PERSPECTIVES OF TREATMENT OF WATER ENVIRONMENTS FROM POLLUTANTS WITH ULTRASOUND-ACTIVATED BENTONITES

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Abstract. The paper analyzes the perspectives for natural sorbents to be used in environmental technologies. The object of the study is the clay rock from the left side of the upper Pivdennyi Bug river (in the vicinity of the Khmelnytskyi city). The rock was enriched in montmorillonite by centrifugation of a clay suspension to obtain the fraction with a size of less than $5 \cdot 10^{-6}$ m. The researchers defined the mineral composition of the enriched clay based on the findings of the X-ray diffraction and complex thermal analyses. The enriched clay was chemically activated with a 5% NaCl aqueous solution and physically activated with the action of ultrasound. Based on the results of the X-ray diffraction analysis, the cation exchange capacity (CEC) of enriched clays, both natural and activated by ultrasound, was found against the methylene blue (MB) dye. The findings of the X-ray diffraction and analysis supported the ability of the dye cations to be absorbed by the interlayer spacings of montmorillonite.

Keywords: natural sorbents, bentonite clays, ultrasound, environmental technologies, montmorillonite.

1. Introduction

Anthropogenic threats to the environment are often associated with air pollution by the release of chemical and mechanical pollutants;[1,2] with the Earth's surface pollution by heavy-tonnage industrial waste;[3,4] along with hydrosphere pollution by oil hydrocarbons,[5] heavy metals,[6] and other hazardous pollutants. For technologies, like the disposal of solid waste or treating of gaseous and water environment from pollutants, the use of adsorption methods is very promising. For the treatment technologies of water from pollutants, the adsorption methods allow the achievement of commercially available equipment design and high-degree treatment at low cost.[7,8] It is typically to use a wide range of adsorbents.[9] The most promising of them are those adsorbents that are synthesized from plant materials[10,11] and natural adsorbents – natural zeolite, montmorillonite, and glauconite.[12-14] From a range of these adsorbents, bentonites should be distinguished. They are widespread in the bowels of Ukraine, both in the form of industrial-scale deposits, such as Dashukivske and Ilnytske and in the form of regional-scale reserves that are present in all regions of Ukraine.

Bentonite clays are complex multicomponent systems, the main clay-forming component of which is montmorillonite. Montmorillonite is a finely dispersed layered aluminosilicate, which structure consists of two layers of silicon-oxygen tetrahedra. Between these layers, there is a layer of aluminum-oxygen octahedra. As a result of nonstoichiometric isomorphic substitutions of the ions of Al^{3+} for the ions of Mg^{2+} or Fe^{3+} in octahedral positions, a structural negative charge occurs. The charge is balanced by the interlayer cations, like Ca^{2+}, Mg^{2+}, Na^{+}, etc.[15] The hydrated interlayer cations can be easily exchanged for other organic and inorganic cations.[16]

The high ion-exchange, adsorptive, catalytic, and swelling properties along with the significant prevalence and simple extraction technologies of the rock-forming mineral of bentonite clay assume the widespread use of the natural mineral in agriculture and various industries. Bentonites are used for the disposal of industrial waste and used nuclear material[17] as well as for wastewater treatment for environmental purposes.[18] The petroleum-extracting industry uses bentonites as the component of drilling muds.[19] The food industry uses bentonites for clarifying wines and juices, as well as industrial and vegetable oils.[20,21] Now, bentonites can be used from a new perspective – as a cheap natural material for the production of catalysts and the creation of modern nanocomposite polymeric materials.[22]

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The properties of bentonites depend largely on the content of montmorillonite within such bentonites and on the nature of a cation exchange complex (CEC) of montmorillonite. Geological conditions of sedimentation and formation of the clayey rock define the crystallochemical properties of montmorillonite.[23]

Depending on the type of CEC that can retain varying quantities of water, the Ca-, Mg-, Na-, and other forms of montmorillonite are recognized.[24] Most deposits in Ukraine are represented by alkaline-earth bentonites which CEC contains the cations of Ca^{2+} and Mg^{2+}. Unlike alkaline bentonites that have the cations of Na^+, Li^+, and K^+ in the interlayer spacing, alkaline-earth bentonites have poorer performance characteristics – low ion-exchange capability and swelling.

