron metasilicate.

The absence of distinct reflections corresponding to crystalline SiO_2 in the XRD patterns of the reaction products suggests that the silica formed during the reactions is likely present in an amorphous or poorly crystalline state.

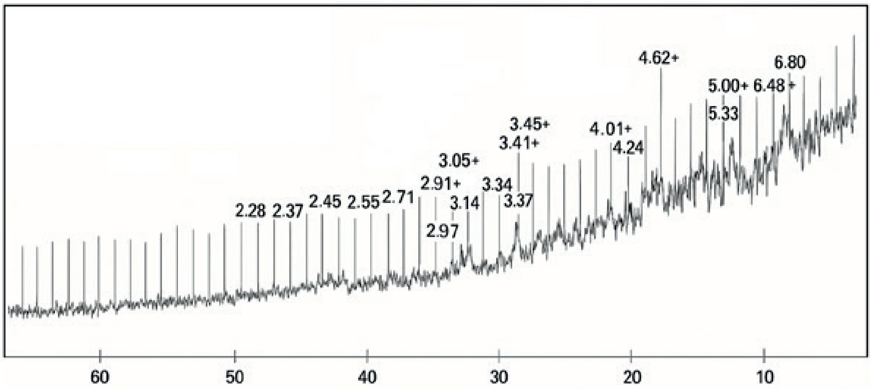

Figure 1. - X-ray diffraction (XRD) pattern of the interaction products between serpentinite residue and phosphoric acid (R-1 condition).

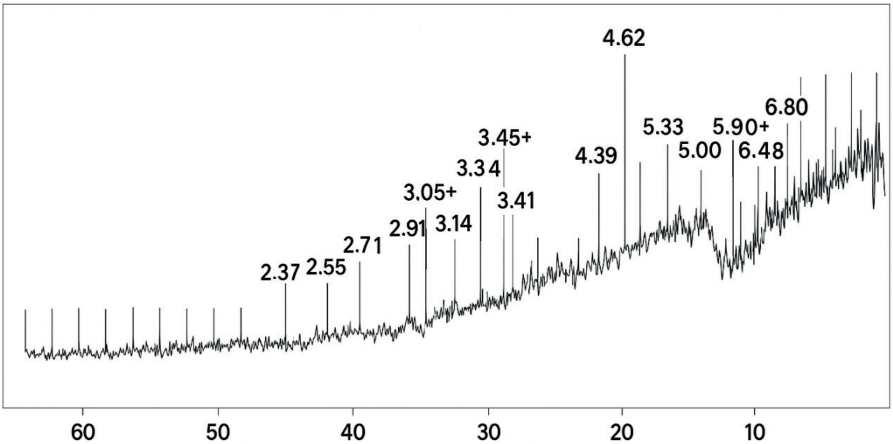

Figure 2. X-ray diffraction (XRD) pattern of the interaction products between serpentinite residue and phosphoric acid (R-2 condition).

Analysis of the FTIR spectra of the interaction products between serpentinite residue and phosphoric acid (Figure 1) revealed the absence of the characteristic absorption band at 941 cm^{-1}, typically associated with the valence vibrations of serpentinite structures. This supports the assumption that serpentinite structures undergo complete decomposition as a result of the reaction.

The FTIR spectra, in turn, exhibit characteristic bands corresponding to various structural units: water molecules (3700–3300 cm^{-1} and 1700–1600 cm^{-1}), phosphate anions such as HPO_4^{2-} and H_2PO_4- (1300–650 cm^{-1}), and Mg_6–O_6 coordination polyhedra (600–400 cm^{-1}) (Arynov et al., Patent KZ 2017).