The achievement of increased operating characteristics of bentonite clays occurs due to the activation of montmorillonite as the rock-forming mineral. Currently, various methods are used to modify clay minerals. A prevalent method is the chemical treatment of clays to be exposed to the solutions of salts and alkalis as well as organic and inorganic acids. The action of salt solutions, like NaCl and Na_2CO_3, ensures the conversion of alkaline-earth montmorillonite from the less active form into the more active Na-form. The monovalent Na^+ cations feature low-energy interactions with the silicate layer of montmorillonite. The presence of such cations in the interlayer spacings causes an increased lability of the montmorillonite structure – the ability to be adsorbed and dispersed.[25] Due to the treatment of bentonite clays with acid solutions, the specific surface area (SSA) of clay minerals increases and the secondary porosity appears in the mineral structure.[26]

The physical methods for activating bentonite clays are also widely used. These methods assume the exposure of layered aluminosilicates to the ultrasonic waves as well as the electric, electromagnetic, or complex fields.[27]

For bentonite clays taken from a specific deposit, the selection of activation conditions depends largely on the clay's mineralogical composition and structural properties. Thus, examining the effect of activation conditions on the properties of bentonite clays and determining the effectiveness of some methods are important to identify the quality of clayey rock and to predict the ways it can be used.

2. Experimental

2.1. Materials and methods

For the research, the researchers used bentonite from clayey manifestations of the forest-steppe zone of the Volyn-Podilsk Upland. Geological engineering surveys were conducted directly in the Northwestern part of Khmelnytskyi where bentonite deposits were uncovered with exploratory wells. The studied clay was taken from a depth of 27–31 m.

The studied rock was enriched in a clayey constituent of the rock by sedimentation of the coarsely dispersed phase. The rock was purified in distilled water at a 1:10 solid-to-liquid ratio. The resulting suspension was settled for 20 minutes. Then, the upper layer that contained the particles of the rock's clayey constituent of less than $10 \cdot 10^{-6}$ m was separated. The researchers removed carbonates under the action of a 9% solution of CH_3COOH.

The clayey constituent of the rock was enriched in montmorillonite by centrifugation (centrifuge OPN-8UKHLN.2) of clay suspensions for 30 seconds (1000 rpm). The precipitate was separated. After the centrifugation was completed, the resulting suspension was settled. As a result, the researchers obtained a clayey fraction with a size of less than $5 \cdot 10^{-6}$ m. The particle size was calculated according to the Svedberg equation.[28] The equation considers the geometric parameters of the centrifuge – a distance from the axis of rotation to the lower and upper levels of the suspension).

The scientific team performed a chemical activation of montmorillonite-enriched clay by using a 5 % aqueous solution of NaCl at a 1:20 solid-to-liquid ratio. Clay was activated for three days at room temperature and pH of 8.8. The suspension was periodically stirred. After separation, the liquid phase was drained off. The solid phase was treated with a 5% solution of NaCl three times.[29]

Ultrasonic dispersion of montmorillonite-enriched clay was conducted in an aqueous medium for 6 minutes. The radiation frequency was 40 kHz. The power of the radiation source was 60 W and the radiation intensity – 3 W/cm^2.

For X-ray diffraction analyses, the scientists used ADP-2.0 diffractometer with the following characteristics: Fe radiation, Mn filter, 30 kV, and 12 mA. The diffractometer was connected to an IBM-compatible computer. The swelling minerals of the montmorillonite group were examined by the behavior of *001* reflex in the area of small angles on the diffraction patterns of oriented specimens. These specimens were air-dried and saturated with ethano-1,2-diol.

For X-ray diffraction analysis of organic clay that was obtained as a result of the sorption of methylene blue (MB) dye by montmorillonite, the basal orientation of the particles was achieved by gravitational sedimentation of such particles from the aqueous phase of MB.

The capability of montmorillonite-enriched clay to adsorb organic pollutants was examined by using the methylene blue (MB) dye:
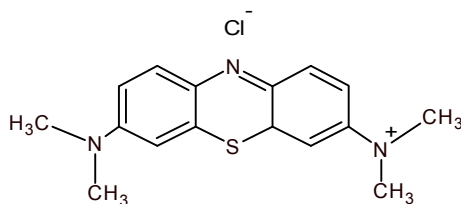
For MB dye of montmorillonite-enriched clays – both original clay and clay dispersed under the action of ultrasound – the sorption lasted for two days. The researchers added 50 cm^3 of the MB dye of known concentration to the air-dried samples of clay of 0.1 g. The system was stirred. In two days, the equilibrium solution was separated from the dispersed phase by centrifugation. The sorption value was defined by the difference between the concentrations of the original and equilibrium dye solutions. The equilibrium concentration of the dye in the solution was found by using the photocolorimetry method (photocolorimeter T-105 with a 30-mm long glass cuvette) at a light wavelength of 582 nm. MB sorption was investigated at pH of 6.5.

For the complex thermal analysis of the samples of montmorillonite-enriched clay and organic clay (obtained due to the adsorption of MB dye), the scientists used the Q-1500 derivatograph of the Paulik-Paulik-Erdey system. The derivatograph was connected to the computer. The samples were heated in the air up to 1000 °C. The heating rate was 5 °C per minute. The weight of montmorillonite-enriched clay was 200 mg. The weight of the samples of organic clay was 84 mg. Aluminum oxide was used as a reference substance.

Before conducting the analyses, the samples were dried for 3 hours at 50 °C temperature.

3. Results and Discussion

The X-ray diffraction analysis shows that the main rock-forming mineral of studied bentonite clay is dioctahedral Ca-, Mg-montmorillonite in association with illite, kaolinite, and a mixed-layer formation – illite-montmorillonite. The clayey constituent of the rock consists of montmorillonite and mixed-layered formations, which content is 75%.[30]

We observed montmorillonite by the position of the most intense line that corresponds to *001* plane in the area of small angles (from 3 to 12 degrees of 2θ angles) where Fe and Kα were radiated – in the area of large values of interplanar distances *d* (3.7–0.9 nm). As a basis for identification, we took the capability of liable "packets" to sorb polar organic compounds (ethane-1,2-diol) by interlayer spacings and to expand as two molecules of $C_2H_4(OH)_2$ are added.[31] In the diffraction pattern of the

saturated specimen, the *001* reflex of montmorillonite is nearly 1.68 nm. In the spectra of air-dried samples, this reflex has the form of a double line ranging within 1.42–1.54 nm in diameter (Fig. 1). The branching of the vertex of the reflex signifies a complicated exchange complex of the montmorillonite structure: the presence of Ca^{2+} and Mg^{+2} cations and, probably, organic compounds to be sorbed in natural systems during the formation of the mineral. The additional lines from the side of small angles (1.97 nm and 1.73 nm) in this spectrum confirm the presence of natural organic matter in the interlayer spacing of montmorillonite.

Montmorillonite examined in clay from the vicinity of Khmelnytskyi supports the data (No 13-135) of the mineral database of the JCPDS International Center for Diffraction Data. Based on this data, the structure of montmorillonite is defined from the following perspectives: by the formula $Ca_{0.2}(Al, Mg)_2 Si_4 O_{10}(OH)_2 \cdot 4H_2O$; by the oxide chemical composition (mass fraction (%): SiO_2 (59.58), Al_2O_3 (22.96), Fe_2O_3 (0.47), MgO (3.67), CaO (3.38), Na_2O (0.06).[32]

Being in association with montmorillonite, the mixed-layered formation of illite-montmorillonite was measured by reflexes of nearly 1.18 nm (in the area of 9–10 degrees of 2θ angles) in the spectrum of the air-dried sample. As the structure expands due to the saturation of ethane-1,2-diol, the values of reflex coincide with the main basal mapping of montmorillonite. In the diffraction pattern of the original specimen (Fig. 1), illite that features structural stability is identified by the following basal prints: 1.0; 0.50; and 0.332 nm whereas kaolinite – by the following basal prints: 0.72 and 0.357 nm.