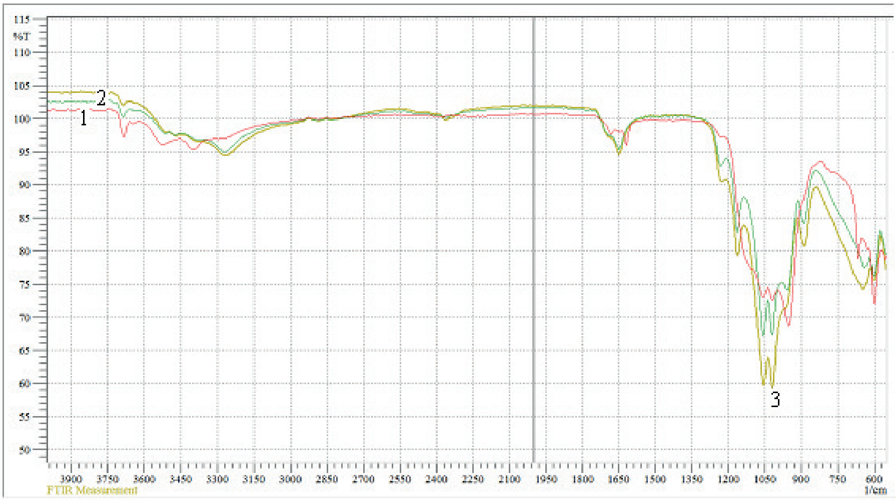

Figure 3. FTIR spectra of the interaction products in the "Serpentinite residue – H_3PO_4" system: 1) R-1; 2) R-2; 3) R-3 (corresponding to the reaction products listed in Table 2).

In the FTIR spectra, three distinct bands in the 3700–3300 cm^{-1} range and a low-intensity shoulder at approximately 651 cm^{-1} indicate that water molecules occupy structurally nonequivalent sites and are not energetically identical. The high-frequency maxima (3700–3300 cm^{-1}) are attributed to weakly bound or non-coordinated water molecules, which are involved in hydrogen bonding either with each other or with phosphate ions. The presence of a deformation band at 1661 cm^{-1} ($\delta(H_2O)$) with a shoulder suggests that water molecules occupy two or three crystallographically non-equivalent positions within the structure.

Characteristic bands observed at 1065 cm^{-1} and 956 cm^{-1} are attributed to symmetric and asymmetric stretching and deformation vibrations of $(O_2PO_2)H_2$ – type anions. Additional bands at 1230, 1165, 1018, and 891 cm^{-1} correspond to $(O_2PO_2)H$ – type anions. The presence of hydrogen bonding between anions and water molecules is supported by the splitting of absorption bands in the anion lattice region (1300–650 cm^{-1}). The absence of distinct absorption bands for $(O_2PO_2)H_2$ and $(O_2PO_2)H$ anion lattices suggests the formation of directed dipole moments as a result of H-bonding between phosphate ions and non-coordinated water molecules. This leads to the collective excitation of phosphate tetrahedra, manifested as a unified vibrational mode of the entire anionic system.

Additionally, the intense bands at 1065 and 956 cm^{-1} are associated with the stretching vibrations of silica (SiO_2), indicating its presence in an amorphous or poorly crystalline form.

Based on FTIR spectral analysis, it can be inferred that under the conditions of Reaction 1 (R-1), the system predominantly forms magnesium dihydrogen phosphate trihydrate. In the cases of Reactions 2 and 3 (R-2 and R-3), the products are similar in composition and mainly consist of magnesium hydrogen phosphates with magnesium dihydrogen phosphate dihydrate as a secondary phase. Although the stoichiometric ratio in Reaction 3 corresponds to the theoretical formation of magnesium orthophosphate, this compound is not detected; instead, HPO_4^{2-} – type hydrogen phosphates are formed. When the molar ratio of the reactants is 1:1 (as in R-2), the pH of the medium approaches neutral (pH = 6.9), which may be considered optimal for fertilizer production in terms of acidity, product yield, and composition.

Conclusion. Physicochemical analysis (XRD and FTIR) of the reaction products in the "serpentinite residue – phosphoric acid" system confirmed that phosphoric acid can completely decompose serpentinite structures within a short period. The qualitative composition of the reaction products corresponds to the thermodynamically predicted phases: various hydrated magnesium phosphates ($Mg(H_2PO_4)_2 \cdot 2H_2O$, $MgHPO_4 \cdot 3H_2O$), iron orthophosphate ($FePO_4$), and iron metasilicate ($FeSiO_3$). Magnesium orthophosphate was not formed, which is consistent with its lower thermodynamic favorability (higher Gibbs free energy).

When serpentinite residue and phosphoric acid are combined in a 1:1 molar ratio, the resulting product shows favorable characteristics-such as optimal acidity, phase composition, and yield—for use as a magnesium- and phosphorus-containing fertilizer.

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