The results of the X-ray diffraction analysis for the sample of montmorillonite-enriched clay are in line with the thermal analysis findings. Fig. 2 shows a thermogram of the sample for the clayey fraction with a particle size of less than $5 \cdot 10^{-6}$ m.

Montmorillonite, illite, and mixed-layered formations lost interlayer water (7.83%) in the temperature range of 20–220 °C. A deep endothermic effect in the DTA curve and a sharp extremum in the DTG curve indicate that loss.[33]

The burning of the natural organic matter adsorbed by the surface of particles of clay minerals occurred in the temperature range of 220–380 °C. While burning, the sample gradually lost its mass (1.92 %). In the DTA curve, a clear exothermic effect appeared. The maximum exothermic effect was observed at 245 °C.[34]

In the temperature range of 380–706 °C, the scientists observed the destruction of the structure of clay minerals and the loss of constitutional water. The endothermic effects appearing in the DTA curve indicate such destruction and loss. As the main clayey constituent of the rock, montmorillonite, when dehydroxylated, was followed by

the burning of the natural organic matter adsorbed by the interlayer spacing of montmorillonite.[35] In that temperature range the mass loss was 3.87%.
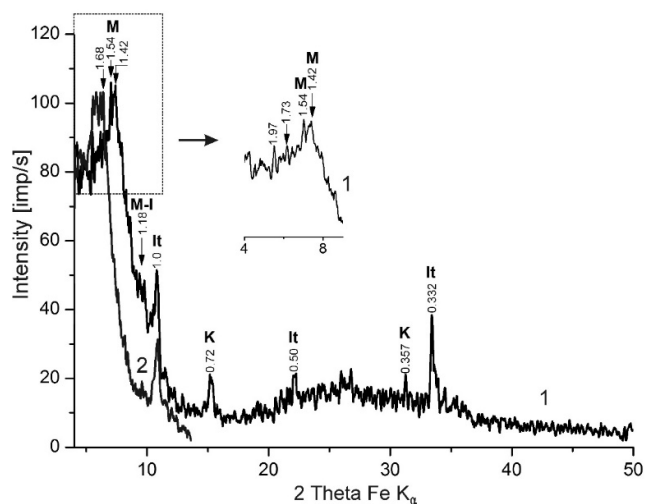

Fig. 1. Curves of the X-ray diffraction of the oriented specimens for the following types of montmorillonite-enriched clay rock: 1 – original (natural), 2 – saturated with ethane-1,2-diol. Designation of minerals: M – montmorillonite; M-I – illite-montmorillonite mixed-layered formation, It – illite; and K – kaolinite

Thus, the results of the X-ray diffraction and thermal analyses show that the fraction of the clayey constituent of the rock of less than 5 nm in size is enriched in Ca- and Mg-forms of montmorillonite. Interlayer spacings of montmorillonite are partially filled with the organic matter adsorbed under natural conditions. Alkaline-earth bentonite clays exhibit low adsorption, cation exchange, and swelling properties. To enhance the performance of such clays, they are transferred to the active sodium form by treatment with salt solutions.[36]

The method of clay modification relies on the enrichment of clay in ions of alkaline metals. As a rule, two-charged cations of Ca and Mg are replaced by ions of Na during the process of so-called alkaline activation. An increase in the relative part of cations Na^+ in the exchange complex of montmorillonite results in a reduced attraction between the layers of montmorillonite; and enhanced penetration of molecules of organic compounds and water into the liable space of the mineral. The conversion of natural bentonite to the Na-form can cause the separation of montmorillonite crystals into separate silicate plates and increase the active basal surface of these plates.

Fig. 3 (curve 2) shows the results of X-ray diffraction analysis for the clayey constituent of the rock that was enriched in montmorillonite and treated with 5% NaCl solution. The findings confirm that the structure of montmorillonite changed slightly during activation. Thus,

the diffraction pattern of the oriented specimen shows the intense reflex *001* corresponding to the interplanar distance of 1.50 nm. The reflex is typical of montmorillonite of Ca-form. Besides the reflex, the diffraction pattern shows a dispersed line of 1.42 nm in diameter. The line indicates the presence of Mg^{2+} ions in the interlayer spacings of montmorillonite. In the branching, at the vertex of the reflex, one can observe the well-defined lines of 1.75 and 1.62 nm. These lines correspond to liable spacings of montmorillonite with the adsorbed organic natural matter. In the slope of the right wing of the main reflex, a moderate peak of 1.26 nm is observed, corresponding to the Na-form of montmorillonite. The compression of the interlayer spacing during ion exchange is due to the ability of Na^+ ions to coordinate one layer of water molecules.[37]
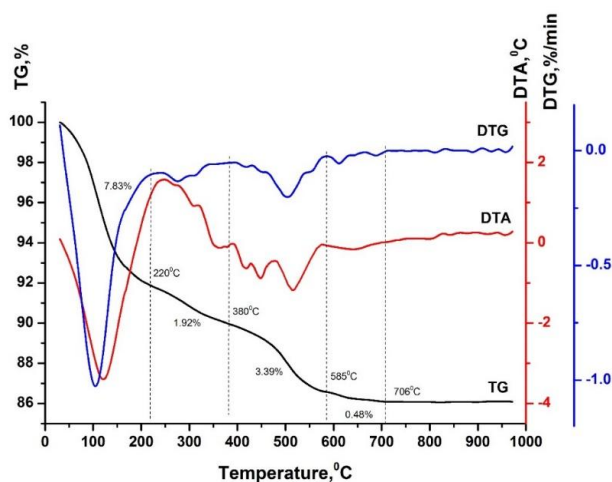

Fig. 2. Thermogram of the sample for montmorillonite-enriched clayey constituent of the rock

Thus, the treatment of the sample of enriched clay with a 5% NaCl solution yielded only a small amount of mineral with interlayer spacings typical of Na-form montmorillonite. At the same time, the structure of montmorillonite retained interlayer spacings filled with natural organic matter that prevented the processes of ion exchange from occurring with the involvement of Na^+ cations.

The use of the higher concentrated NaCl solutions for the conversion of montmorillonite into the active Na-form was not considered reasonable. It is known that an electrical double layer (EDL) occurs during the adsorption of metal cations on the surface of clay particles.[38] The inner part of EDL is made up of basal surfaces of clay particles. The outer part of EDL consists of a layer of hydrated cations. The structure of EDL depends largely on the concentration of a salt solution in which the EDL is formed.

As the electrolyte concentration increases, the thickness of the EDL diffusion part and the diffusion po-

tential of the surface decrease. The decreased charge of the particles' basal surfaces can cause the adhesion of aggregates and the loss of the aggregative stability of the suspension.

To enhance the cation-exchange properties, the montmorillonite-enriched clayey constituent of the rock was exposed to a physical activation – ultrasound. Based on the ultrasound-dispersed samples of clay, the researchers conducted calorimetry examinations of the adsorption of MB dye. Fig. 4 shows the findings represented as the adsorption isotherm. Also, the figure shows the adsorption isotherm for the MB dye by the sample of clay that was not exposed to ultrasound.

By using the maximum value of the adsorption, we found the cation exchange capacity (CEC) of the clay samples relative to MB. For natural clay enriched in montmorillonite CEC was 0.52 mmol/g and for clay activated by ultrasonic vibrations – 0.52 mmol/g.
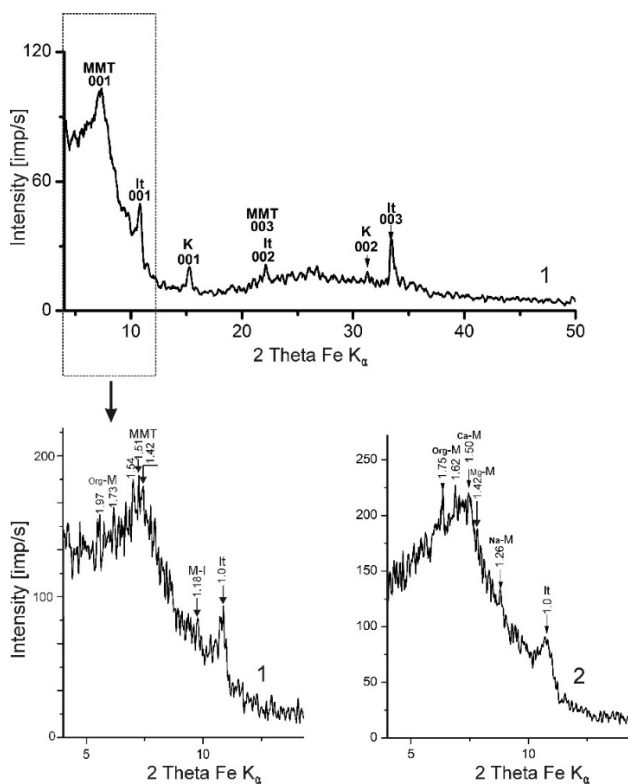

Fig. 3. X-ray diffraction curves for the oriented specimens of montmorillonite-enriched clayey constituent of the rock: 1 – original (natural), 2 – activated with 5% NaCl solution. Designation of minerals: $_{Ca}$-M, $_{Mg}$-M, $_{Na}$-M – Ca-, Mg-, and Na-form of montmorillonite; $_{Org}$-M – organo-montmorillonite; M-I – illite-montmorillonite mixed-layered formation; It – illite; and K – kaolinite

Based on the photocolorimetry studies, it can be suggested that ultrasonic vibrations significantly increase the CEC of montmorillonite-enriched clay. The explana-

tion for the obtained result can be the active dispersion of the particles of clay suspension due to the short-term effect of the ultrasound for 5–6 minutes. The dispersion is followed by an increase in the specific surface area of the solid phase, an opening of basal surfaces of clay minerals, and a growth in the number of active centers capable of participating in the ion exchange.[39]

In parallel to the dispersion of particles, the ξ-potential of such particles increases and dense hydrated shells form around them. The clayey suspension attains increased aggregate stability and the capability to participate in ion exchange processes for a long time. Further exposure to ultrasonic waves is undesirable as such exposure can cause an opposite phenomenon – aggregation of particles.

The efficiency of the modification of bentonites to increase their adsorption capacity is confirmed by the findings of the research on the adsorption of copper ions of natural bentonite and bentonite activated by the magnetic field.[40] For natural bentonite, the maximum adsorption capacity was 11.82 mg/g, and 25.74 mg/g for activated bentonite. The researchers[40] suggest that the adsorption capacity of the activated sample increases due to the formation of new adsorption centers.
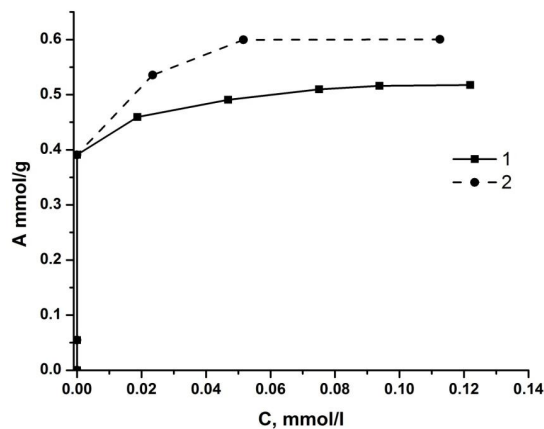

Fig. 4. The adsorption isotherm of the MB dye of the montmorillonite-enriched clayey constituent of the rock: 1 – original (natural); 2 – activated by ultrasonic vibrations

It is a well-known fact that during adsorption dye cations can interact not only with the surface of clay fractions but also can penetrate into interlayer spacings of montmorillonite. This way, these cations enter the cation exchange with natural inorganic cations. When the labile spacings of montmorillonite are filled with intercalated cations of dye, organo-mineral complexes are formed.[41] The findings of the X-ray diffraction and thermal analyses support the capability of the MB dye cations to be adsorbended by the interlayer spacings of montmorillonite.

Fig 5 shows the X-ray diffractograms for montmorillonite-enriched natural clay and organic clay. For both clays, CEC is 0.52 mmol/g. MB dye cations can be interspaced into labile spacings of the mineral in two rows when natural inorganic exchange cations and water molecules coordinated by these cations are substituted completely. By considering the lateral size of the MB molecule, the interplanar spacing of montmorillonite can reach 1.76 nm.[29] The X-ray diffractogram for organic clay illustrates the offset of the main basal reflex *001* to the area of small angles. Some quantity of interlayer spacings rises to 1.76 nm. Thus, two layers of MB cations form in some spacings of montmorillonite as a result of adsorption.

The diffractometric curve has a line that corresponds to the interplanar distance of 1.51 nm and indicates partial preservation of the natural exchange complex in montmorillonite. The lines with interplanar distances of 2.05 nm, 2.21 nm, and 2.51 nm indicate the probable intercalation of dye ions in the interlayer spacing of montmorillonite. It contains natural organic matter in the form of simple components.
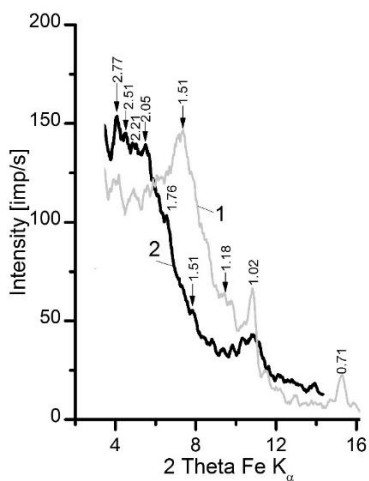

Fig. 5. The curves of X-ray diffraction of oriented specimens of montmorillonite-enriched clayey constituent: 1 – original (natural); 2 – organic clay with COE of 0.52 mmol/g

Fig. 6 shows the thermogravimetric curves for the samples of montmorillonite-enriched original (natural) clay and organic clay. For both clays, CEC was 0.62 mmol/g. Table compares the findings of the thermogravimetric analysis of these samples.

The mass loss (2.49%) of the organic clay sample in the temperature range of 20–158 °C agrees with the release of interlayer water by clay minerals. In this temperature range, dye cations lose crystallization water. Unlike the sample of the original clayey constituent of the rock, the sample of organic clay is distinguishable by less

interlayer water content. This shows that the structure of organic clay has less content of exchangeable cations of Ca^{2+} and Mg^{2+} that are able to coordinate water molecules.
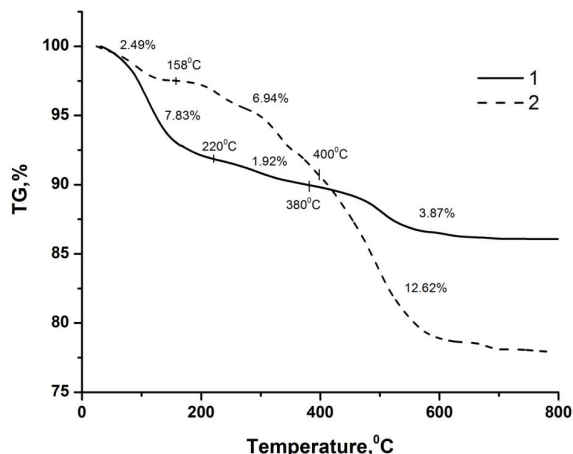

Fig. 6. Comparison of thermogravimetric curves of the montmorillonite-enriched clayey constituent: 1 – original (natural); 2 – organic clay with CEC of 0.62 mmol/g

Comparison of findings of the thermogravimetric analysis of the samples of montmorillonite-enriched natural clay and organic clay

Sample	Temperature range, °C	Mass loss, %
Original (natural) clay	20–220	7.83
	220–380	1.92
	380–706	3.87
Organic clay (CEC of 0.62 mmol/g)	20–158	2.49
	158–400	6.94
	400–700	12.62

The mass loss (6.94%) of the organic clay sample in the temperature range of 158–380 °C occurs due to the thermal oxidative destruction as well as the combustion of natural organic matter and MB dye ions that were adsorbed by the particles' surface of clay minerals. The complicated view of the TG curve in this temperature range indicates the heterogeneity of the organic component of the sample.

In the temperature range of 380–700 °C, one can observe the breakdown of clay minerals, the release of constitutional water, and the combustion of the organic constituent adsorbed by labile spacings of montmorillonite. Unlike the sample of the original clay (3.87%), the greater mass loss for the sample of organic clay (12.62%) is caused by the presence of MB dye cations in the interlayer spacing of the montmorillonite constituent of the sample.

4. Conclusions

Based on the X-ray diffractometry and thermal analyses, dioctahedral Ca-, Mg-montmorillonite in association with hydromica, kaolinite, and a mixed-layer formation of illite-montmorillonite is the main rock-forming mineral of the studied bentonite clay. The clay was taken from the left side of the upper Pivdennyi Bug River, a suburb of Khmelnytskyi. The structure of montmorillonite is defined by the formula $Ca_{0.2}$ $(Al, Mg)_2$ Si_4 O_{10} $(OH)_2 \cdot 4H_2O$ and the oxide chemical composition, %: SiO_2 (59.58), Al_2O_3 (22.96), Fe_2O_3 (0.47), MgO (3.67), CaO (3.38), Na_2O (0.06).

As a result of the modification of montmorillonite-enriched clay by 5% NaCl solution, the scientists obtained only a negligible number of packets, which interlayer spacing is typical of Na-form montmorillonite. CEC of montmorillonite-enriched clay of the clayey constituent regarding the MB dye was 0.52 mmol/g. The physical activation of clay by ultrasonic vibrations resulted in the achievement of CEC of up to 0.62 mmol/g. The increase in the adsorption capacity of activated clay is due to the increase in the specific surface area of the solid phase, the opening of basal surfaces of montmorillonite, and the creation of new adsorption centers during ultrasonic activation. These adsorption centers can participate in ion exchange.

During adsorption, montmorillonite can absorb dye molecules not only on the outer surface but also on the interlayer spacing. The offset of the main *001* basal reflex on the X-ray diffraction curves of organic clay towards the area of small angles confirms the formation of organomineral complexes. A significant mass loss of the organic clay sample in the temperature range of 400–700 °C is due to the combustion of the organic component to be sorbed by the interlayer spacing of montmorillonite.

Based on the conducted experiments, it can be asserted that ultrasonic activation provides additional perspectives for bentonite to be used as a purifier of the aquatic environment from organic pollutants of cationic and polar forms. The tested product of purification will represent the modified organic clayey complex that can be used for various purposes – for example, the removal of organic pollutants of the molecular form.

Ultrasound-activated bentonites can be used effectively in the technologies of the adsorptive treatment of water from pollutants.

Acknowledgements

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ПЕРСПЕКТИВИ ОЧИЩЕННЯ ВОДНИХ СЕРЕДОВИЩ ВІД ПОЛЮТАНТІВ АКТИВОВАНИМИ УЛЬТРАЗВУКОМ БЕНТОНІТАМИ

Анотація. *У роботі проаналізовані перспективи застосування природних сорбентів у природоохоронних технологіях. Об'єктом дослідження була глиниста порода з лівого берега верхів'я річки Південний Буг (околиці м. Хмельницький). Збагачення породи монтморилонітом проводили центрифугуванням суспензії глини з отриманням фракції ≤5 мкм. Мінеральний склад збагаченої глини встановлювали за даними Х-променевого дифрактометричного та комплексного термічного аналізів. Хімічну активацію збагаченої глини проводили 5 % водним розчином NaCl, фізичну активацію – дією ультразвуку. За результатами фотоколориметричних досліджень знайдено катіоно-обмінну ємність збагачених природної та активованої ультразвуком глин відносно барвника метиленового блакитного. Здатність катіонів барвника сорбуватись міжшаровим простором монтморилоніту підтверджували даними Х-променевого фазового та комплексного термічного аналізів.*

Ключові слова: *природні сорбенти, бентонітові глини, ультразвук, природоохоронні технології, монтморилоніт.*